Land husbandry

Components and strategy

FAO SOILS BULLETIN

70

Food and Agriculture Organization of the United Nations

Foreword

Since the 1939 work of Bennett, the father of soil conservation, the world has seen a host of erosion control manuals, most of them in English or Spanish and describing practical experience, technical principles, mechanical (and sometimes biological) methods to be used, and a series of practical recipes that have been adopted with varying degrees of success in specific regions. However, there have been few authors who, having seen at first hand the relative ineffectiveness of the generally recommended techniques, have been ready to re-examine the erosion control principles that Bennett developed for the very specific environmental, social and economic conditions of the large-scale, mechanized cropping of groundnut, cotton, tobacco and cereals, all providing little ground cover, that the European immigrants introduced into the semi-arid Great Plains of the United States of America during the Great Depression of the 1930s. Bennett's approach to soil conservation (based on draining runoff water from cultivated fields along gently sloping channels to designated outlets) was then applied, with no prior testing, in totally different circumstances (for example among small subsistence farmers in tropical upland areas) ... with the very indifferent results that have been seen by all.

Science has made giant strides since Bennett's day.

Firstly, it has been discovered that the kinetic energy of raindrops can lead to degradation of cultivated soils. Risks of runoff and erosion can therefore be cut by introducing production systems that provide better ground cover (Ellison 1944, Stallings 1953, Wischmeier and Smith 1960 and 1978, Hudson 1973, Roose 1977a, etc.).

Secondly, people have realized that there are many different processes in soil degradation and erosion, with a variety of causes – and a similar variety of sometimes contradictory factors involved in any action to alter them. Treatment of sheet erosion has, for instance, sometimes increased the risk of landslides (as can happen with marls).

Thirdly, differences in physical landscapes and in the social and economic conditions of effective application of erosion control methods are better analysed today. The erosion crises facing large-scale, modern landowners in temperate zones are no longer treated in the same way as the subsistence problems of poor, densely-populated communities clinging to tropical hillsides.

Instead of simply describing schemes that have worked in one specific place, today one has to learn to assess different conditions and work with, rather than against, the forces of nature; for example, by progressively modifying the slope of a hillside by slowing down sheet runoff and using farming techniques that will gradually terrace the land, instead of tearing at mountains with powerful bulldozers to produce often unstable and expensive-to-maintain infrastructure.

The author would like to remind agricultural experts that erosion control is not the exclusive domain of specialists working to rehabilitate land degraded because it has been more mined than farmed, but must incorporate the viewpoints of the land-use planner responsible for water and soil fertility management in the development of cropping systems that are profitable, sustainable, and safe for rural and urban environments.

Since the 1980s there has been much criticism of the failure rate of most programmes incorporating erosion control.

It is now recognized that there are two spheres in erosion control:

- **The State sphere**, with the government responding to disasters and sending in engineers to stop landslides, control torrents, replant mountains with trees, or harness watercourses that threaten structural works, lines of communication, inhabited areas, irrigation schemes and dams through siltation. In the public interest, representatives of the central authorities insist on water control in the rural environment. It is expensive and upsets the farmers, but is the only way of controlling the quality of water supplies (the off-site perspective), and only the State is in a position to engage in such large-scale mechanical undertakings.

- **The farming sphere** of land protection (the on-site perspective), which can be assured only by the rural community, so long as it is helped in making a correct diagnosis of the causes of the erosion crisis and the best ways of improving environmental protection, biomass production and living standards.

It is essentially on this latter sphere – that of water, soil fertility and biomass management (GCES), or **land husbandry –** that this work would like to focus, taking stock especially of research by French-speaking soil, agricultural and geographical experts (particularly from ORSTOM and CIRAD), who have worked mainly in Africa, where problems develop much faster than in Europe. After all, the work of English-speaking experts in this sphere is already well known (Wischmeier and Smith 1978, Hudson 1992).

The author presents a personal and intentionally confrontational point of view, offering a new and more constructive approach to the problems small farmers face in their battle with the degradation of their land. This is not a manual with clear-cut remedies for each and every erosion problem, but a work that should allow research experts, teachers and agronomists in the field to appreciate differences in situations, diagnose the causes of crises, and propose a range of technical solutions from which a small rural community (a family, a ward, a village, a slope, a hillside or a micro-watershed) can choose the technological package best suited to its particular needs. Rather more «instruction-oriented» material for training extension agents (Dupriez and De Leener 1990, Inades 1989) and more technical manuals on torrent control and landslides (Heusch 1988, CEMAGREF documentation) or improving soil fertility (Pieri 1989) are available elsewhere.

This document has been used for eight years as a basis for courses on «Land Husbandry as an Instrument in Land Management» given to 700 agricultural or forestry engineers at CNEARC and ENGREF in Montpellier, in France, and ANDAH in Haiti, as well as 50 senior water technicians at ETSHER in Ouagadougou, in Burkina Faso. It is hoped that future editions will be enriched with readers' comments and details of new experiences. It will have met its aim if it provides large numbers of land-use planners and agronomists with pointers for developing intensive and sustainable farming systems suited to specific environmental situations and social and economic contexts.

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Acronyms and abbreviations

ANDAH	Association Nationale des Agronomes Haïtiens
AREAS	Association Régionale pour l'Etude et l'Amélioration des Sols (France)
CEMAGREF	Centre National du Machinisme Agricole, du Génie Rural, des Eaux et Forêts (France)
CIRAD	International Cooperation Centre on Agrarian Research for Development
CNEARC	Centre National d'Etudes en Agronomie des Régions Chaudes (France)
CTFT	Centre Technique Forestier Tropical (CIRAD)
DRSPR	Division de la Recherche sur les Systèmes de Production Rurale de l'Institut d'Economie Rurale de Bamako (Mali)
EC	European Community
ENGREF	Ecole Nationale du Génie Rural et des Eaux et Forêts (France)
ESAT	Ecole Supérieure d'Agronomie Tropicale (France)
ETSHER	Ecole de Techniciens Supérieurs en Hydraulique Rurale (France)
ICRAF	International Center for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IITA	International Institute of Tropical Agriculture
INRA	Institut National de la Recherche Agronomique (France)
INRF	Institut National de Recherches Forestières (Algeria)
IRA	Institut de Recherche Agronomique (Cameroon)
IRAZ	Institut de Recherche Agronomique du Zaire
IRFA	Institut Français de Recherche Fruitière Outre-mer (CIRAD)
IRHO	Institut de Recherche sur les Huiles et Oléagineux (CIRAD)
ISAR	Institut Supérieure Agronomique du Rwanda
ISCO	International Soil Conservation Organisation
ITCF	Institut Technique des Céréales et des Fourrages (France)
LH	land husbandry
NGO	non-governmental organization
ONTF	Office Nationale du Travaux Forestière
ORSTOM	Institut Français de Recherche Scientifique pour le Développement en Coopération
PRATIC	Projet de Recherche appliquée à l'Aménagement intégré des Terroirs Insulaires Caraibes
RML	rehabilitaton of mountainous land
SPR	soil protection and restoration
SWC	soil and water conservation
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation

Acknowledgements

First of all I should like to express my gratitude to ORSTOM, which encouraged me to put to good use the knowledge French-speaking research experts have gained over the past thirty years in the field of soil conservation, water management and fertilization.

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I cannot close these acknowledgements without recalling all I owe to the «elders» who patiently initiated and guided me throughout my career: in France, Bernard Heusch, Frédéric Fournier, Claude Charreau and Georges Aubert; in the English-speaking world, Norman Hudson, Walter Wischmeier, Donald Meyer and William Moldenhauer.

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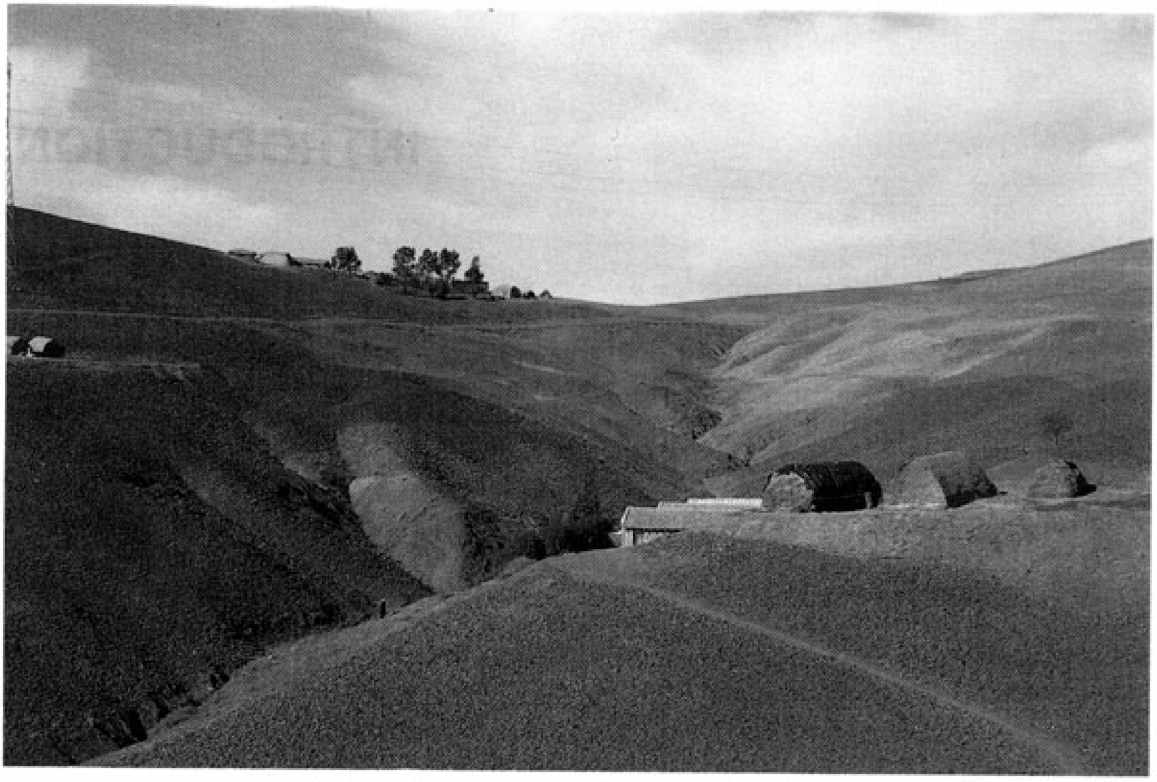
Most of the photographs have been taken from my own collection. Other sources have been cited in the text, and I am grateful for their assistance.

Ideas do not belong to any one person, but are the fruit of a long period of gestation and the encounter between people and a range of environments and socio-economic conditions. May all those who have played a part in this long labour be included in this expression of gratitude.

INTRODUCTION



Mediterranean semi-arid environment – Algeria 1986 (E. Roose)

Since the Earth first appeared it has been shaped by erosion... and for over seven thousand years human beings have pitted themselves against erosion, trying to defend their lands against the assaults of rain and runoff (Lowdermilk 1953). One may therefore wonder whether there is anything left for research to discover, or anything that has not already been said.

The scientific study of erosion, however, did not start until the early 20th century, first in Germany (Wollny), then 40 years later in the United States of America at the time of the Great Depression. Under pressure from a public panic-stricken by duststorms that were darkening the midday sun (the Dust Bowl), the American Government commissioned Bennett to set up the famous Soil Conservation Service, with about ten field stations to measure runoff and sediment load. And it was not until the 1940s that a scientist, shut away in his laboratory while bombs rained down over Europe, discovered that the kinetic energy developed by falling raindrops was the source of soil surface degradation, runoff and a major part of the erosion observed on cultivated land (the splash effect) (Ellison 1944).

Only in the 1950s, following the Madison Congress of the International Soil Science Association, did American methods of measuring runoff and erosion on small plots spread to French-speaking (F. Fournier) and English-speaking (N.W. Hudson) Africa, then Latin America and, more recently, Asia and Europe.

The United States therefore had a 20-year start on the rest of the world in collecting data and developing the first empirical model, the Universal Soil Loss Equation (USLE), to predict soil loss at plot level. The sole claim made for this model is that of helping engineers to design soil conservation systems for specific soil, climatic, topographical and plant-cover conditions, and it has disappointed many scientists who have applied it inappropriately outside this compass. Although it has eventually been seen that the USLE is not universal but is confined to circumstances where erosive energy comes not only from rain (but also from runoff, as in upland areas and on soils rich in swelling clay, or from gravity, as in landslips), this somewhat dated model is still today – and will be for some time to come – the only one sufficiently balanced to be used in many countries where runoff is associated with soil surface degradation. It will take a further 12 years or so to perfect new physical models and adjust them for each region – nor is it certain that they will perform better than the latest versions of the USLE, as long as the latter are restricted to their intended sphere of sheet erosion.

Similarly, in the field of soil conservation, people have long been satisfied to apply American-developed methods throughout the world, without testing their suitability for local conditions. However, in the last ten years, the significance of climatic, social, demographic and economic elements has been recognized, and this fact, together with new trial results, has raised questions about the treatments prescribed in all the manuals since Bennett.

It is primarily a matter of the rising failure rate for erosion control projects in developing countries (Hudson 1992), for American methods do not translate successfully to tropical countries. Local farmers who are familiar with land husbandry strategies in their traditional agricultures have been disappointed by the modern soil conservation methods imposed by international experts and government authorities: they require a lot of hard work and upkeep, and provide no improvement in yields. Even if the soil cover is kept in place, tropical soils are usually so poor that their fertility has to be restored and their infiltration capacity improved if they are to produce significantly more than traditional systems.

Also, farmers will sometimes abandon such developed land or destroy trees donated under projects, suspecting the State of wanting to get its hands on their land – for land traditionally belongs to those who care for it, and trees mark its boundaries. Hence the spate of misunderstandings and failures throughout the Maghreb and West Africa.

Even in the United States, evaluation of 60 years of water and soil conservation – which have swallowed up billions of dollars – reveals only partial success. There are still major problems of pollution (linked to animal husbandry, chemical fertilizers and industry) and of sediment transport in rivers: 25% of tilled land loses over 12 t/ha/yr of sediment, the official tolerance level for deep soils. The situation today would of course be worse had nothing been done, but the need for a change in approach seems clear. Hitherto, soil protection has been carried out by volunteer farmers with State assistance, since everyone realized that the environment must be protected in order to ensure land productivity for future generations.

The American survey shows that erosion does not necessarily lead to a fall in yields, particularly on thick loess deposits. Today the State tends to introduce coercive clauses; for example, if farmers do not participate in a given programme to freeze fragile land, swamps and mountains, or do not abide by instructions for erosion control on tilled land, they will have no right to government subsidies intended to encourage them to diversify production.

Analysis of the effects of selective erosion on tropical land, especially forest areas where chemical and biological fertility is concentrated in the top 25 cm of the soil, shows that:

- it is not enough to improve degraded land (soil protection and rehabilitation) in order to address farmers' problems;

- even soil and water conservation (SWC) tends to be unwelcome, since it requires considerable work and brings little improvement in yields.

To meet the challenge of this century and feed a population that doubles every 20 years, not only must the serious processes of gullying and landslides that produce sediment load in rivers (the sphere of State concern) be halted, but also water and nutrients on good land must be correctly managed before degradation sets in, and degraded but potentially productive soils must be rehabilitated. Only farming communities can manage the rural environment, and if farmers' co-operation is to be assured, they must be shown, on their own land, that sound land management (including a range of technological packages) can quickly increase their output and returns, optimize their labour, and make their efforts more profitable, while effectively protecting their land capital.

It should be noted that it is not always necessary to resort to sophisticated techniques with expensive inputs, or to import machinery that is hard to maintain. Astonishing results can often be achieved simply by combining scientific knowledge of the phenomena to be corrected with traditional know-how. This is the case with zaï, a traditional method of rehabilitating degraded soil among the Mossi of Burkina Faso. With no other input than labour (350 hours/ha) and manure (3 t/ha/yr), 600 to 1 000 kg of grain can be grown on the regenerated fields. And with a little supplementary mineral fertilizer (N and P) results considerably higher than the national average (600 kg/ha/yr) should be achieved (Roose, Dugue and Rodriguez 1992).

Certain favourable circumstances have led to a change in farmers' attitudes to soil conservation projects.

First, **drought** has brought much suffering to the people of the Sahel and reduced livestock by half. It has shown farmers that they must change their practice of extensive farming, balance their livestock holdings against availability of forage, and organize village-based land-use planning, as the boundaries of villages are now known. This crisis has revealed the importance not only of protecting land against erosion (expressed in t/ha/yr), but above all of managing the available water (reducing runoff) and nutrients (mulch, manure, compost, and mineral supplements), and halting the water and nutrient losses caused initially by erosion and then by drainage.

Secondly, and strangely enough, the **"cost-pricing" operation** for mineral fertilizers required by the World Bank in Africa has shown the validity of organic fertilizers and, most importantly, the low stocks of nutrients easily taken up by plants in most tropical soils (other than some volcanic soils, brown vertisols or alluvial soils). It is extremely dangerous to the nutritional status of both human beings and livestock to be reduced to simply recycling the biomass (dung, paddock litter, compost, mulch, and ever-shorter fallow) which inevitably translates into soil deficiencies (N, P, K and Ca + Mg in very acid soils). Mineral supplements incorporated in compost are essential for any intensification of farming, if only to allow the growth of atmospheric nitrogen-fixing legumes.

The third circumstance that has aroused interest in land husbandry projects is **population growth** (an increase of 2.5 to 3.7% per year, or a doubling every 20 years) as a result of improved hygiene and diet. In West Africa the boundaries of village lands used to be uncertain, if not indeed a bone of contention, but land was plentiful and traditional chiefs used to grant plots to anyone asking to farm them. Nowadays, **land availability is frequently exhausted**, and instead of expanding croplands with little thought to their degradation, people have to live exactly where they are, making the most of natural resources.

Three strategies are generally developed to cope with land pressure in African countries:

- emigration, either for the dry season or for good, of some of the children to the less arid zones where there are better returns from work;

- supplementing farm revenue with other activities – craft work, trading, teaching, etc.;

- improving land management, intensifying and diversifying production by choosing more profitable lines (specialized livestock, fodder crop production, vegetables, fruit, forestry products for fuelwood and poles, tree nurseries, etc.).

In Yatenga in north-western Burkina Faso, rural development project activities have enabled some young people to find enough resources locally to live decently. As a result of extension work, and of drought or pressure on land as the case may be, farmers today are much better disposed toward village-based land-use planning projects. Their aim is to protect their land resources, but especially to manage the scarce available water and nutrients in the biomass. Or they may simply want to own the land – for, after the various upheavals, no one knows for sure if the land belongs to the village community, the State, citizens with official documentation, or simply whomever develops and farms it.

Finally, **research has also advanced** in a number of fields. Experts have measured the relative effect of the various factors influencing erosion. They have shown that the slope gradient is more important than its length, whose effect is closely linked to the state of the soil surface, especially its roughness. Under certain conditions, the actual topographical position is extremely important, since the lower slopes quickly becomes waterlogged from hypodermic runoff from uphill or from a rising water table near rivers. Under certain conditions (e.g. the chalky, clayey soils of the Mediterranean region), sheet erosion on hillsides is less serious than regressive gullying, which starts from the streams, attacking rich alluvial soil and irrigated terraces before cutting into the slopes. This means that erosion control operations should not necessarily concentrate on steep slopes. Runoff from barely sloping broad pediments and slaking loamy soils can be more serious than from steep slopes that are well protected by leafy vegetation or a gravel pavement (Heusch 1970). A river can swell in a rainstorm without runoff from steep slopes (the theory of the partial contribution of a catchment basin to runoff; Cosandey 1983, Campbell 1983).

Soil is not necessarily a "non-renewable natural resource". While it is true that if the thin layer of a rendzine covering a chalky rock is lost, that land will be lost for thousands of years and runoff water will concentrate there, if the six rules for restoring soil fertility (page 36, Chapter 2) are respected, it will take one to five years to bring life and productivity back to totally degraded and abandoned soils (e.g. the tropical ferruginous soils rehabilitated by the zaï method in Burkina Faso).

Soil conservation has hitherto been seen as a long-term investment in order to protect future generations' land legacy, and this was in fact the theme of the fifth ISCO conference in Bangkok (Rimwanich 1988). The new strategy of land husbandry represents an attempt to solve the immediate problems facing farmers: ensuring a clear increase in biomass production and income by improving the management of surface water and nutrients on the best land, rehabilitating degraded land that has potential (a sufficiently deep profile), finding the least expensive way of stopping gullying, and collecting runoff water in order to establish core areas of agricultural intensification. Insofar as the farmers must be trained to protect their environment, matters must be viewed from their perspective; in other words, any effort must see a return – and very quickly.

Progress on the technological level is also being made today. For example, it has been realized that mechanical methods of erosion control (terracing, drainage ditches, diversion bunds) are not the main thing, but must be kept to a minimum, using the simplest and cheapest methods as back-up to more effective biological methods (Hudson 1992). Other methods of runoff control seem to be better suited to the African smallholder than the diversion works recommended by Bennett for large-scale mechanized farming in the United States.

Farmers are often more ready to accept water (and nutrient) management methods such as water harvesting in semi-arid zones, total infiltration (mulching) or dissipation of runoff energy through use of grass banks, hedges or stone bunds, for these are approaches that are closer to their traditional methods and enable them to improve security if not production levels.

Another major issue is that of **tillage**.

The validity of deep ploughing and heavy mechanization is being re-examined, for, in contrast to their success in allowing an immediate increase in infiltration, rooting and yields (more than 30% to 50% on soils capable of storing the extra infiltrated water), they also speed up mineralization of organic matter in the soil, destroy its stable macroporosity and structure, increase hydraulic differentiation in the soil profile, reduce its cohesiveness (and thus its resistance to runoff) and in the medium term (10 to 30 years) accelerate its degradation. Major efforts are at present being made in Africa and elsewhere (United States, Brazil, Europe) to develop cropping systems that use minimum tillage, confining the operation to breaking up the soil with a toothed implement along planting rows, which also receive fertilizer.

In the Sudanian zone of Cameroon, for instance, 10 to 15 years of annual ploughing + hoeing + ridging under intensive cropping of cotton + cereals are enough to induce degradation of tropical ferruginous soils, which are all the more fragile, being sandy, poor in organic matter (less than 1%) and exposed to violent rains (Boli, Bep and Roose 1991). Thirty years of fallow, burning and extensive grazing will not sufficiently improve soil fertility: carbon increases from 0.3% to 0.6%, nitrogen remains at around one-tenth the rate of carbon, and the pH goes up by one unit (5 to 6). Animals are the most effective means of improving soil quality: in earthworm casts, *Trinervitermes* termites' nests and former overnight cattle corrals, carbon can reach 1% and the pH exceed 6.5.

There must thus be a return to farming systems similar to forestry systems in which the soil is never completely bare, receiving regular mineral and organic inputs from the litter. As in traditional cropping systems, an attempt is now being made to reinstate spatial variation within the cropped zone, plant deep-rooting trees that will bring dispersed nutrients to the surface, rear animals that enhance the biomass and concentrate scattered nutrients and grow crops combined with an under-storey of plant cover (weeds or a carpeting of legumes).

Developed village land is no longer strictly **divided** into **forest area** (livestock help to control weeds, as do certain interplanted crops), **rangeland area** (forage shrubs play a major role in improving forage quality, especially during the dry season), **inhabited area** (the surrounding highly intensive multi-storey gardens are an important source of revenue) and **cropped area**. There are thus many positive interactions among trees, livestock and crops (see the ICRAF studies).

It was felt that it would be useful to present data gathered over the past 40 years by French-speaking scientists in Africa, Latin America and Europe, in order to provide a good overview of these new situations and a whole new approach to protecting agrosystems.

In **Part One**, after defining the terms to be used, the range of different situations in terms of processes, timescales and places, the aims of those directly involved, and the demographic, sociological and economic conditions of the farmers are indicated.

Part Two contains a brief study of the various processes and a more detailed one of "early" forms of erosion, i.e. sheet and rill erosion and dry mechanical erosion. A systematic analysis of factors governing erosion within the framework of Wischmeier and Smith's 1978 Universal Soil Loss Equation (USLE) for predicting soil loss leads naturally to proposals for a practical approach to defining erosion control.

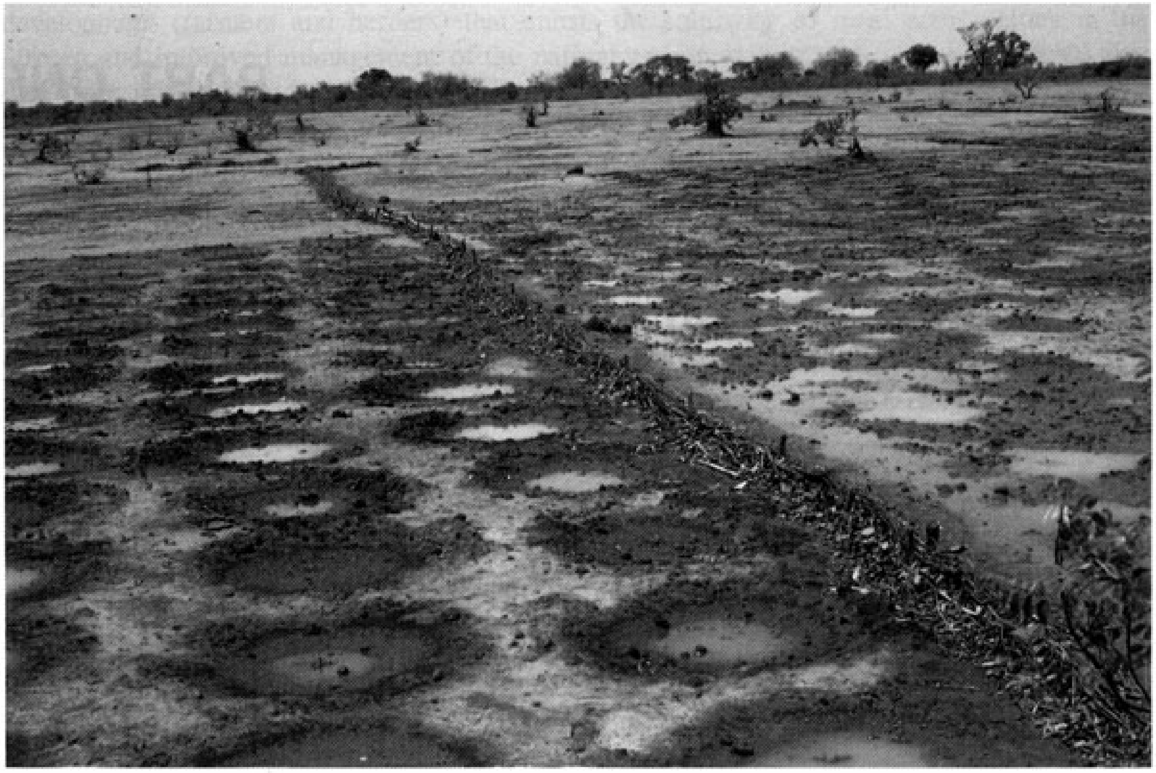
Lastly, **Part Three** presents a series of case studies from densely populated tropical mountainous areas (Rwanda, Ecuador, Algeria, Cameroon), subequatorial areas (Côte d'Ivoire), semi-arid tropical areas (Burkina Faso, Mali) and temperate zones (northern France).

There is no intention here of denying **the responsibility of the State** in the spheres of land-use planning, rural infrastructure, mountain reforestation, torrent control, protection of rivers, dams and other engineering works such as the rehabilitation of mountainous terrain, teaching people to respect their environment, training specialized technical staff, and subsidies for upland agriculture to prevent emigration. However, it may be helpful to complement this hydraulic infrastructural approach with one from the perspective of rural agricultural development (farmers and herders) that enlists the solidarity of rural communities in the upkeep and improved management of the natural resources (water + soil + nutrients) that they have inherited and must responsibly bequeath to future generations.

This work has evolved from a course, "Land Husbandry as a Tool of Land Management," which has been given over the past seven years to agricultural engineers, foresters and water technicians at CNEARC and ENGREF in Montpellier in France, ETSHER in Ouagadougou, Burkina Faso, Chad and in Haiti. It is a working document which it is hoped will be improved as more information and trial results come in. It was produced with a view to offering constructive new ideas and encouragement to agricultural experts in NGOs and national and international institutions who have the task of working in the field to improve people's standard of living and the health of the land that feeds them.

PART ONE

Erosion control strategies and the concept of land husbandry



In the Sudano-Sahelian savannah (400-700 mm rainfall) human-induced land degradation as a consequence of intensive tillage cropping. Impervious crusting soils are being rehabilitated by traditional "zaï" techniques (pitting and manuring).

Chapter 1

Definitions: words conceal a philosophy

The problems of environmental degradation are closely bound up with the development of populations and civilizations. They are of equal interest to agriculturists, foresters, geographers, hydrologists and sedimentologists as well as to social economists. However, each discipline has developed its own specialized language, so that the same words can have different meanings to different experts.

It is therefore necessary to specify the meaning of words and the meanings given them by the various specialists who enter the picture at different points in time and space in pursuit of their own goals. This is vital for the design of more effective erosion control projects.

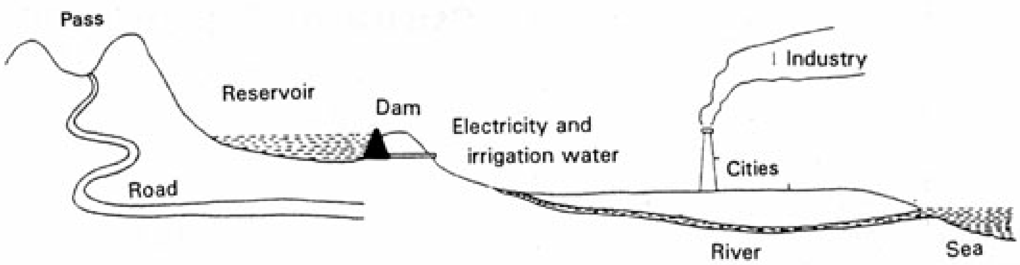
EROSION

"Erosion" comes from *erodere*, a Latin verb meaning "to gnaw." Erosion gnaws away at the earth like a dog at a bone. This has given rise to the pessimistic view of some writers who see erosion as a leprosy gnawing away the earth until only a whitened skeleton is left. The chalky mountains around the Mediterranean well illustrate this stripping away of the flesh of mountains as the trees are cut down and the sparse vegetation burned (e.g. Greece). In reality, this is a **natural process** which indeed wears down all mountains (also referred to by the English school as the denudation rate, which is the lowering rate of the soil level); however, at the same time erosion enriches valleys and forms the rich plains that feed a large part of humanity. It is therefore not necessarily desirable to stop all erosion, but rather to reduce it to an acceptable or tolerable level.

SOIL LOSS TOLERANCE

In terms of erosion, tolerance was first defined as soil loss balanced by soil formation through weathering of rocks. This can vary from 1 to 12 t/ha/yr, according to climate, type of rock and soil depth. However, it was very quickly realized that the productivity of the humiferous horizons, rich in biogenic elements, is far greater than that of alterites, weathered rocks which are more or less sterile. Moreover, this approach ignores the importance of the selective erosion of the nutrients and colloids that are what make soils fertile. Tolerance was then defined as **erosion that does not lead to any appreciable reduction in soil productivity**. Here too, however, there were considerable problems. There is still not enough known about the loss of productivity of different types of soil in relation to erosion; and in the case of some deep soils on loess, high soil losses on slopes entail only a small drop in soil productivity, but do lead to unacceptable damage downstream in terms of pollution of fresh water and siltation of dams.

FIGURE 1
Variety of erosion problems in different places: diversity of perspectives and agents



Locations: Mountains — Lower slopes: Erosion + Transport/Rivers — Plains — Coast
Main process: Detachment — Sedimentation/Pollution

Strategies

RML | SPR + SWC | SWC

≠ different locations ≠ strategies ≠ disciplines ≠ agents' goals

EROSION on slopes (sediment yield) > < Sediment transport in rivers (sediment delivery)

TRANSPORT EFFICIENCY
(sediment ratio)
< 1 if colluvium
> 1 if heavy erosion of banks

Two perspectives

On-site farmers' perspective

Objective land productivity
= agricultural development

Means = improving farming systems
biological erosion control

Agents = Farmers + village authority
Agronomists, soil experts, sociologists)

Off-site urban perspective

Objective protection of water quality
= rural infrastructure

Means = reforestation + mechanical erosion control
gully control
protection of dams and civil engineering works

Agents - Urban dwellers + irrigation cooperative
Central government + engineers
- Hydrologists + sediment experts
- Capital development + forestry
Rural and civil engineering

Three aspects must therefore be considered: speed of soil rehabilitation; maintenance of soil productivity given equal inputs; and respect for the environment in terms of water quality, especially runoff sediments (Stocking 1978, Mannering 1981).

EROSION VARIES ACCORDING TO PLACE: DIFFERENT AGENTS, TWO PERSPECTIVES

Erosion is the result of several processes and can be divided into three phases: loosening of particles, solid transport, and sedimentation. Whatever the scale of study – a square metre or a watershed of hundreds of thousands of square kilometres – these three phases are always found, although they will differ in intensity, with the agents of erosion differing according to the predominant phase.

In mountainous country, when plant cover is destroyed, gullying, torrents and landslides carry away much solid matter, causing widespread damage to communication networks. Public works engineers and foresters then come in to maintain lines of communication, replant rangelands and ski runs, reforest denuded slopes and control torrents. Rural populations are primarily concerned with managing water and nutrients on pastures or irrigated terraces rather than combating erosion (see the Cévennes and the irrigated Alpine grasslands in France).

In the foothills where slopes are still steep, erosion damage comes from gullying by torrents, which transport huge amounts of sediment load, and to a lesser degree from vegetation degradation through overgrazing or fires and "pirate" (unplanned, unsupervised) farming. Here again, foresters will try to solve the problem of dam siltation through rehabilitation of mountainous land (RML) and soil protection and restoration (SPR).

Lastly, in the plains, the most frequent problems are siltation of canals, rivers and ports, flooding of major riverbeds, muddy colluvial deposits in residential areas (ill-advisedly built downhill from land that, though it should not be, is under mechanized cultivation), and water pollution (fine suspended sediment [washload] or toxic discharges from farming or industry).

As Figure 1 shows, the parties to soil degradation and the departments engaged in erosion control vary, as do their goals and strategies. The wide range of forms of erosion in different places is matched by a similar variety of agents of erosion control and interests at stake.

On farms and hillsides, those who manage the land, i.e. farmers, agronomists, soil scientists and geomorphologists, speak of erosion or soil loss (sediment yield). In speaking of rivers, hydrologists and sedimentologists talk about sediment delivery, or suspended load (clay, silt and organic matter in suspension – i.e. the washload), and bedload (coarse sand and gravel). There can be considerable differences – arising from the so-called "sediment ratio" - between hillside erosion and sediment delivery in a river. What happens is that some heavier sediment is deposited, if only temporarily, at the foot of slopes and in valleys, providing nutrients to colluvial and alluvial soils and not reaching the sea or a dam reservoir until much later, so that the sediment ratio is less than 1. Specific washload ($t/km^2/yr$) decreases as the watershed increases in size. For example, on loesses in Brabant, Belgium, Bolline (1982) recorded particle detachment due to splash erosion at a rate of about 130 t/ha/yr under a rotation of beet and wheat. Soil loss from the foot of 25-metre-long plots was no more than 30 t/ha/yr, and sediment transport in the nearby river barely 0.13 t/ha/yr. In France, some experiences (Boiffin, Papy and Peyre. pers. comm., 1990) have shown that erosion on the slaking loamy soils of the Paris basin is worrying only when conditions favouring runoff concentration occur together: soil sealed by slaking crusts, scanty plant cover, extended rainy period, large plots where land consolidation has eliminated runoff management structures.

By contrast, in mountains or wherever drainage slopes are steep (e.g. the Mediterranean region), the erosive energy of runoff is higher than that of rain. Soil loss from cultivated fields may be small (0.1 to 15 t/ha/yr – Heusch 1970, Arabi and Roose 1989), while sediment transport exceeds 100 to 200 t/ha/yr in gullies and wadis (Olivry, pers. comm., 1989; Buffalo, pers. comm., 1990). In this case, the larger the catchment area, the more abundant and fast-moving is the concentrated runoff, the greater are peak discharges, and the more runoff gnaws away at the bed and sides of wadis, causing gullying and landslips on low terraces. In this last case, the sediment ratio can be higher than 1 and specific erosion can increase with the size of the catchment area (Heusch, pers. comm., 1973).

EROSION VARIES ACCORDING TO TIME

- **Normal or geological erosion** (morphogenesis) is generally defined as the process that slowly shapes hillsides (0.1 to 1 t/ha/yr), allowing the formation of soil cover from the weathering of rocks and from alluvial and colluvial deposits (pedogenesis). A terrain is described as stable when pedogenesis (speed of rock weathering) and morphogenesis (erosion, denudation) are in balance.

- However, geological erosion is not always gradual. In zones subject to paroxysmic orogenic upthrust, the sediment transport rate can reach 50 t/ha/yr (Indonesia, Nepal, the Bolivian Andes) and up to 100 t/ha/yr in the Himalayas which are rising by 1 cm every year. Likewise, in cyclone-prone tropical zones, morphogenesis is currently very pronounced, especially where plant cover has been degraded (communication from Heusch 1991). Geological erosion can also occur suddenly and **catastrophically following rare events** – a series of rainstorms which soak the ground, or during seismic or volcanic activity. An example would be the memorable mud flows in Colombia which wiped a village of 25 000 inhabitants (Nevado del Ruiz) from the map in a single night in 1988. At the Telman dam in southern Tunisia, Bourges *et al*. (1979) have recorded annual average runoff of 14% to 25% of rainfall and soil loss of 8.2 t/ha/yr, but on 12 December 1978 there was a once-in-a-century rainfall of 250 mm in 26 hours, resulting in 80% runoff and soil loss of 39 t/ha in a single day. Such **catastrophic phenomena are not rare on the geological timescale**. Flotte (pers. comm., 1984) has described the torrential lava flow at Mechtras in Great Kabylia (Algeria) of about 150 million m^3, covering 18 km^2, 7 km in length, on a 6.8% slope. These catastrophic movements, involving large volumes of mixed material and spreading over several kilometres in a very short time, often depend on climatic factors different from those known today. However, such masses could always be set in motion again if the required climatic factors coincided (exceptionally heavy rain after soil freezing or emission of steam from volcanoes or earth tremors), or after poorly-planned “management” has unbalanced slope equilibrium.

It is very difficult to control these two types of geological erosion, for the necessary means are expensive and not always effective. In France, the Major Risks Department of the Finance Ministry (la Délégation aux Risques du

DIFFERENCES IN EROSION PROBLEMS IN TERMS OF TIME

Erosion arises from two types of problem:

• GEOLOGICAL PROBLEMS	• SOCIAL AND ECONOMIC PROBLEMS
Conflict between:	Growth of population and needs
- weathering of surface layers of rock by water and biosphere PEDOGENESIS	SPREAD of areas that are cleared, grazed, cropped
- erosion that sculpts the earth's surface MORPHOGENESIS	REDUCTION in length of fallow periods
▫ *NORMAL GEOLOGICAL EROSION* = 0.1 t/ha/yr Runoff = 1 %	▫ *ACCELERATED EROSION* = 10 to 700 t/ha/yr Runoff = 20 to 80 %
SCOURING of 1 metre of land takes 100 000 years	100 years

▫ CATASTROPHIC EROSION: 1 metre in a few hours!

▫ GULLYING: 100-300 t/ha/DAY
▫ MASS SLIPS: 1 000-10 000 t/ha/HOUR

Example: the 3.10.1988 storm at Nîmes in France produced 420 mm of rain in 6 hours
produced 4 thousand million FF of damage and 11 fatalities

CONCLUSIONS:

Erosion events are very irregular.
The press and the authorities only show an interest in disasters.
Land husbandry is concerned more with accelerated erosion during the initial phase:

sheet and rill erosion, degrading farmers' good land
restoring productivity of deep soils
management of land fertility for the future
improved use of treated gullies and surface water.

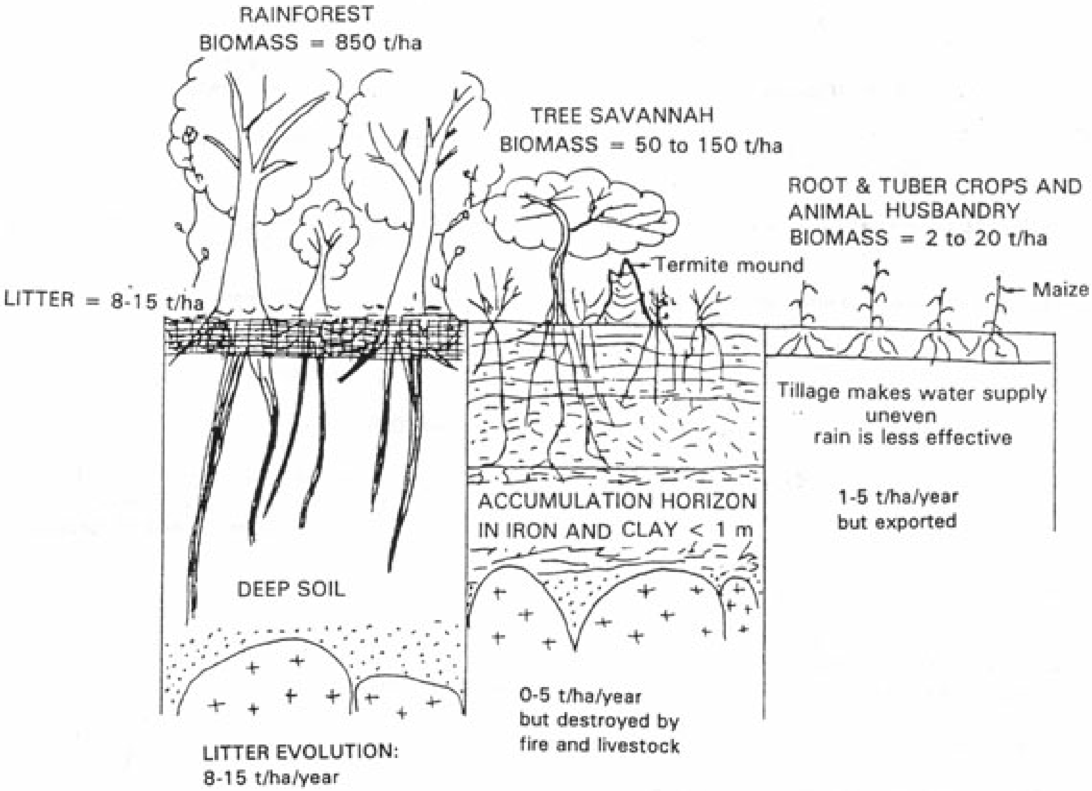
Ministère des finances) will declare a state of natural disaster and require insurance companies to reimburse the damage, so the costs are passed on to the whole community of insurance-holders.

- **Erosion accelerated by human activities**, following careless exploitation of the environment, is 100 to 1 000 times faster than normal erosion. It takes a soil loss of 12-15 t/ha/yr, i.e., 1 mm/yr or 1 m/1 000 years, to exceed the rock weathering rate (20 to 100 000 years to weather a metre of granite in high-rainfall tropical conditions, according to Leneuf 1965). The arable layer loses particles through **selective erosion** ("soil skeletonization") and gets thinner (scouring), while runoff increases (20 to 50 times more runoff under crops than under forests), resulting in peak flows further downstream that are highly prejudicial to the hydrographic network (Roose 1973).

  Definitions must still be given of the **suspended load** (the weight of particles in suspension in water), the **capacity** of a fluid (the mass of particles it can transport) and the **competence** of a fluid (the largest size of particle it can transport in relation to its speed).

FIGURE 2

Nature of problems: imbalances in the "managed" environment lead to soil degradation, then erosion speeds up the process



In terms of:

Vegetation ...
- Simplification of the ecosystem → decrease in biomass ↘
- Protection of the environment against the energy of sun and rain is less effective ↘

Climate ... Rise in temperature → increasing dryness

Soil ...
- ↘ Reduction of depth of cultivated soil → Reduction of biological replenishment
- ↘ less new litter — ↘ amount of organic matter in the soil; ↘ biological activity of the soil
- degradation of structure — slaking crust; ↘ macroporosity; ↘ plough pan — reduction in infiltration
- ↗ risks of runoff + EROSION + leaching

3 consequences
- ↗↗ loss of nutrients
- ↘ storage capacity (water + nutrients) → soil depletion
- ↘ water for biomass production

SOIL DEGRADATION [Plate 3]

There are also a number of causes of soil degradation: salinization, waterlogging, compaction through mechanization, mineralization of organic matter, and skeletonization through selective erosion. In the humid tropics, although erosion comprises three phases (detachment, transport and sedimentation), degradation of cropland affects only the destabilization of the soil structure and soil macroporosity but not particle transport over long distances. Basically it comes from two processes:

- **mineralization of organic matter in the soil** (more active in a hot, humid climate) and mineral uptake by crops (uncompensated by applications of manure), leading to a reduction in the activity of the micro- and mesofauna responsible for macroporosity;

- **skeletonization or relative increase of sand or gravel in the surface horizons** through selective erosion of fine particles, organic matter or nutrients as a consequence of rain splash, which compacts the soil, breaks up clods, and carries off particles which form thin slaked surfaces and sedimentation crusts in the vicinity, which then encourage runoff.

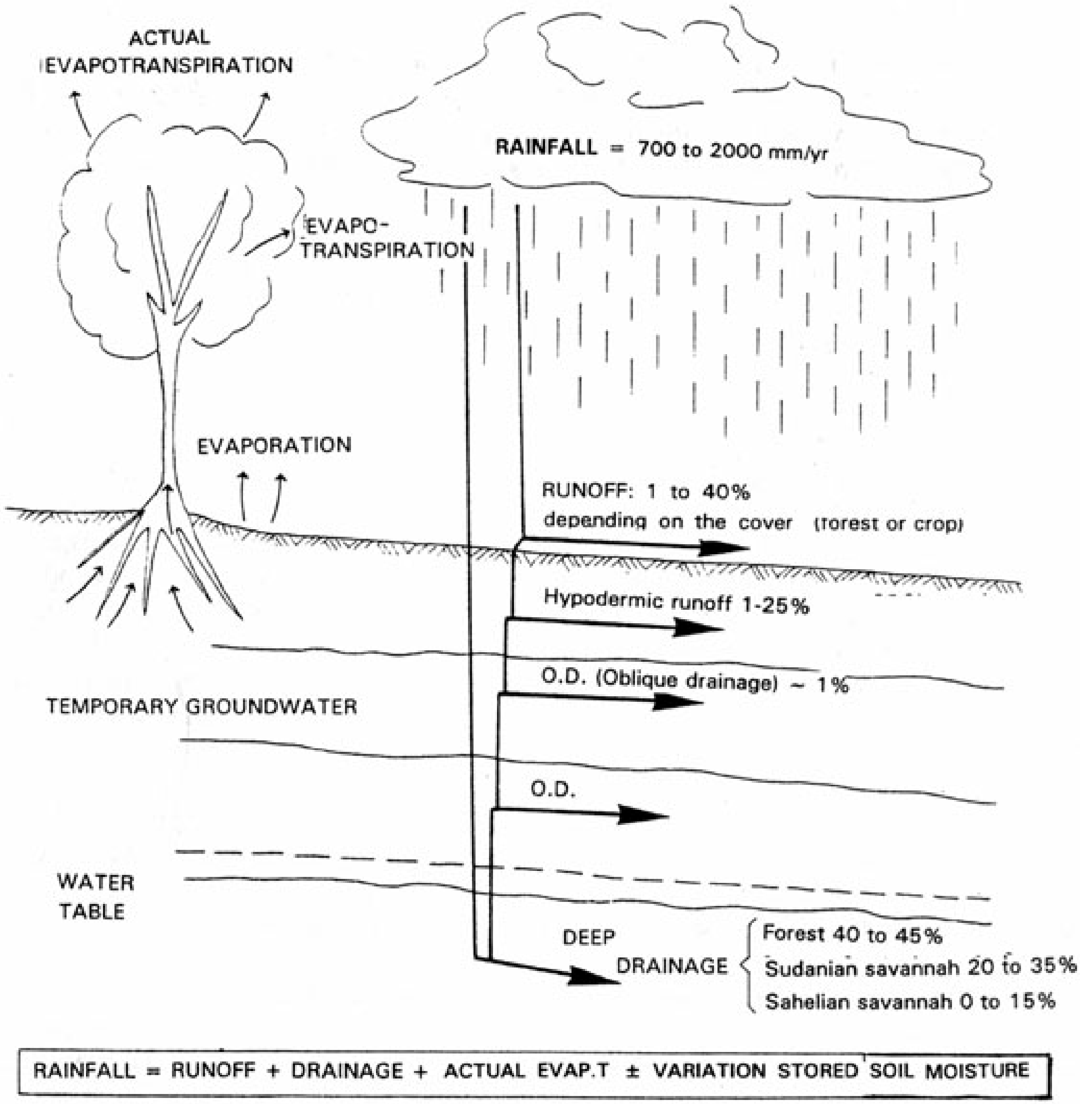
An example of the degradation chain for tropical soil is given in Figure 2.

Under **tropical forests**, soil is very well protected from sun and rain energy by the canopy (850 t/ha of biomass), which tempers temperature fluctuations, and also by the understorey and especially the litter (8-15 t/ha/yr of organic matter recycled throughout the year) which feeds the mesofauna and quickly recycles nutrients (turnover). Roots are plentiful in the topsoil and up to the litter, reducing nutrient loss through drainage and runoff. A small number of roots penetrate to a great depth, taking up water and nutrients when the topsoil is dry. Scanty runoff (1-2%), 50% evapotranspiration and a similar amount of drainage result in the formation of deep homogenous soils, more acid on the surface than at depth. The vigour of forests (with the largest trees dominating at heights of over 35 m) may be misleading as to the fertility of the (ferralitic) soils on which they grow. Tropical forests in fact are continuously recycling their residues and recovering (from deep below) nutrients leached by drainage water or released from deep weathering of rocks and minerals, in a process described as biological upwelling (Roose 1980b).

Savannah is much less efficient in counterbalancing variations in energy. The biomass (50-150 t/ha) is much smaller, and the litter (0-5 t/ha/yr) is burnt off by frequent bush fires, leaving the soil bare to face the first brief but very violent storms. Runoff is therefore much greater than under forest, especially when there are late fires (Roose 1979).

The hotter and drier the climate, the more termites there are and the fewer earthworms, but termite tunnelling and turning under of organic matter (below the fire zone) are less beneficial than the activity of earthworms (Roose 1975). Evapotranspiration and runoff being stronger (because of slaking crusts) and rainfall less plentiful, the wetting front does not penetrate so far into the soil and deposits fine particles detached from the surface and iron compounds containing organic matter. These are the leached tropical ferruginous soils. Horizons vary more widely, and the soil is less homogenous. Roots regularly penetrate to the accumulation horizon, though not as deeply as under forest.

FIGURE 3
Water balance in the rainforest of Côte d'Ivoire and the savannahs of Burkina Faso (from Roose 1980a)



How does the situation develop **under cultivation** following clearance of forest or savannah?

In terms of plant cover, there is a simplification of the ecosystem (under forest there are more than 200 species of trees per hectare, fewer than 25 under savannah, and at best 2 to 4 species with mixed cropping). The biomass (0-5 t/ha) decreases, as does rooting, often hampered by cropping techniques (slaking crusts and deep tillage). Soil cover is reduced in time (4-6 month cycle) and provides poor protection from the sun's rays (higher temperatures are reached) and rain splash (slaking crust formation and heavy runoff).

At the level of the soil, the climate is hotter and drier under cultivation and energy less buffered than under forest:

- litter is much reduced, except where there are cover plants;
- levels of organic matter and micro- and mesofauna activity fall;
- macroporosity breaks down after a few years, and infiltration capacity decreases;
- soil becomes more compacted and spatial discontinuities develop: thin slaked surface and plough pan.

It is thus clear that cropping on cleared forest land is a real disaster, compromising the whole balance of the soil system. Nutrients are lost faster, compensatory deposits decrease, and the physical and chemical fertility of the land collapses after a few years' intensive cropping. There have been many instances of the failure of "modern" cropping, such as that of the Compagnie Générale des Oléagineux Tropicaux in Casamance during the 1950s.

Runoff and erosion are thus very clear **alarm signals that the cropping system is out of balance with the environment and that soil fertility must be restored**, either by a long period of forest fallow (20-30 years) or by robust measures to re-establish macroporosity (tillage), organic matter, the fermented biomass needed to revive it (manure or compost), and the dressing to strengthen its structure and improve pH. What still in fact has to be done is to work out better modern systems of clearing land and intensive production systems more capable of sustainable and balanced production than the traditional ones now in place.

FACTORS IN THE WATER BALANCE

Rainfall and ephemeral inputs (dew, mist: a few dozen to 150 mm per year) vary greatly according to altitude, distance from the sea and orientation of hillsides to moist rain-bearing winds.

The different terms of the water balance must be defined (Figure 3):

Rain = Runoff + Drainage + Actual evapotranspiration ± Var. stored groundwater

Surface runoff is the excess rain which does not filter down into the soil, running along the surface, forming rivulets and quickly joining up with the river where it causes high peak floods in a relatively short time (response time about half an hour in a 1 km^2 basin).

Subsurface flow or interflow is slower, for it moves through the top horizons of the soil, which are often much more porous than the deeper mineral horizons (response time of several hours in a 1 km^2 basin).

Lastly, **temporary and permanent water tables** hold back the base flow of rivers because of much slower discharge (response time of several days for a basin of several km^2, or even some months for the largest basins).

In conclusion, erosion is a combination of processes that vary in time and space on the basis of environmental conditions and poor land management. Erosion control involves various agents, whose interests are not necessarily compatible. The priorities of erosion control must therefore be clearly specified and the most effective methods selected for each situation, either to conserve or restore the fertility and productivity of farmland, or to control sedimentation and improve water quality, which are areas of particular interest to townspeople, industrialists and irrigation corporations.

Chapter 2

History of erosion control strategies

Erosion is an old problem. From the time land emerges from the seas it is lashed by the forces of wind, waves and rain. In response, people try to counter the negative effects of these agents of erosion.

The development of agricultural production involves an increased risk of land degradation:

- either **by expansion** to new land which turns out to be fragile and becomes exhausted after a few years' farming, through mineralization of organic matter and removal of nutrients without adequate replenishment,

- or **by intensification** and the wrong use of inputs:

    - intensive mineral fertilization can lead to soil acidification and water pollution (particularly if inputs are out of balance with crop requirements and soil storage capacity);

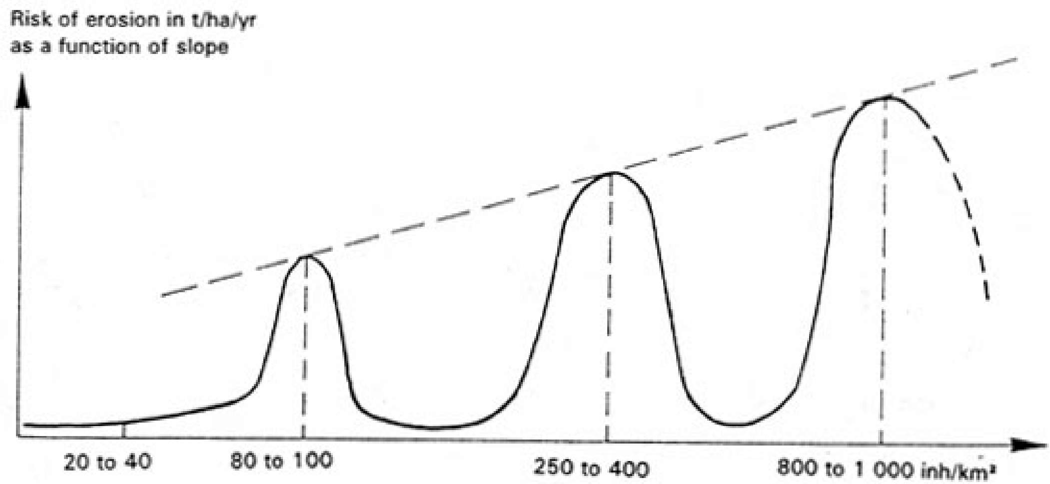
    - irrigation reduces soil structure stability or results in salinization (in arid conditions);

    - mechanization, especially motorization, speeds up the mineralization of organic matter in soil, the degradation of soil structure and the compaction of deep horizons, accentuating the soil's response to wetting (a sharp drop in infiltration rate at the ploughing depth, even when there is no real ploughing pan).

While there is an increased risk of soil degradation when land is put under cultivation, rural societies do their best to gradually build up techniques that will allow the long-term preservation of soil productivity (organic or lime dressing, drainage, multicropping). However, when new needs emerge too fast, a crisis will arise to which rural society cannot respond in time. And here the State must step in to help overcome the crisis by technical assistance (technical guidelines) and financial support (subsidies).

Soil degradation through erosion, acidification or salinization is probably one cause of the decline of ancient civilizations, in that population concentration in countryside and town led to excessive economic pressure on production from the countryside (e.g. 12th-century France, Egypt today). Where fields are no longer left fallow, soil degradation soon sets in, with nothing to compensate for what crops take from the soil or for losses from erosion or drainage.

FIGURE 4
Relationship between population density, erosion, cropping, stock-raising and fertility management



Pop. density <40 inh/km²	100 to 400	400 to 800	> 800
Cropping system			
- **gathering** - **slash-and-burn, shifting cultivation** - root crops, some cereals	**extensive farming** - root crops - cereals: millet, sorghum - groundnut	**intensive farming** - cereals - cassava, yam, potato - groundnuts, soybeans - banana trees	**multi-storey gardens** - fruit trees - banana trees - root crops - few cereals - beans, soybeans
System of animal husbandry			
livestock raising: - little developed - some chickens and goats - separate	- village herd on extensive rangeland - night corralling	- small livestock: stabled/ penned tethered + ½ day on rangeland	- small livestock + corral - semi-permanent stabling - water provided in stable - forage crops, hedges
Fertility management			
- brief crop rotations - then long bush fallow - ash	- little dried corral dung (600 kg/cow/4 ha) - little mineral fertilizer - length of cropping period ↗ - length of fallow period ↘	- dried corral dung + compost - more NPK - short fallows + sometimes legumes - weed management	- continuous cropping . manure or compost + NPK + Ca Mg CO_3 if pH<5 + management of weeds and legumes
Management of trees			
- felling + burning - then fallow	- accelerated clearing - village woodlot - few fruit trees	- clearing steep slopes - hedges - trees as fencing - fruit trees	3-storey garden: - forest trees - fruit trees - mixed cropping

As early as 1944, the geographer Harroy had clearly realized why “Africa is a dying land”: it was dying as a result of the destabilizing methods of colonial systems which intensified soil use, hastened removal of assimilable nutrients and mineralization of organic matter, and pushed the indigenous people on to the poorest and most fragile land, reducing the length of fallow periods. He advocated a three-pronged policy:

- full protection of national parks in order to protect natural ecosystems;
- terrace-type erosion control structures such as bench terraces or infiltration (blind) ditches;
- research on balanced cropping and production systems combining animal husbandry, forestry and agriculture (agroforestry).

SOIL EROSION AND POPULATION DENSITY

Accelerated erosion and excessive runoff are connected with a kind of development that throws the balance of the countryside out of kilter: clearance of fragile zones, denudation and compaction of soil through overgrazing, exhaustion of soil through intensive cropping without compensation from applications of organic matter and nutrients. **If it is true that human activity increases erosion risks through ill-judged farming methods, there is hope that the present trend can be reversed: by improving infiltration to produce more biomass, and increasing plant cover to return more organic residue to the soil, thereby reducing the runoff, erosion and drainage that soon deplete tropical soils. In this context, soil conservation is not the land-use planner’s main aim, but simply one component of a technological package to make possible the intensification of agricultural production vital to meeting this century’s major challenge: to double production every ten years to keep pace with population growth in tropical countries.**

Some writers claim that **erosion increases as a function of population density** (Figure 4). It is true that in a given agrarian system, if the population passes a certain threshold, land starts to run short, and soil restoration mechanisms seize up (Pieri 1989). For example, in Sudano-Sahelian zones, when the population exceeds 20-40 inhabitants/km^2, the fallow period is shortened to the point of ineffectiveness, and one speaks of a densely populated degraded area when the population reaches about 100 inh/km^2. Adults then have to migrate during the dry season to find supplementary resources in order to ensure their families’ survival (e.g. Burkina Faso).

Interestingly enough, in other more humid tropical zones – with two cropping seasons or richer, volcanic soils (Java, for example) – the term high density is not used until the population goes beyond 250-750/km^2. The cases of Rwanda and Burundi are particularly striking: despite very acid soils and slopes of over 30-80%, families manage better on a single hectare than in the Sahel, so long as they intensify their production systems, practise intercropping, plant trees, stable stock, quickly recycle all wastes, and stop the bleeding of nutrients through erosion and drainage.

It may then be concluded that the environment becomes degraded as population density grows, until it reaches a certain level after which farmers are obliged to change their production systems. This is what has happened in Sudano-Sahelian zones with the prolonged drought of the past 20 years (the population is scarcely growing any more because of emigration). Farmers in Yatenga are willing to invest 30 to 100 days a year to install erosion control structures allowing them to manage water and soil fertility on their plots: stone bunds, ponds, rows of trees or grass strips, re-establishing pastures and treed paddocks on cultivated blocks (Roose and Rodriguez 1990; Roose, Dugué and Rodriguez 1992).

TRADITIONAL EROSION CONTROL STRATEGIES

For seven thousand years, humanity has left records of the battle with erosion, soil degradation and runoff, trying to improve soil fertility and water management (Lowdermilk 1953), and it can be seen that traditional methods are closely bound up with social and economic conditions.

Shifting cultivation, the oldest strategy, has been used on every continent wherever and whenever population was less dense (20-40/km^2 depending on soil richness and rainfall). After clearing and burning, crops are grown on the ashes, and the land is then abandoned when it no longer yields enough return for the work (invasion of weeds and loss of the most easily assimilated nutrients). A considerable reserve of land (about 20 times the cultivated area) is required for the system to remain in balance: if demographic pressure increases, the fallow period is shortened, leading to steady soil degradation. These strategies are well suited to sparsely populated areas with deep soils and annual rainfall of over 600 mm.

By contrast, **bench terracing** or irrigated Mediterranean terraces coincide with a dense population and a shortage of land for cultivation (especially in mountain areas) and occur where labour is cheap. Such strategies require 600 to 1 200 days' work per hectare to build and maintain erosion control structures, plus an enormous effort to restore soil fertility, and are accepted by farmers only where they have no other alternative for survival or for the production of profitable crops. This happened in the case of the Kirdis of northern Cameroon as they held out against the ascendancy of Islam, or the Incas of Peru in the Machu Picchu region, who built remarkable bench terraces in the 15th century as a defence against incursions by peoples from the Amazon Basin – and then by the Spanish (*Guide Bleu du Pérou*, Hachette, pp. 246-247).

Ridges, intercropping and agroforestry. In the humid, volcanic forest zones of southwestern Cameroon, despite dense population (150-600/km^2), the Bamiléké have succeeded in establishing a reasonable balance by combining intercropping, which covers large ridges throughout the year, with various systems of agroforestry.

Stone lines and low walls combined with fertility maintenance through use of organic manure. Like various other ethnic groups in Africa, the Dogon of Mali took refuge in the sandstone cliffs of Bandiagara in former days to resist Moslem influence, and had to develop a whole set of conservation practices in order to survive:

- small fields surrounded by sandstone blocks to trap sand in the dry season and runoff during the rains;
- low stone walls and bringing sandy earth up from the plain to create soil on sandstone slabs that act as microcatchments to harvest water;
- honeycomb constructions for onion production, watered with calabashes;

- mulching and composting with crop residues, domestic waste and animal manure in order to maintain household gardens in arid, sandy conditions.

Bocage or the close association of cropping, animal husbandry and arboriculture. Europe has already experienced several erosion crises, the most well-known in the Middle Ages, when population pressure forced abandonment of the natural fallow period. Tilling the soil and ploughing in dung were introduced with a view to restoring the chemical and physical fertility of soil more quickly. Stock farming was combined with cropping, and the countryside was partitioned by a series of thickets, small fields and meadows surrounded by hedges.

Nowadays, however, the mechanization and industrialization of agriculture, the economic crisis and the breakdown of traditional societies are forcing the abandonment of these methods, which geographers and anthropologists have described in glowing terms but which are viewed askance by “modern” soil conservation experts, who consider them inadequate to solve the problems of large-scale watershed management (Critchley, Reij and Seznec 1992).

Such positions certainly require re-examination, and although there is no wish to idealize traditional methods, analysis should be devoted to their spatial distribution, operating conditions, effectiveness, cost, and present vitality; above all, ways of improving them must be developed (see the proceedings of the European Community meeting in Crete, 1993).

MODERN STRATEGIES FOR DEVELOPING RURAL WATER INFRASTRUCTURES

More recently, various modern erosion control strategies have been developed, basically to improve the land, reshape it (terracing), and provide hydroagricultural infrastructures. Priority was given to mechanical means of water management.

Rehabilitation of mountainous land (RML) began in France in 1850, then spread to European mountain areas, where forestry departments sought to protect fertile plains and communication routes from torrent-generated damage by buying up degraded mountain land, re-establishing plant cover, and controlling torrents through civil and biological engineering techniques. They had to deal with a crisis in which upland small farmers could no longer survive without pasturing their herds on common lands, which then became degraded through overgrazing (Lilin 1986).

Soil and water conservation (SWC) on cultivated land in the United States has been the province of agronomists since 1930. The rapid expansion of industrial crops offering little cover – such as cotton, groundnut, tobacco and maize – in the Great Plains had unleashed cataclysmic wind erosion, such as the dustbowl effect, when the sky was darkened even at midday, and water erosion as well. By 1930, during the Great Depression, 20% of arable land had been degraded. Public opinion forced the government to act. Under the impetus of Bennett (1939) the Soil Conservation Service established soil conservation districts, providing advice and assistance to farmers wanting technical and financial help to manage their land. Agronomists and hydrologists at headquarters carried out studies and drew up projects.

Today there are still two conflicting schools of thought in erosion control:

- one school follows Bennett in arguing that gullying is what causes the most spectacular transport of solids; since gullying is a result of runoff energy, which is a function of its squared mass and speed (Runoff energy = 1/2 ms^2), erosion control concentrates on mechanical means of reducing runoff speed and its erosive force (diversion bunds), weirs and grass spillways) without reducing the mass of runoff on fields;

- the other school follows Ellison's work (1944) on rain splash, and that of Wischmeier's team, arguing that runoff develops following degradation of the surface structure from the impact of raindrops; erosion control here centres on the fields, concentrating on plant cover, cropping techniques and a minimum of structures.

These two approaches have been identified in France on large-scale holdings:

- one on slaking loamy soils, especially in winter (closed soil with little cover);

- the other on the same land during spring storms, on seed beds and especially on sandy soils (around the River Sarthe or in south-western France).

Analysis of the dynamics of erosion and runoff (caused by saturation or the condition of the slaking surface) helps assess the relative importance of areolar and linear erosion and determine the implications for erosion control strategies (comm. from Lilin, 1991).

Soil protection and restoration (SPR) [Plates 8 and 9] developed in Algeria, then spread around the Mediterranean basin between 1940 and 1960 in an attempt to deal with serious sedimentation problems in reservoirs and the degradation of roads and land. The primary objectives were those of protecting land degraded by overgrazing and clearing, and restoring its infiltration potential by planting trees, considered the best way of improving soil. Major mechanized resources and an abundant local labour force were mobilized to control sheet runoff on cultivated land (various kinds of bunds, Monjauze embankments, etc.), in order to reforest degraded land and set up zones of intensive farming (Plantié 1961, Putod 1960, Monjauze 1962, Gréco 1979).

The foresters' main concern was with agricultural regeneration, which took place within the framework of the "rural renewal" (Monjauze 1962). For them the SPR concept was more important than it was for the advocates of RML.

However, this operation developed in an authoritarian political context (the Algerian war) and the social goal of fighting unemployment rapidly became a priority (ditch-digging) while other resources were blocked by the political situation (comm. from Mura, 1991).

All these measures have not been in vain, as some critics would maintain, for degradation of the countryside would certainly have been even worse without them. However, people seriously began to doubt the validity of the whole SWC approach after an American study revealed that erosion had in fact hardly affected the productivity of deep soil. It has been shown in many cases that soil is a renewable resource, although the cost of restoring it is often prohibitive in view of the available economic resources. Nonetheless, there are cases – in Burkina Faso, Rwanda and Haiti – where demographic pressure and pressure on land have led to the restoration of degraded land in record time (one year).

LAND HUSBANDRY [Plates 24 and 25]

Since 1975-80 numerous research experts, social scientists, economists and agronomists have voiced criticisms of the frequent failure of water management schemes implemented too hastily and without reference to local people's views (Lovejoy and Napier 1986).

In the United States, despite 50 years of remarkable work by the Soil Conservation Service and the annual expenditure of millions of dollars, 25% of arable land is still losing more than 12 t/ha/yr, the tolerance limit for deep soils. Although there have been no sand-storms as catastrophic as those of the 1930s, pollution and siltation of dams remain major problems. With a view to improving the effectiveness of the purely voluntary efforts of farmers hoping to protect the productivity of their land, federal laws (on cropping grasslands, wetlands and fragile land) now force farmers to respect rules for conservation-minded land use, failing which they lose the right to any of the financial incentives intended to support the American farm sector.

In the Maghreb and West Africa, farmers often prefer to abandon State-improved land rather than maintain protection works of which they do not understand the purpose, and whose ownership is unclear (Heusch 1986).

Many reasons have been advanced for these partial failures (Marchal 1979, Lefay 1986).

- choice of techniques ill-suited to soil, climate or slope;
- bad planning, incorrect implementation or lack of follow-up and maintenance;
- no training or preparation of beneficiaries, who reject the project because loss of surface area is not balanced by increased yields;
- poor organization of production units (fragmented and isolated plots).

A STRATEGY BASED ON AGRICULTURAL DEVELOPMENT

Given these failures, a new strategy had to be developed taking better account of the needs of those in direct charge of the land, both farmers and herders, by offering methods that would improve soil infiltration capacity, fertilization, and yields – or better, farmers' profits (Roose 1987a). This method was named "water, biomass and soil fertility management" by Roose in 1987, then "land husbandry" by Shaxson, Hudson, Sanders, Roose and Moldenhauer in 1989. It starts from the way farmers experience soil degradation problems, and comprises three phases:

1. **Preparatory discussions** among farmers, research scientists and technical support staff. This phase covers **two surveys** to identify problems and assess their importance and causes and the factors that can be brought into play to reduce runoff and erosion. It also includes field visits to the village community to foster their sense of communal responsibility, learn how degradation problems touch them, and discover the strategies they already have for improving water use, maintaining soil fertility, renewing plant cover and controlling wandering livestock. Also looked at are social and economic constraints, limiting factors, land ownership, credit, training and availability of labour.

2. **On-farm field trials** are set up to measure and compare the risks of runoff or erosion and the higher yields resulting from various types of development or improved cropping techniques. This procedure will establish a

technical layout and determine the feasibility, profitability and effectiveness of the erosion control methods recommended: evaluation must be carried out jointly by farmers and technical experts.

3. **A comprehensive land-use plan** should then be established after one to five years of dialogue, with a view to rationally intensifying farming on productive land, characterizing the terrain, controlling gullies and stabilizing soil, preferably through the use of simple biological methods that farmers can handle themselves. Nothing can be done without the prior agreement of the farmers, who must be encouraged to manage their land as a unified whole.

Answers to the different problems will vary according to local social and economic conditions (large modern landholders or small subsistence farmers), even when the physical environment is the same. This is the main difference from previous approaches.

FROM SOIL CONSERVATION TO WATER, BIOMASS AND SOIL FERTILITY MANAGEMENT

It has become very clear in recent times that soil conservation schemes confined to reducing the amount of soil carried away by erosion cannot answer the needs of farmers in tropical regions. Indeed, experts have been saying for a long time that **soil has to be conserved so as to maintain the productivity of the land**; thus, the title of the fifth ISCO conference (Bangkok 1988) was "Land Conservation for Future Generations." This is a duty to society and a **long-term investment**!

Farmers (not always of their own volition) have undertaken to devote considerable efforts to schemes to control erosion on their land, but have been disappointed to see that their land still deteriorated and crop yields still fell. The erosion control structures imposed (drainage ditches, diversion channels, bunds) have often reduced the arable area (by 3% to 20%) without any equivalent improvement in the productivity of "protected" plots. **If farmers are to be motivated, it is not enough to keep the soil in place: water must be managed and soil fertility restored** in order to see a significant increase in yields from these tropical soils, the majority of which are already very poor (especially tropical ferralitic and ferruginous soils that are sandy on the surface).

Land husbandry must show immediate returns: the challenge is to double production in twenty years so as to keep up with population growth. SWC is essential for stopping loss of water and nutrients through erosion and for preserving the soil's storage capacity. But SWC is not enough, for the farmers need to receive immediate rewards for their labour in protecting their land. This is possible – at least with sufficiently deep soils – if improvement of both nutrient and surface-water management (drainage in cases of waterlogging, subsoiling of calcareous crusted or sealed horizons, rough tillage or mulching if the surface is crusted) are undertaken together.

In traditional systems it is the **long fallow period** that allows the recovery of good soil structure, ensures an adequate level of organic matter, and the availability of nutrients for crops. Burning can raise the pH by a couple of degrees and counter aluminium toxicity, particularly in humid zones. With population growth and expanding needs, however, fallow periods have been shortened so much that they can no longer restore soil fertility. The mechanization of farming has expanded the amount of cultivated area rather more than it has increased yields (Pieri 1989). In many regions all the arable land has already been cleared, so now the productivity of land resources has to be intensified.

Initially, farmers understood intensification as meaning a reduction of the fallow period and an expansion of cropping to all arable areas: average yields (600 kg/ha) were maintained by clearing new land.

Then rural organization and training services recommended animal-traction tillage and use of selected disease-resistant seeds from field stations. Only small amounts of mineral fertilization were extended (less than 100 kg/ha of NPKCa). Yields rose from 600 to 1 100 kg/ha (cereals, groundnut, cotton), but as the balance of organic matter and nutrients was negative, soils quickly deteriorated, as did yields. Attempts were then made to improve the fallow period and fodder production.

Finally, development corporations suggested intensive cropping systems: cotton and maize in Sudanian areas, and groundnut and millet in drier, sandier areas. These systems combine larger inputs of mineral fertilizer (over 200 kg/ha on cash crops), tillage (turning under and hoeing/ridging), oxen-traction (which implies fodder and manure production on each farm), rotation with no fallow for ten years or fallow under a fodder crop (often legumes), and selected varieties with good response to fertilizers and the regular use of pesticides and herbicides.

Results were encouraging, but varied greatly according to rainfall, soil type, and socio-economic conditions (Pieri 1989). Crop yields increased two- to fourfold (1 500-2 500 kg/yr) and up to tenfold in field stations with deep, even-textured soil. However, after five to ten years yield improvements from mineral fertilizers were falling annually by 10%. Cropped soil receiving only mineral fertilizers is deficient in organic matter. In savannah areas the amount of humus in the soil declines by 2% a year on loamy-sandy soil, 4% on very sandy soil (Clay + Loam < 10%) and up to 7% where there is considerable erosion and/or drainage.

Ploughing in crop residues – or what is left at the start of the rainy season (less than 10%) – is not enough, especially when such residues can be put to better use by cattle or craftsmen. Ploughing in coarse straw (Carbon/Nitrogen < 40 will produce nitrogen lock-up) or green manure does stimulate microbial activity for some months, accelerating mineralization of reserves of stable humus. The only way of maintaining soil productivity seems to be applications of manure or well-decomposed compost (C/N < 15) (3-10 t/ha/yr), supplemented by essential minerals to correct soil deficiencies. This maintains the level of organic matter in the soil (and thus its structure and its water- and nutrient-storage capacity), prevents acidification, and fosters deep rooting and biological activity (micro- and mesofauna) (Chopart 1980).

Erosion, poor tillage (carried out too late or crushing the soil too fine), plus applications of nitrogen fertilizer hasten depletion of the soil's stores of organic matter. By contrast, rotation of different types of crop, use of full mineral fertilization, tillage leaving a rough surface, minimum tillage along seed lines plus a litter of residue spread on the surface, and fallow crops producing a large amount of root biomass (*Andropogon, Pennisetum* or cultivated legumes) all delay depletion of organic matter.

On tropical ferralitic and ferruginous kaolonitic clay soils, organic matter plays an important part in protecting soil structure and its ability to store water and nutrients. Kaolinitic clay which has a cation exchange capacity of only 14 milliequivalents per 100 grams will give only 1-2 meq in horizons colonized by roots (Clay + Loam 20%), whereas humus will give up to 250 meq per 100 grams.

Although crop yields may not be directly linked to levels of organic matter in the soil below certain threshholds (Organic matter/[Clay + Loam] < 0.07), soil structure breaks down, runoff and erosion accelerate, rooting is less effective as the soil becomes compacted, and nutrients are less easily accessible. Degraded soil gives a poorer return for fertilizer as there is less water available in compacted soil (Pieri and Moreau 1987).

It was believed at one time that massive mineral applications, including the dose needed to correct soil deficiencies (applied every 4 to 10 years) plus the replacement dose (taken up by crops), would solve all these problems: increasing both yields and the available biomass to improve the level of organic matter in the soil. What was forgotten was the risk of acidification from nitrogen and other acid fertilizers (sulphates and chlorides), as well as losses through erosion and drainage and, above all, the rapid mineralization of organic matter, which is further accelerated in tilled soil. Even if such a huge input of fertilizer is technically feasible, it is not always economically viable. For example, it was seen that on an intensively irrigated banana plantation in southern Côte d'Ivoire on highly desaturated ferralitic soils, erosion and (especially) leaching led to losses of 9% of the phosphorus, 100% of the lime and magnesium (1 tonne of dolomite) and 60% of the nitrogen and potassium (at least 300 units), although these were spread out over ten applications a year around the foot of each plant (Roose and Godefroy 1977). A tendency to acidification of sandy soils has also been noted in the case of nitrogen, sulphate and chloride abuse.

A major new development was the insistence of World Bank economists on **cost-pricing fertilizers** in order to reduce wastage. Fertilizer subsidies were intended to offset the huge costs of transport, and their withdrawal meant that small farmers scattered in thousands of villages were denied access to this modern technology and thus the possibility of increasing returns on their labour. They therefore had to turn back to regional resources (crushed natural limestone and phosphates) and more or less converted local biomass. However, it very soon became clear that a fatal imbalance was fast being reached between inputs of nutrients and losses through erosion, drainage and uptake by crops.

Forest fallows are able to draw nutrients from deep down (the product of weathering of minerals and recovery of solutions that have drained down below crop roots) and recycle them at the surface (8-15 t/ha/yr added to the litter). It takes 8 to 20 years to reconstitute soils in subequatorial forest zones, 15 to 30 years in Sudanian forest zones, and 30 to over 50 years in Sahelian zones. By contrast, degradation of the surface horizon is much faster; nutrient reserves are depleted after 2 to 6 years of intensive cropping, and after 15 to 20 years the macroporosity has decreased and a sand horizon is all that is left after selective erosion. Furthermore, if soil is deficient because the parent material is poor in a given element (for instance phosphorus), the vegetation will also be so, equally the litter and humus, so that a **supplementary mineral input** becomes essential.

In savannah areas, where the biomass is mostly composed of grass which burns each year, fertility is concentrated by animals who harvest the biomass dispersed over rangeland (often very poor land unsuitable for cropping) and return it in night paddocks in the form of dung. This is not real manure (which ferments at 80°C, killing seeds), but sun-dried dung trampled into powder by livestock kept in paddocks with no straw. This mixture of muddy earth and poorly decomposed organic matter contains many seeds of weeds and fodder shrubs ready to germinate. The rather poor organic matter has unfortunately lost much nitrogen through gasification in the sun, since there is no straw to trap the nitrogen and form humus. It would be easy to improve and increase manure production through some kind of system of stabling animals on straw litter (which would collect liquid waste and reduce loss from drainage), shaded by a rudimentary roof, until such time as a tree canopy can form. The role of trees in the management of a dung-compost heap is that of providing a more temperate atmosphere, protecting the fermenting biomass from direct sunlight, reducing evaporation (and hence the need for water), recovering some of the nutrients lost in drainage, and producing a litter richer in nutrients than grass straw can provide [Plates 30 and 31].

The contributions of manure from livestock, however, are limited. In an extensive system, one cow gives 0.6 t/ha/yr of dung, whereas it takes 3 t/ha/yr of manure to keep soil carbon above critical level. Five cows are therefore needed to produce 3 tonnes and maintain an hectare of crops, and since it takes four hectares of extensive rangeland to feed one cow, **20 hectares of extensive rangeland are needed for the upkeep of one hectare of cultivated land through the use of organic manure**. This performance can be improved by intensive animal husbandry: one cow can be kept on the crop residues from one hectare; one cow can moreover produce 1.5 tonnes of manure if she is kept on litter over-night and during the hot hours of the day; and, lastly, one hectare of an intensive forage crop can in fact keep the two cows needed to produce three tonnes of manure.

From the soil standpoint, however, only **30-40%** of nutrients in the biomass digested by animals are excreted back to the soil. **All conversions have an efficiency rate**. The best animals fix up to 70% of the nutrients in their diet to form bone (Ca + P), protein (N-P-S, magnesium and various trace elements), most of which are lost to the soil. It would be a good idea if powdered bone, blood, horns, hooves and other animal products not used elsewhere were returned to the soil. In the intensive systems of Rwanda, where population density is over 250 per km^2, **organic manure can maintain only a third of the farm** (often less than one hectare to feed 4-10 people), with the rest of the land being used for very undemanding crops such as cassava and sweet potato. Small animal husbandry with the stock feeding on communal lands and along roads is often the only way small farmers can survive and build up a modest nest-egg to cope with life's emergencies (illness, accidents) and social relations (marriages, funerals, etc.) (Roose *et al.* 1992).

Composting is an even longer way of transforming the biomass (6-18 months) with returns no greater than from manure. However, it is a valid technique for those without livestock (the poorest farmers) or with large amounts of industrial waste available (coffee husks, brewery draff, town sewage, etc.). The main problem is the amount of work required to produce good compost. Compost pits dug in the fields have been tried, in order to avoid double transportation of straw and crop residues, but most of them stay empty, and any compost is poor. The only effective ones are the compost-manure-rubbish pits close to the house, which receive all available residues plus ashes and domestic waste. To help the mixture ferment with minimum waste, small pits (4 m x 2 m) are recommended, planted with trees, which will give shade, a cool, damp environment and a biomass rich in minerals, and whose roots will recover solutions leached from the compost by drainage water. Since the maximum is 5 t/ha/yr per family (i.e. 0.2-0.5 ha manured per farm unit), additional solutions must be sought in order to fertilize the whole farm. However, it is a good basis for starting to grow vegetable crops.

Turning in residues and weeds: people often tend to overlook the mass of crop residues, roots and particularly weeds which farmers turn in when tilling and hoeing. However, it is a short process (1-3 months), allowing speedy recycling of the nutrients in the biomass. There are also various traditional methods of gathering weeds into piles to dry, then covering them with a mound of earth in which sweet potatoes are then planted. After the sweet potato harvest, the organic-matter-rich earth is then spread. Repeatedly turning in fresh organic matter throughout the year in this way does allow maintenance of a certain level of organic carbon in the soil, but its effect on soil fertility and resistance to erosion is limited. Moreover, farmers are increasingly using this biomass for their livestock, since fallows are disappearing. Also, a 1% increase in the amount of organic matter in the soil brings a mere 5% reduction in soil erodibility (Wischmeier, Johnson and Cross 1971). Sizable applications of broken-down organic matter are needed for a 1% rise in the amount of carbon in 10 cm of soil (1% of 1 500 tonnes of soil). Simply ploughing in 15 tonnes of barely broken-down straw only leads to lock-up of the nitrogen fixed by the microbial mass, and lower yields.

A thick mulch (7-10 cm, or 20-25 t/ha) is a very effective way of reducing evaporation and weed growth, maintaining soil moisture during the dry season, and halting erosion. It is also a short-cycle means of restoring the whole of the biomass and its constituent nutrients (K, Ca, Mg, C, initially by leaching, and N and P by mineralization and humification through the action of meso- and microfauna). The litter on the top of the soil disappears 30% more slowly than when the organic matter is ploughed under, and there is less risk of nitrogen deficiency. Under forest, where the soil is often best, litter is never ploughed in but is left to the action of earthworms, termites and other mesofauna: soils which are not degraded are fully capable of absorbing organic matter deposited on the surface. Mulching has been successfully tested on coffee and banana plantations which proved to be the least eroded and degraded plots on hillsides long cultivated. Unfortunately there is never enough plant residue to cover all the cultivated land. Nevertheless, **a light mulch** (2-6 t/ha), spread at the start of the rainy season, once the soil has been tilled and sown, cushions the force of raindrops and runoff and maintains good infiltration longer, as well as encouraging good mesofauna performance. Even if only 50% of the soil is mulched, erosion risk can be reduced by 80%. On crusted soil mulching is effective in reducing erosion, but less so runoff. In any case, mulching improves soil structure by providing the surface soil with nutrients and fresh organic matter.

None of these recycling techniques is perfect, but must be used in combination to draw the best from each [Plates 28 and 29].

Agroforestry [Plates 18 and 19], and especially planting hedges every 5 to 10 metres, gives a mass of fodder and mulch which can be returned to the soil during tilling. Usually, deep-rooting leguminous shrubs capable of producing 4 to 8 tonnes of dry organic matter/ha/yr are used (Balasubramanian and Sekayange 1992, König 1992, Ndayizigiyé 1992). Despite all this organic matter, **a supplementary mineral application** will still be necessary, both **to condition the soil**, raising the pH above 5 in order to suppress aluminium toxicity and allow legumes to grow, and also **to offset soil deficiencies** by directly giving plants the necessary nutrients where they need them and when they can store them.

It is often too expensive to correct soil mineral deficiencies with direct applications, and it also makes little sense unless the soil storage system is improved (organic matter and clay content). In many cases there is also a retrogradation of phosphorus in the presence of iron and lime, or of potassium if the environment contains swelling clays (montmorillonites). The soil systems in high-rainfall tropical zones also suffer from many kinds of loss, first through erosion, then through drainage, and finally through gasification. The risks of leaching can be reduced by observing the following rules:

- split applications of fertilizer (at sowing,   at shooting or heading, and   at ear-emergence);
- liming after the period of heavy rains;
- gauging dosage to soil and plant storage capacities;
- choosing nutrients in a form that plants can assimilate;
- enhancing soil storage capacity by applying organic matter or clay with a high fixation capacity (swelling smectite);
- spreading fertilizer over the whole area penetrated by roots;
- encouraging a certain amount of weed cover, which is then cut down at the right time to form litter (such vegetation will temporarily hold nutrients that could easily be leached);
- balancing applications according to plant needs and availability in the soil.

While trials of biomass production in plant containers (control + NPK + NP + PK + NK) reveal the relative importance of soil deficiencies and soil potential, the level of uptake indicates the minimum nutrient applications needed to attain a production goal (Chaminade 1965). Monitoring plants (leaf analysis) and soil (soil analysis) is expensive, but it does show what the plants are consuming and what is lacking in the soil. Sampling is essential for meaningful results (Boyer 1970, Pieri 1989).

SOIL RESTORATION AND LAND REHABILITATION

Population pressure, drought and overgrazing in many semi-arid tropical regions have degraded plant cover and impoverished soil in organic matter, nutrients and fine particles (selective erosion). Eventually, the soil may be acidified, then scoured, destructured, crusted by rain-splash and compacted in depth following tillage and the mineralization of organic matter. There are therefore significant sterile areas (5-20% of the land) which are non-productive but give rise to considerable runoff that then causes gullying problems on good arable land further downstream.

Until now such degraded land has been turned over to foresters for restoration. Their response is to declare the land off limits, (i.e. protect it against bush fires, herders responsible for overgrazing and farmers who have cleared these fragile soils), planting it with some pioneer tree species and managing surface water through the use of bunds or diversion ditches. People and animals are asked to live elsewhere or be liable to fines ... which leads to the classic tension between foresters, herders and farmers. Closing land off is often a very effective method if plant degradation has not progressed too far, but it is difficult to enforce under strong population pressure, and its effectiveness decreases in low-rainfall areas.

From a land husbandry perspective, it seems more effective – and cost-effective too – for farmers to **concentrate on the sound management of good, productive land before it becomes degraded**, since there is a faster and larger increase in yields on deep soil than on exhausted stony soil. Prevention is better than cure! However, there are cases where restoration of degraded land is a priority for the population:

- rehabilitation of stony land (what Haitians call “finished land”) on hilltops, for runoff from them will gully good cultivated land lower down;
- restoration of land that is degraded but still has an agricultural future, with a possibility of water- and nutrient-storage in a profile thick enough to ensure a cropping cycle despite climatic vagaries (more than 30 cm of clayey soil, more than 60 cm of sandy soil);
- when pressure on land becomes acute, not only must soil be restored at all costs, but productive soil must be created wherever rocks can collect rainwater (as with the Dogon people of Mali).

LAND REHABILITATION TO PERMIT EXTENSIVE USE OF NATURAL RESOURCES

The procedure here is gentle intervention in order to encourage plant cover to regenerate, without major changes in the nature of the soil:

- improving water storage in sandy semi-arid zones by the use of an “imprinter” roller which pits the ground to trap runoff water, sand and wind-borne seeds (Dixon 1983); this method, called pitting, works well in sandy zones, but is almost useless on degraded vertisols;
- rough tillage or criss-cross ripping (subsoiling) with direct sowing of perennial grasses or fodder shrubs; this method has a temporary effect in Niger, but little effect in southern Mali on denuded bunds (700 mm rainfall) (Poel and Kaya 1989), north-western Burkina Faso (Roose, Dugue and Rodriguez 1992) on a gravel pediment (500 mm rainfall) and northern Cameroon on degraded vertisols;
- closing land off to prevent fire and grazing: very effective on soil still partially covered, at Gonsé in Burkina Faso (rainfall 700 mm) (Roose and Piot 1984, Roose 1992a) and at Kaniko in Mali (Poel and Kaya 1989), but of no use if the soil is completely bare and crusted (Poel and Kaya 1989);
- spreading twigs and bark (Chase and Boudouresque 1989, in Niger), cotton stalks (Poel and Kaya 1989, in Mali – Table 1) or sorghum stalks (Roose and Rodriguez 1990, in Burkina Faso); this is the most effective way of trapping wind-borne seeds and sand and attracting mesofauna which will drill through the slaking crust, thereby restoring soil infiltration capacity;
- stone bunds to catch rain – or lines of straw, grass, pebbles and branches – act in the same way as above, but only foster vegetation regrowth three metres on either side of the permeable obstacle which slows down runoff and encourages sedimentation;
- *Euphorbia balsamifera* hedges have difficulty surviving on the deeply degraded and acid soils of Kaniko (Poel and Kaya in southern Mali), whereas *Opuntia* hedges in Algeria and zizyphus, acacia and various thornbushes in Burkina Faso have fixed the soil well .. when protected from livestock (Roose *et al.* 1992);

TABLE 1

Recovery of degraded soil protected from grazing (cf. Hijkoop, Poel and Kaya, 1991)

Treatment	Soil recovery in %		% of grass in 1989
	after 1 year	after 3 years (1989)	
1 m strip of cotton stalks	45	98	70
Stone lines (h = 20 cm, b = 30 cm)	48	98	74
Half-moon bunds	2	52	62
2 rows of *Euphorbia balsamifera* cuttings	0	0.5	50
Tillage + sowing of *Cenchrus ciliaris*	0.5	0.5	+
Control	0	0	-

- earth bunds, whether straight or semi-circular, are short-lived and allow only grass to grow at the points where runoff collects, in Burkina Faso (Roose, Dugue and Rodriguez 1992) and Mali (Poel and Kaya 1989);

- on degraded vertisols in Cameroon, only when earth bunds were used to isolate the small pits was there a slight improvement in infiltration - and in cereal production;

- if the area is used by livestock during the dry season, there will be less biomass and the surviving species will differ (Chase and Boudouresque 1989; Poel and Kaya 1989).

RESTORING THE PRODUCTIVITY OF FARMLAND

With deep, healthy soil which has been scoured by erosion or degraded by crops that have upset the balance of organic matter and nutrients, the use of a single approach, whether biological, physical or chemical, will rarely be successful. On the other hand, soil productivity can be restored very fast (1 to 4 years) in tropical semi-arid and especially semi-humid and humid zones as long as the following six rules are observed [see box] (Roose *et al.* 1992)

In a Sudano-Guinean climate, fallow periods of luxuriant tall grasses may improve the physical properties of rich soil which has not become too degraded through cropping (Morel and Quantin 1972), whereas in Sudano-Sahelian zones a short fallow period of natural grass-growth (2-6 years after 2-3 years under crops) cannot be expected to maintain – much less, restore – the land's agricultural productivity (Pieri 1989). On tropical ferruginous sandy soil in the Tchollíré region of northern Cameroon, Roose (1992a) observed only very slight improvements in carbon content (0.3-0.6%), nitrogen content (0.01-0.06%) and pH (5.3-6) of grasslands after 30 years of burning and extensive grazing each year. The best results (C = 1%) were produced by earthworm casts, and termite mounds in old paddocks where livestock were kept overnight. Infiltration capacity, on the other hand, is much better on old fallow land, because of roots and the tunnelling of earthworms and termites.

An excellent example of the rapid restoration of productivity of degraded land is the traditional Mossi method known as zaï (Figure 5). During the dry season, farmers dig out pits 15 cm deep and 40 cm in diameter on degraded plots every 80 cm, tossing the earth downhill. The dry desert *Harmattan* wind blows various organic residues into

SIX RULERS FOR SOIL RESTORATION

1. If the soil is scoured by erosion, runoff must first be brought under control (stone contour lines, hedges etc.).

2. If the soil is compacted, deep tillage will be required to restore macroporosity to the soil cover.

3. Since the structure is usually unstable, a stabilizer must be ploughed in (well-decomposed organic matter, gypsum, lime), while also sowing plants that produce deep roots and a luxuriant biomass capable of stabilizing the macropores in the profile (e.g. sorghum, *Stylosanthes*, *Pennisetum*).

4. If the surface horizon has been depleted or stripped, microflora and mesofauna should be introduced which can restore positive changes in soil structure and promote the assimilability of mineral nutrients (manure or well-decomposed compost).

5. If the soil is acid, it should be limed up to a pH value of over 5 and until aluminium and manganese toxicity are eliminated.

6. Finally, soil mineral deficiencies should be steadily corrected by feeding crops as they require, and enveloping mineral supplements (N and P) in organic manure so they will not be leached through drainage or bound up by iron or free aluminium.

them. These are quickly attacked by termites (*Trinervitermes*) which dig tunnels through the crusted surface, allowing the first rains to soak down deep, out of danger of direct evaporation.

Two weeks before the onset of the rains (15 May to 15 June), farmers spread one or two handfuls of dry dung (1-2.5 t/ha) in the bottom of the pits and cover it with earth to prevent runoff from carrying away dry organic matter on its surface.

Some sow a dozen seeds of millet if the soil is light, or sorghum if the soil is loamy-clayey (about 8 kg/ha of seed in seed holes before or after the first rains).

The first rains run copiously over the surface crust (of the land): the basins capture this runoff (enough to soak a pocket of soil up to a metre in depth). The seeds germinate together, break up the slaking crust and send roots down deep to where they find stores of both water and nutrients recycled by the termites. The concentration of water and nutrients around the seed holes can make yields as high as 800 kg/ha the first year and steadily increase for 30 years as the whole field improves.

At harvest time, stalks are cut at a height of one metre and left to reduce wind-speed and trap wind-borne organic matter.

FIGURE 5
Zaï: traditional method of soil restoration (cf. Roose and Rodriguez 1990)

December to April

- Digging pits 40 cm in diameter, 15 cm deep, at 80 cm intervals, earth piled up in a crescent on the downhill side.
- The *harmattan* brings sand and organic matter.

April to June

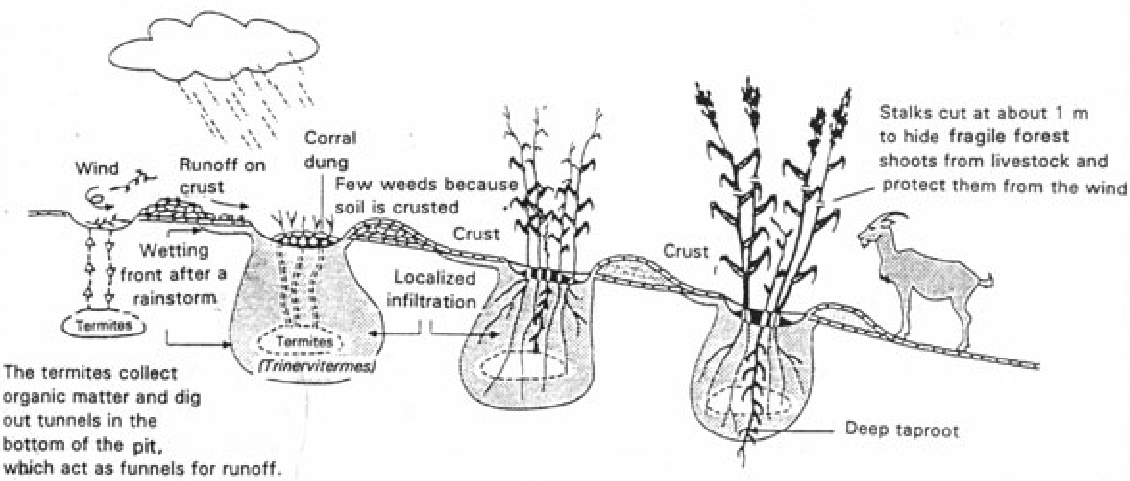
- Application of 2 handfuls of powdered corral dung after the first rain (= 3 t/ha).
- Termites dig tunnels lined with excrement.
- Seeds planted in holes at the second rain.
- Water seeps down and is stored deep down, away from direct evaporation.

June-July

- Onset of the rainy season.
- Early emergence.
- Deep rooting.
- Weeding restricted to plant holes.
- Germination of forest seeds.
- Concentration of water and nutrients.

November

- Harvesting of panicles and forage.
- Stalks cut at 1 m, hiding forest shoots from livestock and inhibiting drying wind and erosion.



- Zaï means: hurrying to dig packed, crusted soil in the dry season.
- Abandoned land can be recovered and made to produce about 800 kg/ha of grain from the 1st year, maintaining soil fertility for more than 20 years.
- It concentrates water and fertility under the planting hole and allows combination with suitable forage trees (agroforestry).
- Limitations: the starting date of work is decided by the village chief... after celebrations, and sometimes too late;
  it takes 300 hours' very hard work, i.e. 3 months/person, to restore 1 ha; it needs 2 to 3 tonnes of organic matter, and carts to carry the corral dung and compost;
  to succeed, the field to be restored must be surrounded with a stone line to control runoff.
- Improvements: criss-cross subsoiling with 1 tine up to 12 to 18 cm, after harvesting, every 80 cm (11 hours with well-fed oxen), then digging zaï for 150 hours;
  supplementing organic manure with N and P which are lacking in dung exposed to the sun;
  introducing other forest species grown in nurseries (3 months gained).

In the second year, the farmer either finds time to dig new basins between the first ones and dress them with manure, or pulls up the stubble and resows in the old basin. Stubble-clumps laid between basins are in turn attacked by termites. After five years the whole area has been turned over and manured so that the soil is now pliant enough to be tilled normally. Some farmers say that land restored by the zaï technique can be cropped for over 30 years.

A variation known as "forest zaï" is especially interesting. Dried, unfermented goats' dung contains a lot of seeds that have passed through the animals' digestive systems and are ready to germinate. Some astute farmers noticed that fodder shrubs, mostly pod legumes, were growing in the basins. During weeding they now leave two young forest plants every 3 metres, which then benefit from the water and manure meant for the cereals. At harvesting, sorghum stalks are left about 1 metre high, so that they protect the soil from wind erosion and keep the young forest shoots out of sight of the goats (see Figure 5). Cereals are sown and harvested every year, and every five years the forest transplants are cut for poles and firewood. In this way, without the use of wire fencing, an agroforestry intercropping system is set up that restocks *Acacia albida* and other legumes that can maintain cereal production while providing fodder, litter and wood. The forest zaï method can also be used to plant live fences.

There are three obstacles to the expansion of the zaï method: the work is very hard during the dry season (about 300 hours at 4 hours a day), runoff has to be controlled by a line of stones around the plot, and there are limits to supplies of manure. If the land is prepared in December, the oxen are still well-nourished on crop residues, morning temperatures are still cool, and the soil not too hard; and criss-cross subsoiling can cut tilling time by half. Lacking manure, termites can be attracted by twigs and other organic residues. Not all farmers are aware of the positive role of termites, but in fact fear them, preferring to recycle biomass by producing manure or compost rather than by mulching. However, it should be noted that it is even easier for termites to attack manure under the ground, although it is less visible. This method could be further improved with supplementary applications of nitrogen and phosphates, both of which are in short supply in the soil and in dung (due to gasification from exposure to sunlight) (Roose, Kaboré and Guénat, 1995). So here there is a traditional technique of soil restoration and reforestation oriented toward agroforestry and well-suited to slopes in Sudano-Sahelian zones that have become severely degraded after periods of drought (Roose and Rodriguez 1990).

MANAGEMENT OF LAND STRIPPED DOWN TO ROCK

- **If rocks are hard and weather very slowly**, and the storage capacity of the soil is very poor, the best practice in semi-arid zones (with at least one dry season) is to use these plots as a catchment area, collecting runoff in a gutter or a concrete track and leading it to a roughcast, waterproofed tank dug in the ground. After removing the sand, this water can be used for stock-watering and household purposes, as well as providing supplementary irrigation for small intensively cropped plots of legumes and other highly profitable crops out of the rainy season. Examples of this method of localized intensification can be found in Haiti (Smolikovski 1989) and Burkina Faso (Roose and Rodriguez 1990) (see Figures 37 and 38).

- **If the rocks are soft** (soft sandstone, schist, argillite, marl, etc.) or weather quickly (basalt and other volcanic or rough-grained rock), it is hard to cover the whole surface as the soil is too thin, too steeply sloping and scoured during the heaviest rains. However, it is possible to use the flower-pot technique of concentrating water, available nutrients and care on a few plants of primary local interest. Pits of at least 1 m^3 are dug every 5 to 10 metres. The small amount of mineral earth available is then mixed in the bottom of these pits with two handfuls of complete fertilizer and a bucketful of well-decomposed manure/compost/peat. Banana or aby other suitable fruit-tree is planted in each pit, with a series of (preferably leguminous) creepers around it, which will steadily fill up the space between the patches under intensive cultivation. The only other task now is to divert surface flow to the pits, drain off any excess, and place ash and any vegetable residues that can turn into compost around the trees. A classic example of this technique can be seen in the Canary Islands, where grapevines are planted in pits dug in a lava field.

- **Van der Poel and Kaya's system** (1989). This method tries to combine regeneration of natural vegetation (grassing) with plantations of crops more profitable for farmers. Lines of stones or strips of cotton stalks are set along contour lines every 7 metres and a line of *Anacardium occidentale* planted between them – by sod seeding – after the second rainy season. This is a thrifty species well-suited to tropical ferruginous soils, and makes an excellent firebreak since its dense foliage smothers any other plants. The recovery rate and growth of the fruit trees can be improved by cutting the grass encroaching on the buffer strips and spreading it around the trees as a mulch. Clearly the plots have to be off limits to livestock for the system to work, and this can be reinforced by explaining the land-use plan to the village shepherds (plus coloured tags on the trunks of surrounding trees). The whole arrangement reduces runoff and the risk of erosion further down, and at the same time steadily restores land productivity (fodder, fruit and wood). This system is rather like "striped shrubland" in which runoff from a bare crusted area will irrigate an area of shrubland (grass + shrubs) which benefits from this additional water. There could be a whole series of variations adapted to each semi-arid zone according to soil type, vegetation and the needs of those managing the soil.

- **Agricultural rehabilitation of soils on hardened volcanic ash** in Mexico. Quantin (1992) and a research team financed by the EC studied the rehabilitation of *tepetate* or hardened volcanic ash whose topsoil has been severely eroded. A variety of preliminary tilling techniques were used in order to restore the agricultural production capacity of this sterile material:

  - criss-cross crawler-drawn subsoiling with teeth penetrating to 50 cm every 60 cm;
  - levelling slope terraces isolated by banks and ditches;
  - successive tilling and harrowing to reduce blocks of hardened ash to 3-5 cm in diameter.

  As extensive farming is the practice (rangeland), farmers have very little manure available – barely enough for 0.5-1 hectare. The cost of tilling the soil comes to 8 000 FF/ha. If maize is planted the first year, yields are very poor, even with a dressing of NPK, either on its own or with a little dried paddock dung.

  However, wheat can give 1 500 kg/ha from the first year if there is a dressing of NPK, alone or with dung. From the third or fifth year, biological problems disappear, and yields normally amount to 6 000 kg/ha/yr if weather conditions are favourable. If the farmer repays only the basic costs, this operation of rehabilitating degraded land will become profitable after eight years. The new manured soil has better infiltration and is more stable and less vulnerable to erosion than the original cultivated soil.

CONCLUSIONS

The development of human settlements inevitably raises problems of degradation of natural resources. In facing this challenge, rural communities have developed traditional techniques of water and soil fertility management that are in harmony with the physical, social and economic environment of their time. Although these traditional methods are now declining, and have been too often ignored or scorned by SWC experts, it is worth studying their workings and dynamics, for they can serve as a point of departure in the dialogue with farmers for a sustainable improvement of their environment.

Given the enormous problems of protecting land resources and public works (roads, etc.), and the quality of water needed for the development of towns and irrigation schemes, the technical experts have for the most part developed mechanical approaches which have turned out to be expensive and relatively ineffective. It is now realized that land protection is the business of those who actually manage and use the land, in other words, the farmers and herders. If their participation is to be enlisted, it would seem that present strategies must be changed and their most urgent problems addressed first (food security, improved standard of living, etc.). Soil conservation is still vital, but it is not enough to guarantee real and sustainable development: the land is already too poor and too degraded. Land husbandry tries to meet the challenge by improving both water and nutrient management in order to obtain a marked improvement in biomass production.

Land-use planning is still the province of the State, which alone has the expertise and resources to solve such problems as mountain reforestation, torrent control, river management, stabilization of the road network and areas prone to landslides. RML and SWC are therefore strategies that are still valid today, but they must be combined with approaches that are more in tune with farmers' interests.

Chapter 3

Some social and economic aspects of erosion

Erosion is not simply a technical problem, and if erosion control has enjoyed only a qualified success so far, the reason lies not only in the failure to solve certain technical aspects of the problem to full satisfaction, but also in the need to pay more attention to the social and economic roots of erosion crises.

In the name of the public good, civil engineers have tried to impose their own solutions without bothering too much about the specific interests of each of the "beneficiaries" of engineering schemes. Here an attempt is made to enter into dialogue with the people who actually work the land, and to define their reaction in terms of their immediate concerns.

An analysis is then made of the extent of erosion problems throughout the world and the special importance of exceptional rainstorms.

After this, known facts about the cost of erosion are schematized; on the one hand, the immediate on-site effects of erosion and runoff on production, nutrient losses and the long-term productivity of degraded soil at the plot level; on the other hand, the off-site problems and damage caused by runoff when it swells peak floods, reactivates river gouging and riverbank degradation, pollutes water through nutrients and suspended matter, or silts up dams and reduces the quality of the water indispensable for the development of towns and intensive farming.

Lastly, an attempt is made to orient the choice of an erosion control strategy on the basis of the economic objectives of such engineering projects, and define the conditions for their success. A brief case study of an erosion control scheme in Morocco is also given.

EROSION CRISIS DIVERSITY (comm. from C. Lilin)

Moving from one age or one country to another, major categories of erosion crises can clearly be defined – even though closer analysis will reveal the unique aspects of any given situation. If this diversity is under-estimated, a chosen approach may turn out to be unsuitable.

EROSION AND THE POPULATION/RESOURCE IMBALANCE

Population growth is reflected in a growing pressure on the natural resources of a given area, which in turn leads to their over-exploitation and degradation. The history of many countries is marked by such erosion crises, which can be classified either according to the causes of degradation or according to the response to the problem.

- **Factors involved in degradation.** In many cases, the effects of the population/resource imbalance are aggravated by other processes. Thus in many developing countries, the presence of wide social differences in rural societies can be noted. Already disadvantaged social groups are sidelined, with their access to land resources reduced, and they are **pushed onto marginal land** (often also the most fragile). These disadvantaged groups also often have poor land tenure status. Now, land insecurity and conditions such as sharecropping or undivided ownership (land held in common) are disincentives to investment, inasmuch as the risks are too great or the possible benefits for the actual workers of the land too small.

  Other processes also help create difficult conditions for the investment inherent in erosion control measures: scarce financial resources, for example. Marginalization also leads to the adoption of **survival approaches, which favour the very short term**. And these may persist even when conditions come to favour the disadvantaged sectors of the farming population.

  In many countries the mechanical effects of population growth are aggravated by social processes that create what might be termed **spiralling degradation**. In such cases, erosion constitutes one indissociable aspect of under-development.

- **Working out a response.** An erosion crisis can be compared to a disease that attacks a body, in this case a rural society. Historians studying past crises have shown how local societies have reacted in an effort to control erosion. For example, Blanchemanche has analysed the response to the 17th- and 18th-century erosion crises in the pre-alpine French Mediterranean region. Rural societies met the challenge by stepping up farm production through techniques such as terracing and irrigation, taking ideas from more technically advanced regions such as Tuscany. Local élites played a key role in the search for techniques (technology transfer), their adaptation to local conditions and their dissemination.

  In many developing countries, however, local élites are not capable of taking responsibility for the erosion problem. Rural societies are often in crisis and traditional structures have lost their authority, while the modern structures in place are incapable of playing their role effectively. Such societies do not have the necessary local structures to meet the various challenges of under-development, and there is a great temptation for a social actor such as the State to take the place of weak local structures, setting up projects to provide the technical elements of a response to the erosion problem.

  Such a strategy might have been effective in the very specific context of erosion in mountain areas in 19th-century France, just as a strategy of State intervention favouring the technical aspects of the problem may also be valid in treating the present erosion crisis in certain large-scale farming and wine-growing hillside areas in France, inasmuch as the rural societies in question have efficient local structures (e.g. at the level of the commune, the county council, the modern agricultural sector and the department-level agricultural authorities). The main role of the State is then that of encouraging the production and spread of suitable technology so as to help speed up implementation of measures ensuring erosion control.

On the other hand, where an erosion crisis affects rural societies that are themselves in crisis, erosion control to a large extent means reinforcement of the authority of local structures. It is important not to neglect the institutional aspect of the problem in such cases.

EROSION AS A FAILING OF MODERNIZATION

Erosion can be seen as a result of over-hasty modernization in certain large-scale farming or wine-growing areas of Western Europe. The last few decades have seen a series of changes, which are reflected in substantial increases both in productivity per hectare and, even more strikingly, in the productivity of the individual farm worker. These myriad and rapid changes (greater specialization of production systems, mechanization and motorization, increase in plot size, and elimination of structures instrumental in rural hydrology, etc.), have had major effects on the soil, and have led to an erosion crisis in some regions.

In tropical countries, a similar situation is observed where traditional farming has been replaced by modern, mechanized monocropping.

Similarly, in older times, changes in cropping practices or the introduction of some new crop – for example, the move to obligatory three-year rotation, or the introduction of potato-farming – sometimes led to the development of erosion.

Where erosion can be analysed as a consequence of agricultural modernization, priority must be given to the technical aspects of the question. Once the necessary technology has been worked out and tested, implementation will be all the easier inasmuch as the most forward-looking farmers are in general those most concerned by this problem, which is bound up with the introduction of new technology.

EROSION CONTROL IS NOT SIMPLY A TECHNICAL PROBLEM

If the diversity of erosion crises is taken into greater account, it will be easier to adapt strategies to specific situations, with major variations in the emphasis on the design and dissemination of technology, treatment of the problem of under-development as a whole, and the institutional aspects.

A major difficulty springs from the fact that in developing countries the simultaneous treatment of these different aspects is vital, often constituting the key to the effectiveness of any action. Now, it is also in such difficult contexts that the production of appropriate technology can leave much to be desired, coordination of the activities of different administrative offices is problematic, and the sheer weight of projects enjoying foreign aid acts against their continuity.

WHO IS CONCERNED BY EROSION CONTROL?

In general, big landowners (> 500 ha) are usually little concerned by erosion, for they can easily abandon degraded land as wasteland.

In France, erosion problems are relatively rare on smallholdings (livestock production or multi-cropping mixed with livestock), for the small farm units are often well manured by animals raised under the zero grazing system. The most enterprising farmers are in fact the ones with serious erosion problems, for they contract debts to purchase large tractors and other equipment to prepare seed beds in the most advanced manner, as well as heavy-duty trailers to transport harvests. They have accepted land consolidation in order to make their farms as cost-effective as possible by eliminating all obstacles (ditches, hedges, copses) that can impede the advance of machinery. It is the people downstream who actually raise the question of erosion control, when they suffer the ill-effects of peak runoff flows, pollution of groundwater and rivers, gullying, and mud flows in inhabited areas. The big landowners should take an interest in no-till techniques, especially since the new EC agricultural policy calls for downsizing production, set-aside for particularly fragile land, and extensive livestock production on grasslands (Seguy *et al.* 1989; De Ployey 1990).

In developing countries, large numbers of poor small farmers are hard pressed to assure the survival of their large families (5 to 10 members in Rwanda) on tiny farms (0.2 to 1.5 ha). Despite falling yields, they cannot allow the depleted soil to rest, so that it is often barely covered (especially in semi-arid areas), fragile, located on steep slopes, and ill-protected from runoff from neighbouring plots and roads. Some families put off investing in land management until erosion damage is so serious that they have no choice. Other families in similar conditions simply up and leave, abandoning everything to try their luck in towns, or else they send some adult members to neighbouring countries to bring in a little extra income. Farmers' interest in land management depends greatly on the land tenure system. If they are the actual owners, they will invest their time (often the only input available) to mark the boundaries of their plots (hedges, low walls, lines of stones) and improve the land (organic dressing, liming, progressive or radical terracing, trenching to break up calcareous crusting, clearing the land of stones, agroforestry). It is relatively easy to introduce agroforestry or intensive cropping under orchard trees, but in cases of sharecropping or tenancy, farmers cannot improve the land they work for fear of being accused of trying to appropriate the land and therefore having their permission to work the land withdrawn, or of suffering rent rises on the basis of improvements.

In Haiti, there are three kinds of land. An "A plot" will hold the owner's house, and is a multi-storey garden, encompassing fruit trees, forage for tethered small livestock, a vegetable garden, and pigs, all protected from pilfering and very well kept. "B plots" are further away, less well guarded, less intensively farmed, and less well protected against erosion. Lastly, most farmers rent some more distant land – "C plots" – which are unfenced, very little developed, and often with trees and soil in an advanced state of degradation. A recent survey showed that all farmers give priority to managing their A plots, which are the best protected – even if this means putting off management of their most degraded land – which is where SWC specialists have been unsuccessfully focusing for half a century, trying out every known method of ditching and terracing (Naegel 1991).

THE IMPORTANCE OF EXCEPTIONAL RAINSTORMS

When the press mentions erosion, it is usually talking about natural disasters which have led to exceptional damage and the loss of human life in the space of a few days – or even hours. People are very often not directly responsible for such disasters, which are caused by natural forces beyond our control, for example, volcanic eruptions, earthquakes, or torrential rain falling on frozen soil. However, human beings can aggravate such damage through ill-advised development. Forgetting the wisdom of their forebears, they have built structural works or homes in the path of avalanches or mud flows, or close to geological faults (San Francisco is an example here), in main river-channels or any other area subject to occasional flooding, thus increasing the catastrophic effects of such exceptional events.

The recent floods at Nîmes in southern France are a good example (Davy 1989). On 3 October 1988, a violent storm unleashed 420 mm of rain in 6 hours on two small Mediterranean catchment areas that dominate the town. The torrents and springs flowing from the limestone hills swelled inordinately and swept violently through the old town, carrying everything with them: vehicles, the contents of shops, etc. There are channels capable of evacuating such huge quantities of water, and these were respected by the Romans in ancient times. In recent years, however, they have been blocked by buildings, Highway 113 (which is designed for flooding and is not a problem), the embankment carrying railway lines, 20 metres of which were swept away (the drains being blocked by the wrecked vehicles) and lastly the motorway, which is slightly elevated. A vast area was therefore flooded, with 4 thousand million FF of damage and 11 fatalities.

The question is whether most erosion damage is a result of such very widely reported but rare disasters, which are very difficult to prevent, or is rather caused by the aggregate energy of rain falling on cultivated soil which could be better protected. A detailed study of erosion damage in the wine-growing areas of Alsace (Schwing 1979) showed that the annual cost of retrieving eroded soil from downslope and loss of inputs following normal storms was about 2 000 FF/ha/yr, whereas the additional damage caused by exceptional events amounted to 15 000 FF/ha/every 25 years, plus local community expenses.

While it is well known that exceptional rains generally produce major damage, the extent of such damage varies in different environments. In temperate areas, according to Wischmeier, the sum of the rain erosivity of all significant showers (over 12.5 mm) is what decides the annual erosion level at the catchment level. In sub-equatorial areas (e.g. Côte d'Ivoire) the situation seems similar (Roose 1973), whereas in areas subject to frequent cyclones (e.g. New Caledonia, the West Indies, Réunion), cloudbursts are so heavy (500 mm in a few hours) that they deeply mark the landscape (regressive gullies, broad river-beds and large numbers of alluvial terraces). Similarly, in semi-arid, Sahel-Saharan or Mediterranean areas nothing may happen for years, and then in the space of a few hours, an exceptional storm, or series of storms, savagely reshapes the landscape for years or even centuries to come, with deep gullies, landslides, the undermining of wadi banks, and large-scale sediment-ation in flooded plains (e.g. the events in Tunisia in 1969; Claude, Francillon and Loyer 1970). This means that it is not always easy to distinguish active gullies from forms that are a legacy of the past, and there is sometimes no direct link between forms of erosion and surrounding land use.

Another major economic question is whether erosion control measures are as effective for exceptional storms as for ordinary rainfall. Hydrologists generally agree (the gradex methodology) that after a certain amount of rain has fallen – whether exceptionally heavy or exceptionally long – the runoff from a catchment area tends towards 100%. This peak is attained for highly variable recurrent storms depending on the kind of rain, the status of the soil and plant cover, and how the whole catchment area has been managed. In such exceptional events, there is hugely swollen streamflow in the outlet channels and impressive sediment loads from the bed, banks and low terraces. However, at the watershed level, the more intelligently planned the erosion control measures are (terraces protected by hedges, grass banks, well-structured soil under a mulch or thick plant cover, etc.), the less danger there is of damage during such exceptional storms. Moreover, torrent-control dams are designed to withstand the effects of such cloudbursts (comm. from Mura 1992).

TABLE 2
Runoff in the Manakazo watershed (Madagascar)
Effect of plant cover and erosion control techniques (cf. Goujon, 1972)

Plant cover		K_{aar} %	Max KR %	Max. flood flow l/s/ha		
				freq. 1/1	1/20	1/100
Burnt steppe:	- years burnt	16	50 - 70	180	320	400
	- other years	13	40 - 50	-	-	-
Steppe off-limits to livestock		6.5	40 - 50	125	200	250
Crops		2.6	>20	45	140	200
Pinus patula forest:	- 0-5 yrs	2	15 - 38	20	95	205
	- >10 yrs	0.5	1 - 5	9	30	40

Kaar: Annual average runoff coefficient
Max KR maximum runoff coefficient

The problem was considered in connection with watershed management in the Tananarive basin in the Malagasy uplands. Since this basin drains five rivers and has only one small outlet, which is partially blocked by a rocky bar, it is regularly flooded by cyclones from the Indian Ocean. These floods are all the more damaging in that they destroy rice harvests and can sometimes drive over one hundred thousand people to flee their homes (Roose 1982).

Three solutions have been examined. The first is that of broadening and deepening the outlet by blowing up the rocky bar, but this entails the risk that regressive erosion could destroy the rice fields that provide food for the capital. Secondly, part of the catchment area could be eliminated, and flood crests could be checked by building dams to store runoff from the heaviest downpours; this is a very neat solution, but costly in foreign currency. Lastly, the hill areas could be managed and afforested, erosion control structures reinforced (terraces with grass embankments) and cropping techniques improved; this solution would take some years, but it is within the financial reach of a poor country with strong governmental presence.

The only available trial results (four 4-ha catchment areas at Manakazo on the Malagasy high plateaux; Table 2) show that peak discharges from the regional control catchment (burnt savannah with *Loudetia stipoïdes*) are ten times greater than under young pine forests (*Pinus patula*) and four times greater than on farmed catchments with progressive terraces (Goujon 1972). For the rare storm, peak discharges do in fact tend to blur the picture, but only for storms occurring once every five hundred years under forest and once every hundred years on farm land. Despite its long-term effectiveness, the method has not been developed on a large scale, since it takes too long (over 10 years) for forests to be effective against runoff.

EROSION EFFECTS IN DIFFERENT REGIONS

The severity of erosion will vary considerably from place to place.

At the 1982 New Delhi International Congress of Soil Science, Kanwar (1982) showed that of the world's 13 500 million ha of land not under water, 22% is suitable for cropping but only 10%) is currently farmed. Losses in arable land have increased over the past ten years to a current rate of 7 to 10 million ha/yr as a result of erosion, salinization or urbanization. At this rate, it would take three centuries to destroy all arable land. Erosion is hence a serious world problem, although it is particularly worrying in certain regions.

Around 1930 in the United States 20% of arable land was seriously damaged by erosion as a result of the earlier and ill-considered decision by European settlers unaccustomed to such semi-arid conditions to plough and farm the Great Plains. This was the grim "dust bowl" era, when dust clouds darkened the sky at noon. Such a public outcry was raised that the American government decided to set up a full-scale soil and water conservation service, offering farmers technical and financial support in each district to volunteer to join the programme. At the same time a network of research stations was set up, which 30 years later led to the formulation of the Universal Soil Loss Equation, or USLE (Wischmeier and Smith 1958; 1978). In 1986, Lovejoy and Napier observed that after 50 years of massive investment in human resources and funding, 25% of agricultural land were still losing over 12 t/ha/yr, the recognized tolerance limit. So the issue remains topical, although water pollution and water quality attract more attention today than soil conservation.

In France, a survey by Henin and Gobillot (1950) established that an estimated 4 million ha of farmland had been degraded by water or wind erosion. Since the danger was considered limited, little research funding was available in this area. Thus France still has no proper erosion control technology, which causes considerable problems in the case of impact studies.

Taking the European Community as a whole, De Ploey (1990) estimates that 25 million ha have been seriously affected by erosion. France is thought to account for 5 million of this total, and the cost of erosion-caused damage is put at 10 thousand million FF, excluding the intrinsic value of the lost soil, which is hard to quantify.

Much more dramatic figures in tropical countries were cause for alarm. In 1977 Combeau reported that 80% of the land in Madagascar was suffering accelerated erosion. Also 45% of the surface area of Algeria is affected by erosion, which translates into 100 ha of arable land lost for every day of rain.

In Tunisia, Hamza (1992) estimated the average annual sediment load transported by the different watersheds. Assuming an average soil depth of 50 cm, the equivalent of 15 000 ha of land are washed into the sea by water erosion each year!

More serious than these dramatic extrapolations are the soil losses recorded on 100 m^2 plots established since 1950 by ORSTOM and the CIRAD institutes (Roose 1967, 1973, 1980a), under Professor Frederic Fournier's influence. Soil losses range from 1 to 200 t/ha/yr (and up to 700 tonnes in mountain areas on 30 to 60% slopes) under crops adapted to average forest slopes (4 to 25%), with losses of 0.5 to 40 t/ha under millet, sorghum, groundnut and cotton on the long tropical ferruginous pediments of the Sudano-Sahelian regions (Roose and Piot 1984; Boli, Bep and Roose 1991).

If an apparent surface horizon density of 1.2 to 1.5 is assumed, the amounts removed by erosion range from 0.1 to 7 mm (and even 15 mm in mountain areas) depending on topography, climate and crop. This corresponds to 1 to 70 cm (150) cm/century or 0.2 to 14 m in the past two thousand years, though the same soil has obviously not been cropped for two thousand years! Land exhausted after 2 to 15 years of relatively intense and unbalanced cropping (removal and losses not being made up for by replacements and supplements) was left fallow, which has the primary effect of reducing erosion (Roose 1992b).

The length of soil life can also be estimated on the basis of mean annual soil loss, the depth of soil to which roots can reach, the rate of soil fertility regeneration, and the soil yield curve as a function of the depth of the arable layer (Elwell and Stocking 1984). In a forest environment, with aggressive rainfall and steep slopes, soil losses can be considerable, and degradation very fast (a few years). However, soil regeneration is equally fast, for degraded soil provided it is quickly covered by vegetation.

In semi-arid areas, the life span can be several decades, despite slight slopes and aggressive rainfall, but the restoration of soil fertility is slower in that biomass production is poor in low-rainfall areas and the soil is greatly depleted.

Analysis of the sediment load of hundreds of American and European rivers shows that there is a semi-arid climatic zone (mean annual rainfall 350 - 700 mm, depending on how continental the watershed is), where specific degradation of watersheds is greatest. In lower-rainfall zones, the specific sediment decreases with rain energy (Fournier 1955). In higher-rainfall areas, the plant cover intercepts a good part of the energy of rain and runoff energy (Fournier 1955 and 1960). Although this is statistically true at the macrofocus of an entire watershed, it is not so at village level, and even less so on the plot level. The specific management system used for each plot leads to major local variations – a valid reason for developing cropping techniques encompassing erosion control.

The economic impact of erosion can be analysed from two perspectives:

- the on-site perspective of plots on which the signs of runoff and erosion have developed;
- the off-site perspective of damage further downstream.

EFFECTS OF EROSION ON THE ERODED SITE: LOSS OF PRODUCTIVITY

The economic cost of erosion on the eroded site itself can be expressed in a variety of terms.

LOSSES IN PRODUCTIVE LAND AND OTHER OBSTACLES TO DEVELOPMENT

Taking the example of the Salci pineapple plantation at Ono in southern Côte d'Ivoire, land clearance, followed by mechanized farming of a 1 000-ha industrial plantation very quickly brought erosion problems, which were countered by installing access tracks along contour lines, establishing grass-covered ridges and alternating rows of pineapples of different ages and ground-covering capacities: it takes six months for a pineapple to cover more than 90% of the soil and protect it against erosion. However, in about 1973, the importation of new mechanized cropping techniques from Hawaii, based on a tanker with a 17-m sprayer arm for fertilizer, weed-killer and nematicide meant a further redesign of the plantation, eliminating the banks and contour tracks to allow for 34-m wide planted rows more or less following the contour lines. Gullying erosion appeared at once, preventing the heavy machinery from reaching whole sectors, which therefore had to be worked once more by hand (which was not very cost-effective). The proportion of productive land lost to erosion (gullying, plants uprooted, the burying of plants under a layer of sterile sand, etc.) amounted to barely 2%, which is a more than acceptable figure. However, the affected area that had to be abandoned for mechanization was much greater (70 ha for one large gully alone) and production delays increased every year. Once channels have formed, runoff water generally follows the same route, so that soil loss increases over time. It is interesting to note that 1 000 ha of small plots cleared and manually farmed by small African planters have never had any erosion problem. The use of heavy vehicles reduces soil infiltration capacity and increases runoff, which collects on tracks before creating gullies on the plots. In tropical areas erosion takes effect very fast – about two to four years – whereas it takes 30 years for similar effects of excessive mechanization to be observed in Europe.

Another example. In England, Evans (1981) studied erosion on a 10 x 10 km area north of London. Here again, the actual area affected by erosion was small (2.9%) but concentrated in certain points: the steep slopes bordering the loess uplands and farmed by the poorest farmers, who could not afford to rest the land or put it under permanent pasture, since they have to ensure food self-sufficiency or at least a corresponding cash income. The potential risks of erosion on these steep slopes and of damage in the case of heavy rainstorms are much greater than on the plateaux, which belong mostly to rich landowners. There may therefore be a connection between erosion risks, the social and economic level of small farmers, fragile land, and the interest of such farmers in erosion control.

LOSSES IN YIELD AND PROFIT MARGINS

Although production losses (2 to 5%) may be slight and easily compensated for in regional terms through the use of new inputs (fertilizers, drainage, mechanization of tillage), the situation is very different for individual small farmers. As much as 10% of topsoil can be lost on this steeply sloping land, with a 30% fall in production and a 50% fall in net income once inputs have been paid for, so that the profit margin essential for the farmer's family shrinks seriously. Erosion therefore has a greater effect on small farmers, who will be marginalized for lack of credit facilities, initiative or know-how. And they can do nothing about it without a radical change in production methods (high-return production). So there is spiralling impoverishment for the poor and a search for new solutions by those who have the means.

VARYING EFFECTS OF EROSION ON SOIL PRODUCTIVITY

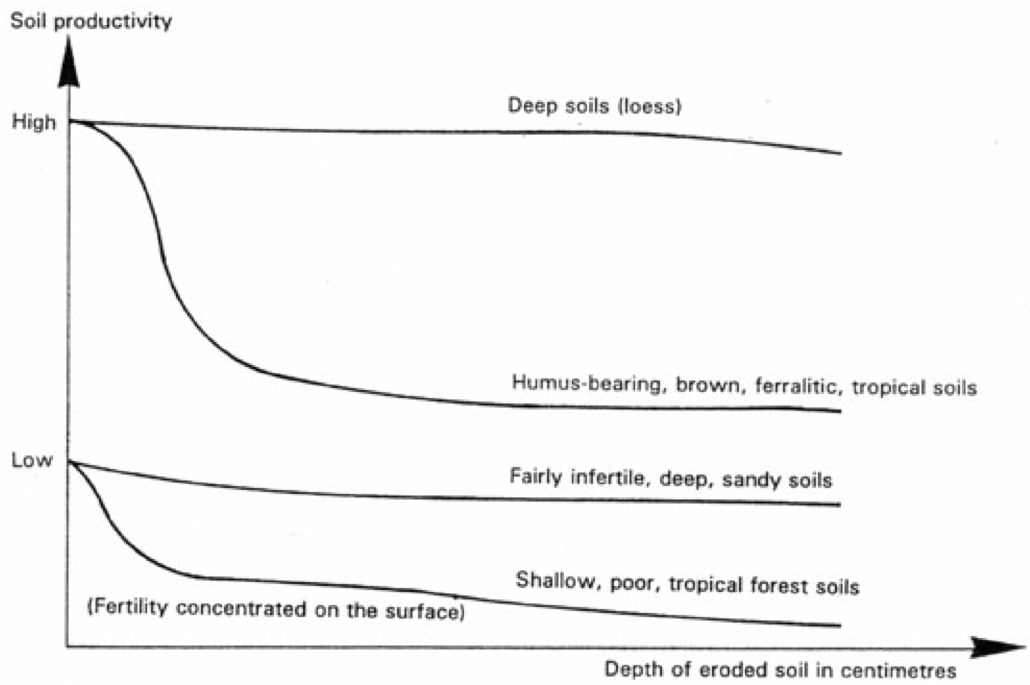
In the United States the cost of the Soil Conservation Service and its slight impact on soil loss led people to question the effects of erosion on soil productivity (the basis of Bennett's SWC system). It was observed that productivity had hardly fallen at all on deep loess soils, which are homogenous to a depth of several metres; indeed, the ill effects of erosion (-1% in yields) were easily made up for by providing new inputs (Dregne 1988) (cf. Figure 6). On the other hand, thin rendzines (forest soils where fertility is concentrated in the topsoil) and many tropical soils very quickly lose their productive capacity.

SELECTIVE EROSION OF FINE PARTICLES, NUTRIENTS AND ORGANIC MATTER

If the quality of eroded soil and the runoff water collected downstream of the eroded plots is compared with the soil left in place to a depth of 10 cm, in terms of plant cover and extent of losses through erosion (Table 3), the following results are seen (Roose 1977a):

- nutrient losses grow in parallel with the volume of runoff and eroded matter; but the nutrient content of soil falls more slowly than the rise in the volume of displaced soil and water;

FIGURE 6
Cumulative effect of erosion on soil productivity at different levels of fertility (cf. Dregne 1988)



- much higher proportions of nutrients are found in the water and eroded soil than in the soil in place (horizon: 10 cm); this is clear for carbon, nitrogen, phosphorus, clay and loam (up to 50 ì) but still more striking for exchangeable bases (14 to 18 times more on cropped land); sheet erosion is thus selective in terms of the nutrients and colloids that are the essence of soil fertility;

- the lower the eroded volume the greater the selectivity of sheet erosion, i.e. from bare to cropped and from cropped to forest land.

This is easily explained in two ways (Figure 7). On the one hand, the removal capacity of sheet runoff is slight since it is slowed down by the roughness of the soil surface, stalks, exposed roots and litter. Sheet runoff can remove only the light matter: the organic matter, clays and loams to which most nutrients are bound. Forest soils, on the other hand – and to a lesser extent savannah soils – accumulate organic matter and nutrients on the surface. When the rain beats down on these soils the first few millimetres – the richest – are the first to be eroded. The more erosion advances, the more it comes from rills and gullies, and the more the generally poorer subsurface is involved. Scoured land is thus less selectively enriched than in the case of surface sheet erosion.

THE COST OF NUTRIENT LOSS

Another aspect of economic loss from erosion is the amount and cost of fertilizer needed to replace the nutrients lost through erosion. This has been calculated by Roose (1973 and 1977a) for southern Côte d'Ivoire. Under secondary

TABLE 3
Selective losses from sheet erosion on a 7% slope at Adiopodoumé (Côte d'Ivoire) as a function of plant cover (cf. Roose, 1977a)

	Total erosion (kg/ha/yr)			Selectivity factor as a function of soil in place (10 cm)				
	Forest	Crop	Bare soil	Forest	Crop		Bare soil	
Total carbon	26.4	855.6	2 725	12.8	2.1		1.5	
Total nitrogen	3.5	98.3	259	22.5	3.1		1.9	
Total phorphorus	0.5	28.5	111	6.6	1.4		1.3	
Exchangeable CaO	3.0	49.9	113	492	18.5		9.7	
Exchangeable MgO	2.2	29.0	45	327	14.1		5.1	
Exchangeable K_2O	1.2	17.7	35	550	2.4		1.1	
Exchangeable Na_2O	0.6	9.5	15	849	15.4		5.6	
Total CaO	3.7	57.1	139	216	8.8		5.0	
Total MgO	2.3	39.0	78	60	5.8		2.7	
Total K_2O	1.3	35.1	87	18	1.7		1.0	
Total Na_2O	0.6	12.6	27	49	3.2		1.6	
Clay 0-2 microns	64.5	5 142	18 275	5.9	1.2		1.1	
						1.5		1.2
Loam 2-50 microns	33.8	2 179	7 115	7.7	2.5		1.9	
Fine sand 50-200 microns	1.7	5 174	23 135	0.1	0.6		0.6	
Coarse sand 200-2000	0	19 305	89 375	0		0.9		0.9
					1.1		1.2	
Total erosion t/ha	0.11	32	138					
Runoff m^3/ha	210	5 250	6 300					

- The first observation is that the total eroded products are less than the erosion indicated at the bottom of the table, inasmuch as the amounts of Fe_2O_3, Al_2O_3 and SiO_2 (clays) have not been counted – nor, more especially, that of the residue insoluble in triacide (quartz sands).
- The increase in chemical losses is almost parallel with that of soil losses, and is thus in inverse proportion to plant cover. Nutrient concentrations in the eroded substances decrease somewhat as erosion increases, but this decrease is not proportionate to the increase in water and soil losses.
- Since erosion has short- and medium-term repercussions, a distinction must be made between directly absorbable (exchangeable) nutrient elements and those included in mineral reserves.
- Carbon and phosphorus depletion takes place mainly in solid form (bedload and suspension), whereas nitrogen, total bases and especially exchangeable bases migrate exclusive in solution.

rainforest, chemical losses from erosion are slight: 26 kg/ha/yr of carbon + 3.5 kg of nitrogen + 0.5 kg of phosphorus, and a few kg/ha/yr of bases. These losses are easily made up through biological upwelling (OM deposits in litter) and the nutrients in rainwater.

On the other hand, under extensive cropping with fairly poor ground cover, nutrient loss from erosion in kg/ha/yr amounts to 98 kg of nitrogen, 57 kg of calcium, 39 kg of magnesium, and 29 kg of phosphorus and potassium. To compensate these losses by fertilizer applications would take 7 tonnes of fresh manure, 470 kg/ha of ammonia sulphate, 160 kg of superphosphate, 200 kg of dolomite, and 60 kg/ha/yr of potassium chloride. Unsurprisingly, then, the soils of southern Côte d'Ivoire are exhausted after two years of traditional cropping, especially when removal by harvesting and losses through drainage (800 mm per year) are also added into the equation.

FIGURE 7
Selectivity, the danger of sheet erosion

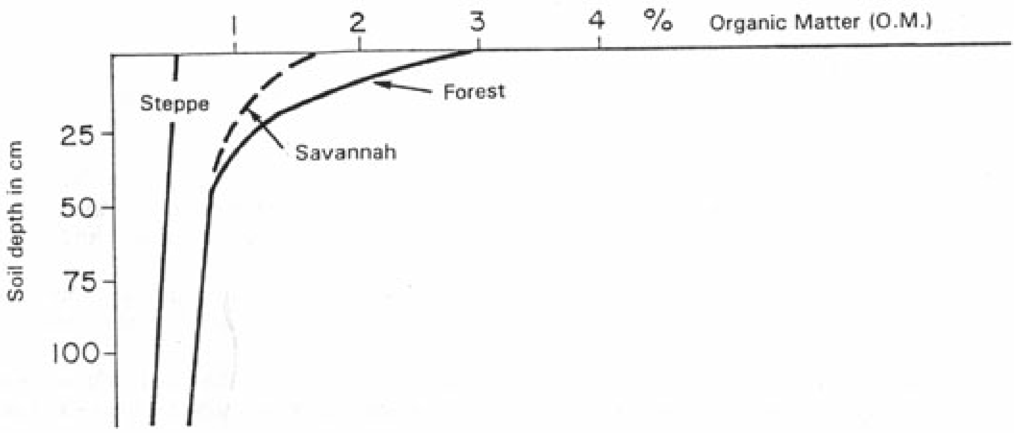
SHEET EROSION IS DANGEROUS, inasmuch as:

- it is hard to recognize:
  even if erosion = 12 t/ha/yr = 1 mm of soil, it is less than natural soil respiration;
- it greatly reduces the infiltration capacity of soils (slaking crust);
- it selectively removes the fine, light particles (organic matter, Clay + Fine loam).

TWO REASONS FOR THE SELECTIVITY OF SHEET EROSION:

1. The energy of sheet runoff is too weak to move coarse particles: the roughness of the soil surface reduces the speed and competence of sheet runoff. Only organic matter, clay, silt and their associated nutrients leave the plot; sand moves over the soil surface and forms colluvial soil at the bottom of the slope. If erosion speeds up, rills appear in which erosion is no longer selective.

2. The soil surface is generally richer in organic matter, especially under forest.



THREE EFFECTS

1. Accelerated imbalance in nutrients (see Table 4)
2. Accelerated imbalance in organic matter, leading to degradation in structure, macroporosity and infiltration capacity.
3. Soil skeletonization through the relative accumulation of coarse particles on the soil surface.

CONCLUSION

Sheet erosion speeds up physical, biological and chemical degradation in the surface horizons of cultivated land.

Stocking (1986) later took Hudson's data from analyses of soil and water collected on different plots in the 1960s, together with a map of present-day land use in Zimbabwe, and calculated that each year the country lost 10 million tonnes of nitrogen and 5 million tonnes of phosphorus as a result of erosion.

Fortunately, the nutrients lost to these plots are not definitively lost to the country, but can be recovered on plots downstream, nourish fish, or perhaps end up on rich alluvial or colluvial land, though they may equally well provoke eutrophication. Nevertheless, before launching a mineral fertilization project, nutrient losses from erosion must first be halted, for they cause a serious chemical imbalance in cultivated land (Roose 1980a; Roose, Fauck and Pedro 1981).

PRODUCTION LOSSES CAUSED BY RUNOFF

In hot countries with temporary arid seasons, biomass production depends on soil fertility, but still more on water availability when the crop needs it.

Now, if the water balance is calculated even roughly (Roose 1980a, or Somé 1989), it can be seen that in subequatorial zones, development of 25% runoff (a frequent rate on land under cereals, cassava and other foodcrops) leads to a reduction in the volume of water draining below the roots. This means that there is a certain compensation between nutrient loss through runoff and through drainage, although very few effects of runoff are seen on real evapotranspiration, biomass production and crop yields.

Against this, in semi-arid zones (mean annual rainfall less than 700 mm), the same percentage of runoff actually observed under foodcrops and cotton not only limits the possibility of drainage (and hence of groundwater recharge), but also reduces real evapotranspiration and hence the potential for biomass production (Figures 8 and 9).

In the day-to-day reality of arid zones, the depressive effect of runoff on production is even more acute if water storage in the soil is lowered by runoff at the start of the cropping cycle (delayed seedling planting), or low during flowering (few ears fertilized) or at the end of the cycle (grains imperfectly filled) due to poor runoff and groundwater management (Nicou, Ouattara and Somé 1987). In Sudano-Sahelian zones the impact of runoff from the first storms at the onset of the rainy season deserves emphasis. These storms clear the surface of organic residues and animal wastes that have collected throughout the dry season. Such losses of organic matter lead to a considerable drop in the productivity of land on the broad pediments of Sudano-Sahelian zones.

Another generalized effect of runoff, whatever the climate, is to reduce the concentration period of rainwater, increase peak discharge (and hence sediment load and the scale of structural works), and cause a reduction in the base discharge of rivers, particularly in the dry season when water is needed for irrigation purposes.

Hydrologists, who often look for catchment areas with heavy runoff after each rainfall to feed lakes, reservoirs or towns, have a very different viewpoint from agronomists, who look for better infiltration and better actual evapotranspiration for better plant production. Hydrologists and agronomists are, however, of one mind in looking for clear water and the most even year-round flow possible, in keeping with the principles of good management. Even

FIGURE 8
Graph showing the water balance for the Sudano-Sahelian region of Ouagadougou, Burkina Faso

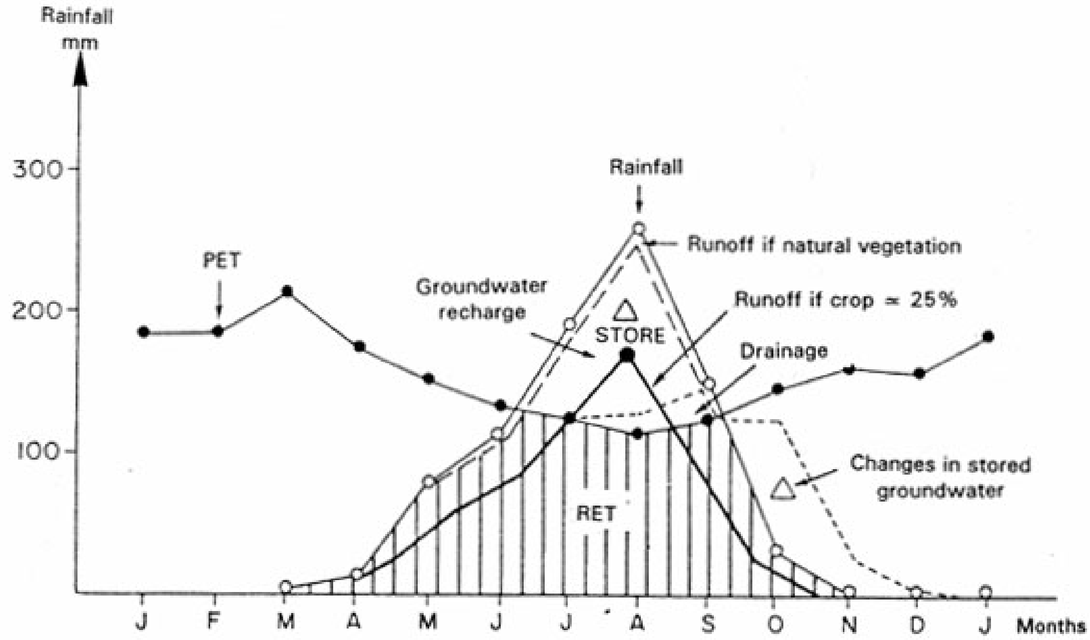


TABLE 4
Chart of the average water balance for the Ouagadougou region, Sudano-Sahelian savannah
(cf. Roose 1980a)

Month	Rainfall (mm)	Potential evapotrans-piration (mm)	Runoff (mm)	Actual evapotranspiration (mm)		Drainage (mm)	
				(1)	(2)	(1)	(2)
January	0	187	0	0	0	0	0
February	0	188	0	0	0	0	0
March	1	216	0	1	1	0	0
April	19	178	0	19	19	0	0
May	81	155	2	79	79	0	0
June	116	136	3	113	113	0	0
July	191	129	5	129	129	57	0
August	264	116	7	116	116	141	4
September	151	126	4	126	126	21	21
October	37	149	0	37	149	0	0
November	0	165	0	0	82	0	0
December	0	160	0	0	0	0	0
Total	860	1 905	21	620	814	219	25
%	100	222	2,5	72	94,6	25,5	2,9

(1): gross (2): corrected

so, in arid zones, certain areas of the watershed may be needed for water harvesting to ensure the growth of crops on small areas (runoff farming) (Critchley, Reij and Seznec 1992).

In conclusion, runoff control has different consequences depending on the water balance (Table 4). In high-rainfall areas, runoff reduction leads to a slight improvement in the actual evapotranspiration, but mainly to increased drainage and hence increased risk of leaching – and in the rate of flow when the river is at its lowest. Agroforestry can be brought into play to increase the actual evapotranspiration.

In semi-arid zones (with less than 700 mm of mean annual rainfall) runoff reduction increases the stored water available for the actual evapotranspiration, and hence biomass production (and yields).

LONG-TERM EROSION-INDUCED REDUCTION IN SOIL PRODUCTION POTENTIAL

Runoff and erosion can have an **immediate** deleterious effect on yields of standing crops, but can also progressively modify the physical, chemical and biological nature of the soil (through selective erosion of the most fertile components) and reduce the long-term potential of certain soils, especially thin soils (with poor water- and fertilizer-storage capacities) and forest soils (where fertility and biological activity are concentrated in the surface horizons). It may be wondered whether the productivity of these soils can be restored simply by stepping up the amount of fertilizer used (cost of soil restoration).

In Nigeria, Lal (1983) examined the impact of erosion on the productivity of an alfisol at the IITA station near Ibadan, using three approaches:

- On 24 erosion plots (125 m^2) with 1, 5, 10 and 15% slopes, subject to different treatments from 1971 to 1976, he measured different levels of cumulative erosion and calculated the depressive effect of erosion on the characteristics of the surface horizon, particularly for carbon, nitrogen, assimilable phosphorus, pH and total porosity. Multiple regressive analysis of the effect of three soil properties on maize yields indicates that erosion-induced changes in the soil have a significant effect on yields.

  $$\text{Maize yield} = 1.79 - 0.007\,E + 0.7\,(Co) + 0.07\,(Po) + 0.002\,(Ic) - r = 0.9$$

  Maize yields (in t/ha) fall with cumulative erosion (E in t/ha), but increase with the level of organic carbon (Co in %), total porosity (Po in %) and infiltration capacity (Ic in cm/h). r is the regression factor.

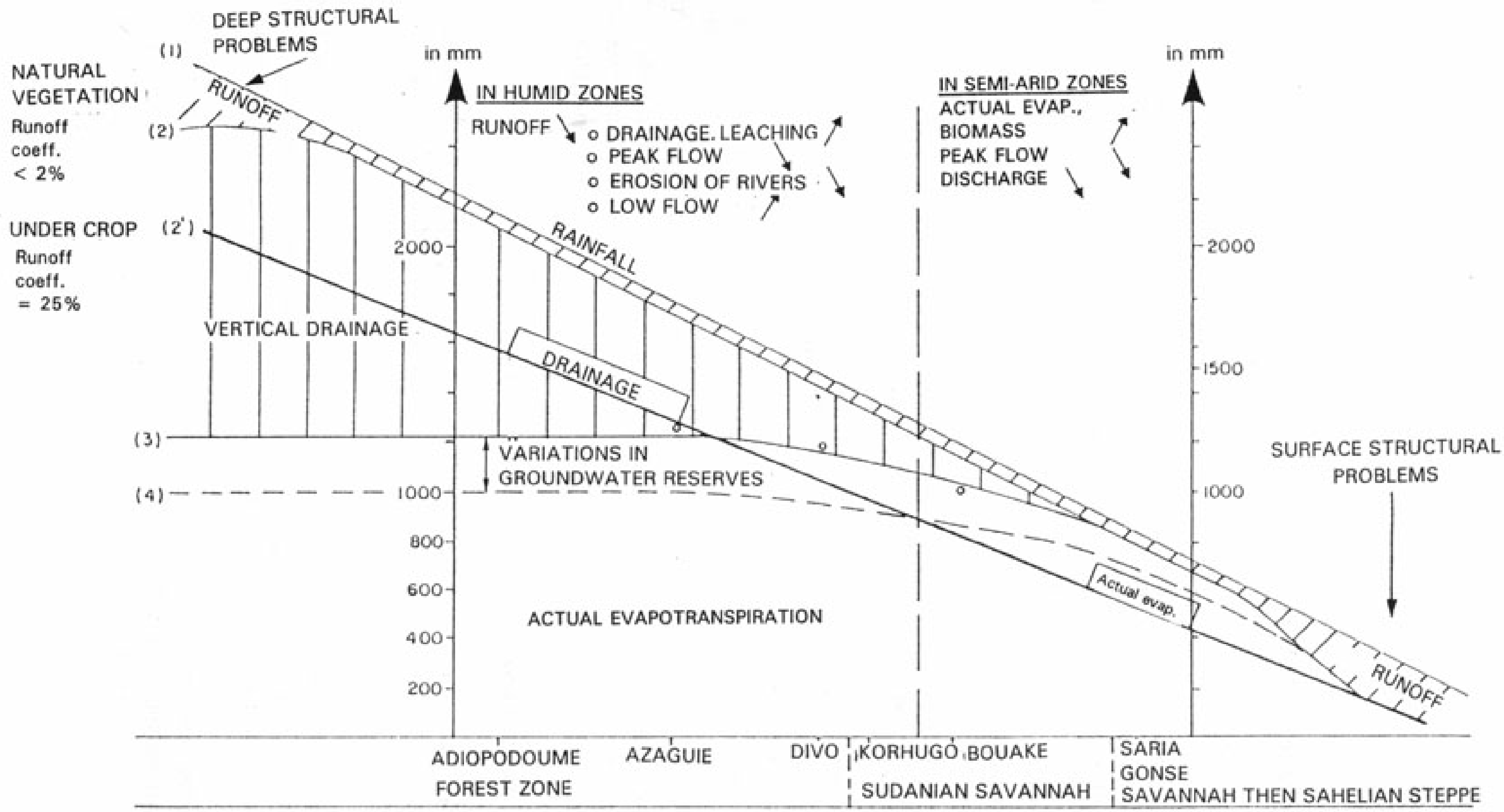
  This regression seems to indicate that erosion-induced reduction in soil productivity can be countered primarily by adding organic matter, and secondly through cropping techniques that improve porosity (or water-storage capacity) and infiltration capacity.

- Having obtained varying erosion levels on the same plots, Lal then monitored maize yields during four cropping seasons (1977-78), using the same treatment and average fertilizer rates (40 + 80 N + 26 P, + 30 K per ha).

  As foreseen, the least erosion was on the plots with a 1% slope. Despite this low rate, however, the best yields were not from these 1% slopes but on plots with 5, 10 and 15% slopes.

FIGURE 9

Changes in the water balance under natural vegetation as a function of climate (cf. Roose, Lelong and Colombani 1983)



NOTES ON FIGURE 9:

EFFECTS OF RUNOFF CONTROL AS A FUNCTION OF THE WATER BALANCE

IN SEMI-ARID ZONES

From the agricultural viewpoint:

- increase in the stored water available for plants
  in the actual evapotranspiration of plants
  in the biomass ... and possibly in yields

From the hydrological viewpoint:

- reduction in the peak flows of rivers
  in total annual discharge
  in suspended sediment
- stabilization of gullies and rivers

IN HUMID ZONES

From the agricultural viewpoint:

- modest increase in stored water available for crops, actual evapotranspiration, biomass, and yields
- large increase in risk: of drainage
  of nutrient leaching
- need to intensify actual evapotranspiration (agroforestry and mixed cropping) to avoid nutrient leaching and soil acidification

From the hydrological viewpoint:

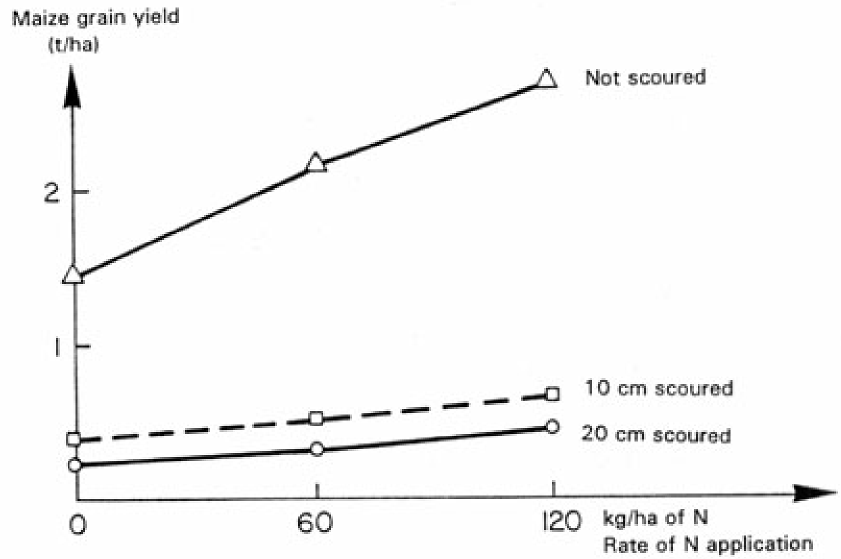
- reduction in peak flood flows
- stablization of gullies and rivers
- reduction in suspended load, but
- increase in the base flows of rivers
  in low flows
  ... and in useful water

IN CONCLUSION:

Farmers will be appreciative of improved infiltration in their fields as it allows improved biomass production in semi-arid zones.

It must go hand-in-hand with intensified cropping and sound nutrient management, especially in humid zones (Rainfall > 1000 mm).

FIGURE 10
Maize yields for varying depths of scouring and three levels of N application (IITA Ibadan Station) (cf. Lal 1983)



On average, maize yields fell by 0.26, 0.1, 0.08 and 0.1 t/ha per millimetre of eroded soil on plots with 1, 5, 10 and 15% slopes, respectively. The yield reduction rate for a 1% slope is thus two to three times higher than on steeper slopes that are more seriously eroded. This can be attributed to the fact that runoff increases sharply on these flatter plots where infiltration declines faster due to rain splash.

Apparently, above a threshold of 4 mm (60 t/ha) of cumulative erosion in six years, maize yields fall fast. This would give a tolerance rate of roughly 10 t/ha/yr of erosion for this type of soil, although it is difficult to generalize, since productivity reduction rates, as a function of the decrease in soil depth, could have been greater if there had been greater water stress during these four farm seasons.

· Lal tried to speed up his experiments by mechanically scouring the surface of plots with a 1% slope just beside the erosion plots on a ferralitic soil over a gravel sheet at about 25 cm (paleustalf) that had been under bush fallow for 15 years.

The soil was scoured to 0, 10 and 20 cm, and treated at three fertilizer rates (N = 0, 60 and 120 kg/ha; and P = 0, 25 and 75 kg/ha) using a split plot layout, with each treatment repeated three times, and the maize grown without tillage.

Variance analysis shows that scouring has a significant depressive effect on plant height, leaf nutrient content, and the grain and biomass yields. The surprising finding is that the effect of nitrogen application is observable only on plots that have not been scoured, implying that accelerated erosion can irreversibly reduce the soil productivity of shallow soils (negative interaction of erosion with mineral fertilization).

TABLE 5
Three fertilization levels on degraded soils

Fertilization	N	P	K	Mg	Zn	Mo	Lime (kg/ha)
F_o	0	0	0	0	0	0	0
F1	110	50	0	20	5	1	0
F2	220	450	250	100	10	2	3 500

Moreover, the reduction rate in terms of grain (0.13 and 0.09 t/ha/cm of scoured soil) and straw (0.16 and 0.12 t/ha/cm) is much higher for the first centimetres of topsoil scoured, and would be even more marked if less than 10 cm had been scoured at a time.

Nitrogen and phosphate applications had positive effects on N and P content in the leaves of cultivated plants. If grain yields did not rise in economic terms, this was because of other limiting factors, particularly the porosity, structure and water-storage capacity of deep horizons now exposed to rain splash.

Comparison of productivity losses from artificial scouring (0.013 t/ha/**mm**) and natural erosion (0.26 t/ha/**mm**) on the same shallow soil shows that **the effects of natural sheet erosion are 20 times more serious than simple mechanical scouring**, since sheet erosion selectively removes the most fertile elements: organic matter, clays and loams, and the most soluble nutrients.

Lal concludes that the studies on “scoured plots” gave only relative indications of the impact of erosion on soil productivity, especially on shallow soils (Figure 10).

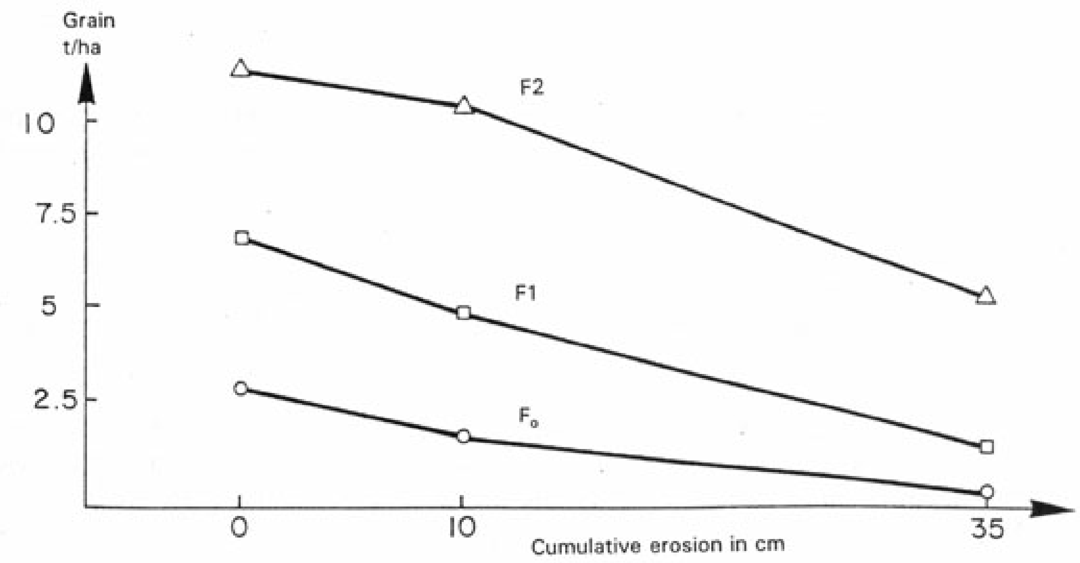
Another example has been given on a recently cleared oxisol (tropeptic eutrustox, kaolinitic clayey) on the island of Oahu (Hawaii) (El-Swaify, Dangler and Armstrong 1982). Preliminary studies showed that this soil had a strong concentration of fertility in the first ten centimetres as well as in a compact layer at about 35 cm. It was then decided to assess the harmful impact of scouring the first ten centimetres and exposing the subsoil with its unfavourable physical characteristics. The three treatments (scouring of 0, 10 and 35 cm) were restored with three levels of fertilization (0, 50 and 100% of requirements to attain peak production) (Figure 11).

The results showed that this oxisol has a much higher potential (11 t/ha) than the Ibadan alfisol and that fertilization (especially N and P) has a decided influence in almost all situations. Even so, yields fall very sharply when 35 cm of soil is removed, probably because the rooting system develops poorly in this extreme case.

Without fertilizer (Fo), yields fell by half for a 10 cm scouring, and by 90% when the whole humiferous horizon was removed. There appears to be a threshold beyond which yields fall sharply even if large doses of fertilizer are applied (110 N + 50 P) (Table 5).

The cost of restoring severely scoured soil becomes uneconomic (220 N + 450 P + 250 K + 3 500 CaO), for the physical properties of the subsoil are unsuitable for root growth and the soil’s phosphorus fixation rate is very high. The economic impact of erosion is particularly marked when restoration of the subsoil requires major phosphate and lime inputs, a syndrome very frequent in tropical soils.

FIGURE 11
Maize production as a function of the level of mechanical scouring and mineral fertilization with a view to restoring productivity (2nd harvest) (cf. El-Swaify, Dangler and Armstrong 1982)



These two experiments on tropical soils with very different productivity demonstrate clearly how sheet erosion, although hard to see, can have a serious long-term effect on the productive capacity of soils. Even if it is modest in annual terms, this depressive effect is cumulative, eventually thrusting itself into the limelight when certain properties of the soil pass tolerance thresholds:

- levels of organic matter (0.6% according to Pieri 1989) and clay (10%),
- structural stability and infiltration capacity,
- water- and nutrient-storage capacity.

A soil degraded through sheet erosion is a tired soil and barely reacts to applications of mineral fertilizer. This is what happens with shallow ferralitic soils on ironstone or gravel sheet, and soils with compacted horizons close to the surface.

Even so, not all soils are non-renewable natural resources. In the section on "Restoring Soils and Rehabilitating Land" in Chapter 2, it was seen that if a series of six rules is respected (and not simply the application of mineral fertilizers), the fertility of a good number of sufficiently deep soils can quickly be restored. However, the cost of such restoration rises the longer the delay in protecting the soil: thus the soil has to be tilled in depth, fermented organic matter, fertilizers and conditioners have to be applied, the induced porosity has to be taken over by an abundant biomass ... and the soil has to be protected against runoff.

Lastly, in the very special case of old ferralitic soils that are acid and completely desaturated (ultisols), it might seem best to speed up their erosion in order to improve their productivity. However, the price would be high, for one must take account of the impact of huge quantities of sterile matter that would clutter up the richer plains, and also envisage a major investment in order to restore fertility to the rejuvenated soils. When experimental bench terraces were built on the Rwanda hills, nothing grew on these soils altered down to Horizon B without a huge application of manure (30 t/ha) combined with liming (3 t/ha every two years) and supplementary mineral dressings (50 N + 50 P + 50 K) (Rutunga 1992).

So erosion affects the production potential of a soil. In the case of a desaturated ferralitic soil (e.g., alfisols), if it has been eroded it can no longer store water and nutrients and supply them to crops as and when needed. It has also lost some of the biogenic components of the topsoil, and so micro-organisms are inefficient or slower at recycling the nutrients contained in the soil. Lastly, rooting is usually insufficient in the subsoil when the topsoil has been eroded.

NEGATIVE OFF-SITE EFFECTS OF EROSION

On-site erosion affects individuals and is often viewed fatalistically, whereas the downstream damage disturbs groups who have access to public opinion and the media, and who can organize protests against those responsible.

The negative effects of erosion on yields and the production potential of land vary widely (from nil to heavy). However, the cost of off-site damage in terms of eroded fields is generally much higher, and the effects much more spectacular, amply justifying the majority of large-scale erosion control schemes.

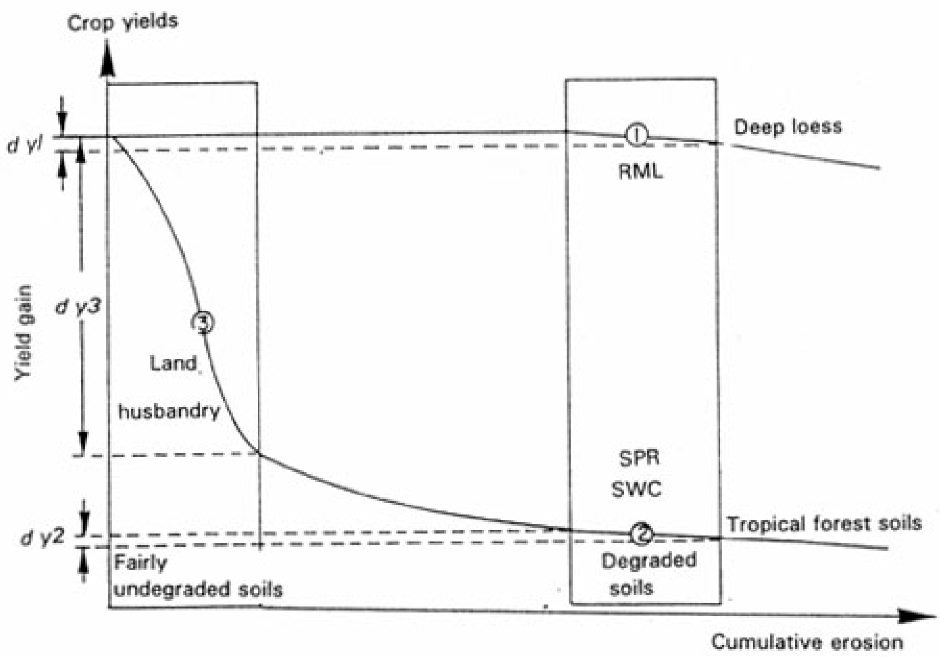
This observation is true of RML, which seeks to maintain communication links in the mountains and protect restructured valleys. It is also true of SPR, which seeks to protect soil, but especially to prevent dams from silting up too fast, and structural works, roads and villages from being destroyed.

Even soil conservation, officially designed to maintain land production capacity, also concentrates on protecting water quality, which is so essential for urban dwellers. This is why the State makes considerable efforts to provide technical and financial assistance to farmers to develop their land (a task undertaken with varying degrees of willingness or coercion in different regions). In the United States, nearly 50% of scientists in the Soil Conservation Service work on water quality and various types of pollution problems rather than on soil protection.

Off-site damage consists firstly of **a deterioration in the quality of river water** due to the suspended load that accompanies flood waters formed mostly by runoff. Suspended load includes organic matter (a threat to the oxygen essential to river fauna) resulting, for example, from intensive stock farming (liquid manure), as well as nitrogen and phosphorus (from mineral fertilizers used by farmers), which can lead to eutrophication of ponds (invasion by algae which will in turn asphyxiate the fish). While abundant runoff at certain times of year increases peak discharge into spillways, it also reduces supplies to groundwater and the rate of low-water flow. On the one hand, it causes downstream sediment on the river bed and banks to be recycled downstream – an erosion phenomenon often seen in small watercourses in Africa. On the other hand, the reduced low flow in the dry season can no longer carry away pollutants from industry, towns and intensive farming, resulting in the eutrophication of water-

FIGURE 12
Effect of cumulative erosion or scouring on production potential of soil

Advantages of rural infrastructure strategies (RML, SPR, SWC) and rural development (land husbandry) with regard to soil conditions.



courses and the death of many tons of fish each year in Europe. Peak flood sediment loads also cause damage, leaving torrential mud flows at the bottom of fields, in ditches, on roads and in cellars. Once the peak flood is over, considerable amounts of sediment are deposited in lakes, rivers, canals and harbours.

This is why there are wide variations in the life-span of dams – an essential consideration in their economic viability – from one region to another, and even within the same region, depending on the respective size of the reservoir and catchment area, but also on climate, plant cover, and watershed management (basin gullies and river banks).

While the **Kossou Dam** in the tree savannah of central Côte d'Ivoire is unlikely to silt up in a thousand years, the main Maghreb reservoirs have a very short life-span (25 to 60 years) and the hill or check dams (small reservoirs very close to the source of silt) may well last less than two years and no more than ten.

Bearing in mind the cost of even the smallest dam, it is easy to appreciate why such huge efforts are made to reduce sediment load in the Mediterranean area, where the lithology is clay layers, marls, and soft sandstone or schist, alternating with hard limestone or sandstone strata, combined with steep slopes and plant cover often heavily degraded by overgrazing and fires.

In Algeria laudable efforts have been made since 1945 to reforest valley heads (50 000 ha) or badlands, check further gullying, control wadis, and manage 300 000 ha of cropland by putting in flat and graded channel terracing (built by the SPR service, then by the National Forestry Department). Since 1978 terrace construction has been suspended, following criticism by experts, rejection by farmers, and above all economic problems. Erosion control has been reduced to protection of structural works, reforestation, plant cover for gullies, and construction of major dams. Only RML is left to watch over water quality, irrigation schemes and the needs of urban populations. For small farmers, the only activity of the State today concerns land improvement (i.e. subsoiling of calcareous crusted soils to increase cereal productivity) and the building of small check dams to provide water for stock, household use and a few irrigated hectares at valley heads. Even this policy is questioned by hydrologists, who point out that the level of dam siltation remains the same after upper watershed management. The works of Heusch (1970 and 1982) and Demmak (1982) show that most of the sediment trapped in reservoirs comes from gullying, landslips, the collapse of river banks and streambed displacement. On the basis of erosion control projects intended to reduce downstream damage or preserve land resources in catchment areas, a compromise will be sought allowing work to be carried out in the valleys to trap silt and stabilize banks while managing the watershed to reduce and delay runoff (land improvement, grass banks, farming techniques to cover the soil in winter and replant overgrazed areas). There are methods of economic calculation that provide for selection of the most effective erosion control, balancing the costs of this against the expected damage in the absence of intervention (cf. the CEMAGREF courses in Grenoble).

THE ECONOMIC RATIONALE FOR LAND HUSBANDRY

Erosion control has in the past been seen as a means of conserving long-term soil productivity, and it has been very difficult to justify the short-term economic viability of erosion control projects. In view of the size of the task, large sums (several thousand million dollars worldwide) have been spent on land protection programmes, but their effectiveness has been limited by the approach used and methods not really suited to social and economic conditions. Since available finance is limited, choices must be based on specific objectives. The most effective and economical methods must be identified; then, on this basis, the best sites for intervention can be worked out, depending on the objectives of each project. Figure 12 shows the different reactions of two types of soil to erosion. Curve 3 shows the rapid productivity loss of a forest soil in which fertility is concentrated near the surface. Curve 1 shows that productivity loss for a deep loess is slight even under heavy erosion, for there is a thick layer of fertile soil, and its water and nutrient storage capacity is barely affected (except by the loss of surface organic matter).

The conventional strategy applied by foresters and land-use planners (RML and SPR) entailed intervention wherever sediment transport is heaviest: steep slopes, gullies, scoured areas and sterile, exhausted soils. Such action has very little effect on the productivity of very degraded soils (yield gains (d y) 1 and 2 in Figure 12) – which is why farmers are reluctant to adopt the practices imposed, such as terraces, which do not improve yields, and why they also resist restricted grazing.

Major improvements in soil productivity (d y 3) will be seen only if work is carried out on soils that still have a good surface fertility, not on exhausted or deep soils (Curve 1). Curve 3 is much sharper in the case of slight erosion than when erosion is already high and soils too degraded. Land husbandry advocates this approach, in which a modest improvement in production systems results in improved rainwater storage, higher biomass production, improved soil cover, and therefore much less erosion.

ECONOMIC EFFECTS OF EROSION

1. On-site losses in eroded areas: affecting farmers

- Losses of water, fertilizers and pesticides
- Immediate production loss
  - in regional terms: 2 to 10%: compensation possible through inputs
  - in local terms: 2 to 50% = individual disaster = loss of profit margin
- **Loss of arable land**
  - in world terms: 7 to 10 million ha per year
  - in regional terms: 2 to 5%
  - in individual farm terms: as much as 20 to 100%

  It would take 200 years to destroy all arable land
- **Long-term productivity loss = SOIL MEMORY**

  Reduced depth of topsoil
  Reduced water and nutrient storage
  Reduced effectiveness of rain and inputs
  Reduced economic viability = soil depletion

  CONCEPT OF SOIL LIFE-SPAN

2. Off-site - or downstream - damage: affecting townspeople

- **Deterioration in water quality**

  pollution of rivers, death of fish, silting up of reservoirs, cost of dredging harbours
- **Increase in suspended load (SL)**

  higher costs for drinking water
- **Flooding of inhabited areas**

  mud flows, sanded up ditches
- **Rise in peak flows of rivers**

  destruction of structural works, bridges, etc.

3. Major consequences for erosion control

Erosion on deep soils causes only off-site damage, but barely affects yields
Erosion on thin soils causes rapid falls in yields

Choice of an economically viable erosion control policy:

- **RML and SPR** on degraded soil bring little improvement in yields, but do reduce sediment transport
- **SWC** reduces soil loss from fields, conserves soil, but does not improve its fertility
- **LH**
  - **is concerned primarily with productive land**
  - **improves yields by restoring its fertility**
    reducing runoff
    increasing plant cover and rooting depth
  - **indirectly or in the long-term reduces peak flows and sediment transport by rivers**

CONCLUSIONS

- **Soil degradation creates serious problems only for some smallholders.**
- **Off-site damage is much more costly, and forces the State to act.**
- **Drainage is generally improved (concrete channels) to reduce damage.**
- **Land husbandry seeks to act on the cause and improve infiltration by modifying production systems.**

If the money earmarked for soil protection is to be used to the best advantage, it is logical to invest it in the best productive land in order to prevent its degradation or else to restore production on soils just beginning to deteriorate, rather than pouring money into completely scoured land which requires large-scale investment and considerable time before recovery to an acceptable level of productivity. However, there are cases (e.g. Haiti) where the tops of very eroded hills (known as "finished land") are the source of heavy runoff which can destroy fertile soil on the lower slopes. These hill-tops must therefore be planted and protected from grazing, and the runoff water collected in tanks for supplementary irrigation of the deep soils of the lower slopes.

The conventional intervention on scoured soils rarely has positive effects on yields (d y1 and d y2). To enlist the farmers' involvement, it is best to choose land that is still viable and will respond fast and significantly to new production systems.

Nevertheless, from a social point of view, it is not possible to abandon all degraded and unprofitable land, for this would accelerate migration, with the attendant problems. There are also circumstances where erosion-degraded soils are the only kind available and can in fact be restored with a small financial outlay. This is the case for certain land on the Mossi plateau (Burkina Faso), which can at present be restored in one year using the zaï method (300 hours of digging and pick-work + 3 tonnes of manure and its transportation – Roose, Dughe and Rodriguez 1992).

On the other hand, **if the aim is that of limiting sediment transport and the risk of siltation –** or if the objectives are social (providing work for the poorest members of society in high emigration areas) – action must be taken in the most severely eroded areas and those closest to the river bed (gully, bank and torrent control).

In conclusion, the objectives must be clearly defined before erosion control methods can be advanced.

If the aim is that of reducing land degradation (on-site, small-farmer perspective), farming systems must be developed that can rapidly increase soil productivity (increased infiltration capacity, fertilizer input, selected seeds, plant health care, etc.): farmers will quickly become interested in participating in such projects.

If, on the other hand, the aim is that of reducing siltation risks (off-site perspective), the only way that will attract farmers in the high valleys is incentives or compensation for the loss of productive land, hours of work, and drawbacks of the structures (channels, banks, terraces, etc.). These farmers cannot really be relied on to maintain the structures, which are always dangerous if they overflow (gullying) (Roose 1991).

A compromise is often reached in practice: putting a rapid stop to the most active processes on degraded land and gullies, intercepting runoff on scoured gravel slopes and elsewhere, initiating a gradual change in cropping systems on good but deteriorating lands.

CRITERIA FOR THE SUCCESS OF SOIL CONSERVATION PROJECTS

The 136 experts taking part in the 1987 Puerto Rico Seminar – research experts and developers, all of whom had practical experience of soil conservation in steeply sloping tropical areas – talked at length about the reasons for soil conservation project success (Sanders 1988, Hudson 1991), and here we offer our conclusions, including other experiences as well (Critchley, Reij and Seznec 1992).

- **No universal solution.** While rules for water and soil-fertility conservation may be universally valid, environmental, social and economic conditions vary so widely that universal solutions must not be extended. The effectiveness, cost and limitations of each technique must first be studied, then the regions in each country that have more or less similar environmental conditions must be defined, and lastly an array of solutions must be proposed on the basis of local conditions – slope, land tenure system, economic possibilities, farmer training, and the availability of labour, equipment and supplies.
- **Taking account of farmers' immediate priorities**. i.e. increased production, security, income and standard of living, getting the best return from labour. If soil conservation is planned exclusively on the basis of the off-site problems caused by siltation or flooding, high-valley farmers will not feel involved, and the State will have to step in and assume responsibility for rural hydraulic works. Soil and water conservation requires a major effort in terms of shaping the landscape, managing runoff, altering cropping techniques, and maintaining structures through the years. If farmers see that the soil continues to deteriorate (through mineralization of organic matter and rain splash) and crop yields keep dropping, they will quickly stop expanding – or even maintaining – the erosion control mechanisms that cost so much effort for nothing in return. Inexpensive, effective water management systems are therefore needed that can also be combined with a package of techniques to improve yields and net farmer income substantially, reduce risks or simplify work (new and more profitable crops, markets where farmers can sell at higher prices and buy selected seed, fertilizers, herbicides, pesticides). Since the soil already tends to be poor and poorly structured, measures must be taken to ensure the rapid recovery of soil fertility (turning in fermented organic matter to improve structure, restoring macroporosity, improving infiltration and water- and nutrient-storage capacity, correcting pH and soil deficiencies indicated by plants, providing nutrients directly to plants as and when necessary in cases of reduced storage capacity, encouraging deep rooting) while also minimizing water and nutrient loss through erosion and/or deep drainage.
- **Taking traditional methods as a starting point.** These all-too-often scorned methods must be reviewed, and variations from one farmer to another assessed, together with their limitations, economic potential and possible improvements. Conclusions can also be drawn on the environment, the water balance and major risks (very dry years or exceptionally severe storms). Traditional farmers cannot allow themselves the luxury of harvest failure, and therefore take account of what happens on the land during exceptional phases (Roose 1992c).
- **Highly flexible long-term programmes.** Since the aim is a radical change in behaviour (based on the knowledge that erosion is not inevitable, but the result of unsound management), it will take time to convince people, to finalize the techniques and to train the future leaders of rural communities. Some financiers already realize that they cannot demand the same immediate rates of return nor the same project durations when the intention is to improve the environment; however, evaluation teams still need to be persuaded that it is difficult to fix a time-frame for each operation when it is difficult to know *a priori* which technological package will be acceptable to the inhabitants. One poor rainy season can also hold up progress on a project. Financing

should therefore be staggered, while one time-frame is needed for evaluation by farmers and local technical staff, and another by international experts.

- **Modest projects that are gradually expanded (replicability).** Since it is vital for the rural community to take responsibility for its environment, it is best to start on a modest scale with simple operations to intensify production, and then move on – depending on the farmers' level of participation – to the various phases of finalizing, implementing, evaluating, maintaining and extending techniques to the whole of a slope, local area, hill or small watershed.
- **The need for land security.** Farmers who rent their land are not sure of holding on to it once it has been developed, for the owner may be afraid that the improvements are an attempt at appropriation and therefore take it back, perhaps even renting it out to a competitor at a higher rate. This is a major problem in connection with agroforestry.

  Clear examples of this were seen in a small watershed near Jacmel in Haiti, where farmers first chose to improve Plot A – land in good condition, well covered by a multi-storey garden surrounded by a hedge to protect the house and the produce of this fully-owned plot against theft. Only later would they turn their attention to the more degraded land, which was being farmed but not managed since it was rented from absentee landlords.

  In other places (e.g. Yatenga in Burkina Faso) it has been observed that farmers view stone lines, grass strips or trees planted around their plots much more as confirmation of property rights and as aids to water and nutrient management than as protection against erosion. Without the landlord's agreement, a farmer will seldom feel inclined to improve rented land.
- **Making use of existing structures.** When a totally new structure is set up, there is a danger that not enough attention will be paid to the views and customs of the local population, so that the erosion control mechanisms will be abandoned at the end of the project. It is better to choose NGOs and local organizations with care, and to bolster existing government structures (with vehicles, staff training and means for self-advancement); this is the price of ensuring sustainable project impact.
- **Taking account of local production systems and family constraints.** Often the first question is to understand the economic, social and political organization of a farming community (village, district, etc.), and to grasp the constraints (availability of labour, energy, manure and inputs, and the possibility of marketing or processing surpluses through livestock production, crafts, trade).
- **Women** account for over half the work force on SWC schemes, which means training must be planned for female groups. Traditional strategies for water management, soil fertility and erosion or acidification control must be reviewed, and representatives of farmers' groups chosen to communicate, train and gradually encourage farmers to introduce new techniques, taking care to avoid creating tension between "model progressive farmers" (who often receive too much aid to be truly representative) and the many conservative and mistrustful graduates of previous unfortunate experiences.
- **Initiating action simultaneously for agriculture, animal husbandry and tree production.** Small farmers are generally concerned first and foremost with food crops (for food security), and next with animal husbandry – their "savings bank" or cash reserve in case of need. The only trees "grown" are fruit species:

trees are traditionally considered a gift of nature to be used according to needs, and land, wood, trees and their fruit do not necessarily belong to the same owner. In some countries, the inland water and forestry department issues permits only to recognized woodcutters, who fell trees according to the market for fuel- or construction wood (posts and beams) in the local town, with no reference to the owner of the land. Landowners will quite obviously be reluctant to plant trees if they have no guarantee of profit from them. If "wood has no owner until it has been cut into logs," it is easier to understand the destruction of the tree cover in West Africa, since anybody can lop branches off a tree to provide forage for his/her flock.

Similarly, temporarily ruling a part of communal rangeland off-limits in order to allow regeneration of perennial plants and fodder shrubs is something of a challenge, given the risk that people from neighbouring villages will then send their hungry animals to graze it. However, when population density is high and land pressure intense, there comes a time when farmers realize that since the time when all the trees were cleared the microclimate has become drier, runoff damage more extensive (gullying) and water a rare commodity in the dry season. However, if trees are to be reintroduced in the form of hedges, contour lines or orchards, livestock cannot be left to wander at will, and a more intensive stock farming system must be developed (semi-confinement with grazing only on the way to the watering point, the clearing of tracks and forests, and tethering on fallow). Providing litter, supplementary fodder (crop residues) and mineral supplements for animals certainly entails more work, but it makes stock farming more profitable (less loss, improved health, better-quality meat), gives a better return from the dispersed biomass, and improves the quality and quantity of manure: up to 5 tonnes of composted manure/farmer/ha/yr in Rwanda and Burundi.

Traditional land-use planners tend to make a clear-cut distinction between land for crops, animal husbandry and forests, whereas the positive interaction between trees, crops and stock should be exploited. Stock draw as much advantage from crop residues as from pasture, particularly in forest areas. In the Mediterranean region, forest areas need herds to reduce fire risks by grazing the bushy undergrowth. Elsewhere, trees profit from association with crops, for they grow better on deep tilled and weeded soils than on wastelands that are too exhausted to make cropping economically viable (viz. village woods, which are often poorly managed since nobody knows who owns the wood). Crops need manure, and particularly nitrogen, phosphorus and other nutrients that are cropped over a large area and subsequently excreted by animals kept overnight in stables or corrals. Trees can help crops, providing litter, recycling nutrients from deep in the ground, and reducing wind speed and the risk of wind erosion. So, although each kind of land will have its main purpose, all positive interactions between these three sectors of agriculture must be fostered.

- **Subsidies, food aid, wages.** It is now agreed that incentives, gifts of food, tools, wages, etc. (anything given in exchange for participation in a development project), should be limited, for what often happens is that participants lose interest when the assistance stops. Particularly in the case of private land under development schemes, aid must be kept to a minimum (fertilizer, trees and selected seed, etc.), and eliminated as soon as the positive effects are clear to the recipients. However, there are some especially harsh environments, e.g. the Sahel, with large landless families and young people in search of work, where some kind of wage must be paid if a sizeable labour force is to be on hand during the dry season: without this indispensable input for group survival, the most able-bodied adults emigrate to other countries to earn more from their work. Even in cases such as this, however, payments must be kept small to allow the participants to develop a sense of ownership vis-a-vis the improvements and to feel responsible for their upkeep and protection. On the other hand, it is a good idea to make the farmers' task easier by providing tools and other items at subsidized prices so that they have to spend less time on management activities (picks, shovels, pickaxes, sickles, fertilizers, wheelbarrows, carts to transport stones).

- **Training of men and women farmers in simple techniques.** If the schemes are to continue to spread once the project itself is over, particular care must be taken to choose simple techniques accessible to all villagers once one villager has been trained, and needing no input that cannot be produced in the village. Each person must be able to work his or her own land as and when he/she wants.

  Projects that introduce heavy machinery offer the best guarantee of rapid development of SPR in the field followed by failure once the project ends for lack of upkeep on the part of farmers. This approach short-circuits the dialogue phases and the preliminary tests to assess project feasibility, effectiveness and economic viability of the methods with the farmers.
- **Project design.** At present it takes two or three hurried field missions to formulate a project, with too little time to talk with farmers about their problems and traditional methods. Each mission then draws up its report without much concern for the findings of its predecessor(s). Some people are now recommending that the three phases should be condensed into one, so that a single team has time to reach a deeper understanding of the country and gather first-hand information in the field.
- **Research and project monitoring-evaluation.** There are still many technical aspects of erosion control to be clarified, but study of the interlinkage between the human environment and technical know-how (particularly the economic cost of erosion) is clearly needed. Research experts unfortunately seldom have the means to set up individual erosion control schemes. On the other hand, reviewing the history of earlier projects, and monitoring and frequent evaluation of new ones, could make it easier to grasp the technical and human constraints.

MORROCO CASE STUDY: SOCIO-ECONOMIC STUDY OF EROSION CONTROL IN THE LOUKKOS BASIN (cf. Alaoui 1992a, b)

A social and economic study of the problems connected with erosion control was recently carried out in the Loukkos Basin by a Moroccan consultancy firm (Agroconcept). The main conclusions of an economist on the team can be summarized as follows:

THEORETICAL RELATIONS BETWEEN FARMERS' ATTITUDES AND ECONOMIC VARIABLES

There is a simple theoretical relationship between farmers' attitudes and such economic variables as price rises, subsidies for inputs, the "risk effect" or landownership. Field studies are the only way to determine the local effect of these variables.

A FIELD SURVEY OF FARMERS' ATTITUDES TO SPR IN FRUIT-GROWING

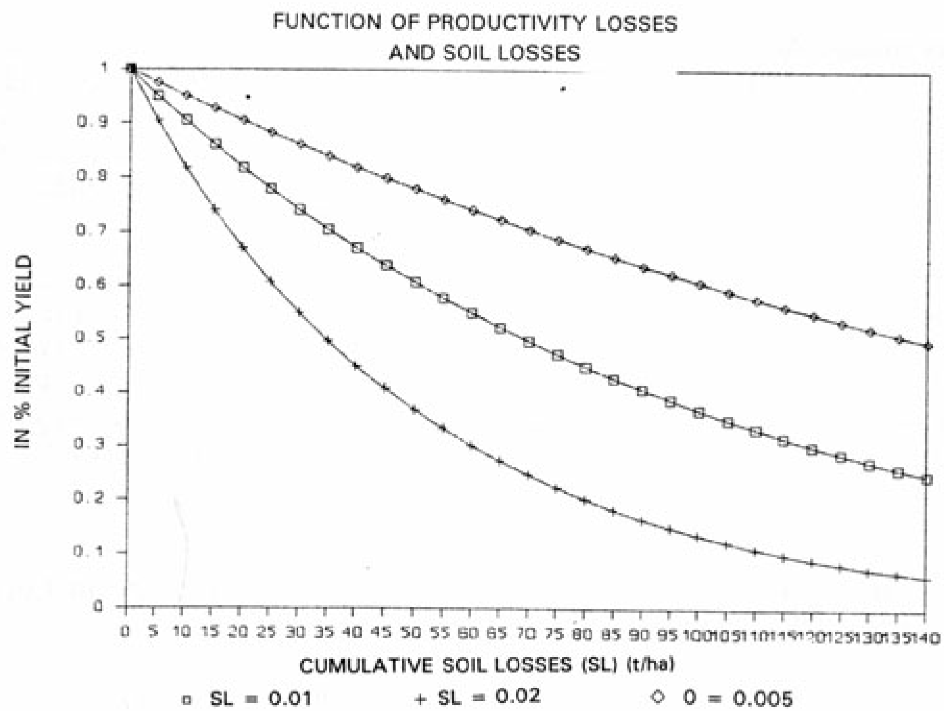
Importance of the local factor: the attitudes of farm leaders in the same district tend to be fairly similar. Out of 117 farmers in the 22 districts surveyed, 41% were in favour of terracing for fruit-growing, 48% against, and 11% uncommitted, but the views within each individual district were much the same.

TABLE 6
Cost of farm erosion in dirham/ha/yr for a cereal-fallow-grassland rotation on medium slopes ($US 1 = 25 dirham [1995])

	Erosion t/ha/yr		Cost DH/ha/yr	
	Min	Max	Min	Max
Beni Boufrah (eastern Rif)	0.4	2.7	0	37
Mda (pre-Rif)	0.3	44	0	257
Mokrisset (western Rif)	2.7	24	33	100

For: discount rate = 0.08 ; coefficient a = 0.04 to 0.15

FIGURE 13
Production loss as a function of cumulative erosion (cf. Alaoui 1992a, b)



Technical factors (inappropriate techniques, fruit trees and terrain) are less often determinants of attitude than factors connected with land use (right of use, ownership, grazing, etc.).

The State sets up physical structures for erosion control. Farmers will also anticipate future State intervention: shorter fallow periods, cropping on rangeland as a reaffirmation of ownership rights, more intensive use of land or requests for development to take advantage of promised wages.

THE COST OF EROSION

Potential losses in fertilizer equivalent: 680 DH/ha/yr in 1978 in the Tleta Basin, or $US 100 (at May 1992 rates).

Erosion operates by decreasing selectivity of the richest elements in the soil, supporting soil scientists' claims that:

$$Yt = iY\ e^{-aSL}$$

Yt = annual yield in t/ha
iY = initial yield

where a = initial parameter
SL = cumulative yearly soil loss in t/ha/year

The costs of erosion from yield losses range **from 0 to 257 DH** at 1990 financial prices for discount rate of 0.08 and a coefficient "a" of 0.04 to 0.15 (Table 6).

> These survey results confirm **farmers' views on the low average costs of erosion**. Erosion costs are low in comparison with the cost of other production factors, and **land values vary little** as a result of erosion-related factors (slope, SPR improvements), but widely as a result of factors linked to production costs (distance, status, mechanization possibilities) and yields (soil and plantation type) (Figure 13).
>
> Moreover, farmers do not see erosion as a sure and steady factor, but more as a chance process linked to exceptional weather combined with the state of certain plots at a given moment, further reducing the cost of erosion in their minds.

THE COSTS OF EROSION DAMAGE DOWNSTREAM

The site costs and benefits of water control can be seen in the following curves:

- the benefit curve rises over time as water is put to ever-varied use;
- the cost curve falls with the passage from construction investment to upkeep investment.

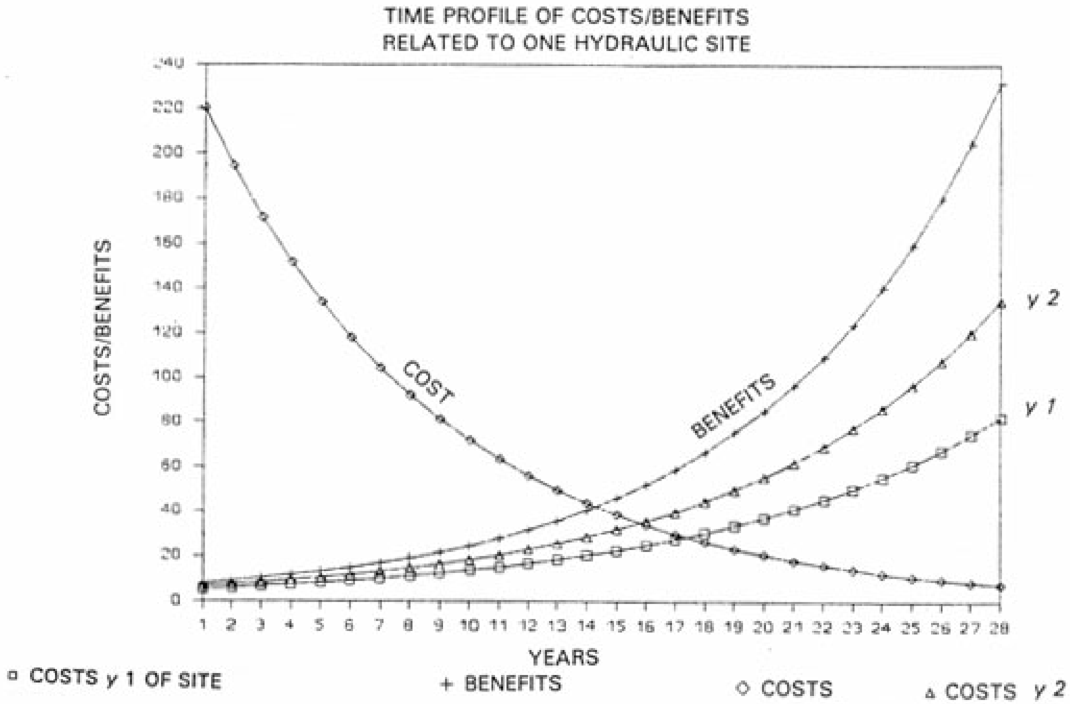
In theory, a site with a very steep curve must be seen as a non-renewable resource.

At Loukkos (Morocco), two simulations were produced for management of the reservoir:

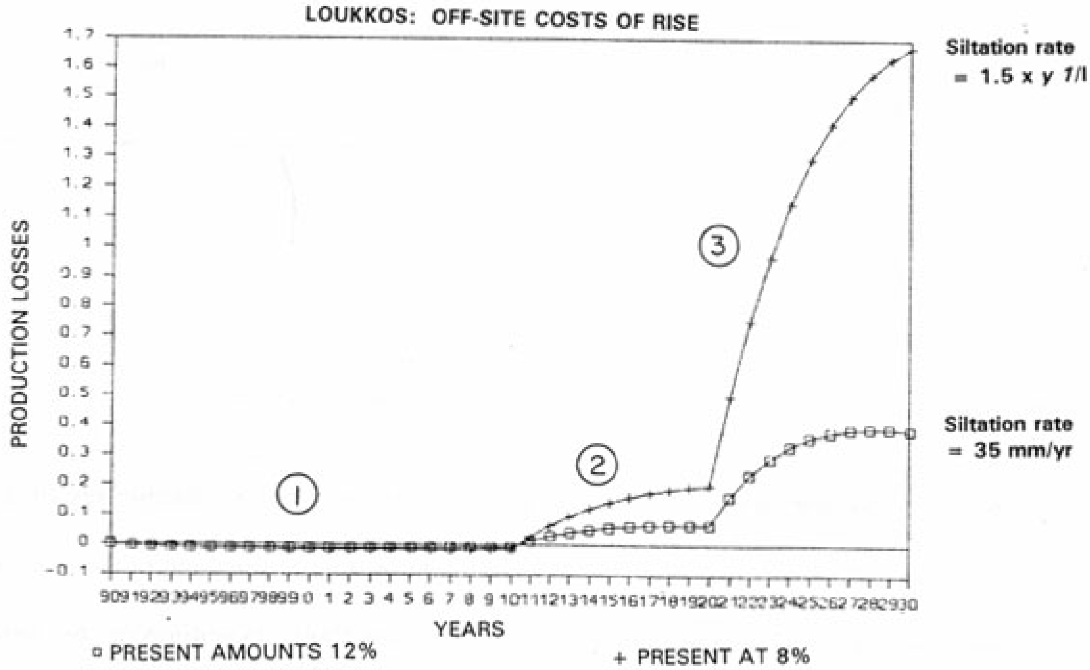
- the first looked at the annual rate of siltation for 1979-1990: 35 million m^3 per year;
- the second showed an increase of 50% in the siltation rate.

The cost of siltation is then calculated as the difference in production levels in these two situations evaluated at market prices.

FIGURE 14
Off-site cost of the rise in siltation rate (cf. Alaoui 1992a, b)



y 2 = **site of water storage, the rarity/infrequency of which is greater than for *y 1***



① before the still-water section was filled
② the more frequent overflows increase power production through more frequent turbine action
③ loss of irrigation water

TABLE 7
Cost of siltation

Value of m^3 of water in irrigation (DH/m^3) Discount rate	0.4 0.12 to 0.08	0.8 0.12 to 0.08	1.0 0.12 to 0.08
Cost of m^3 of sediment (DH)	0.03 to 0.11	0.05 to 0.19	0.08 to 0.28

As long as agricultural demand does not exceed a certain level (50% of the reservoir), the reduced storage capacity due to siltation is reflected in more frequent discharges and greater availability of water at the level recommended for turbine generation of electricity: **this is the positive effect of siltation on power production** (Figure 14).

With the rise in agricultural demand towards the year 2020, the major effect of siltation becomes **the reduction in average agricultural supply.**

These cost curves were obtained by valuing energy production and irrigation water at their opportunity cost (0.7 DH/kwh): market cost of substitute energy production and value of lost farm production (0.4 DH/m^3).

If the cost of siltation in cubic metres of sediment is calculated on the basis of the discount rate and opportunity cost of water, this gives indicators of the off-site costs of soil loss that can be used to justify investments in soil conservation. Any investment in erosion control can be analysed by reckoning the total cubic metres stabilized over the period under consideration in terms of the major costs (Table 7).

Bearing in mind the site, this indicator is more sensitive to discount rate than to other parameters.

This indicates that on this site the choice of mechanical techniques with immediate impact (civil engineering) cannot be justified by reasons of siltation control if they are more expensive or less reliable in the medium term than less-immediate biological conservation techniques (e.g. reforestation).

ANALYSIS OF AGRICULTURAL POLICIES

Historians have often seen the loss of competitiveness of farming in the upper watershed compared to that in the lower as a major cause of population transfer and pressure on resources.

If such migration is to be reduced, mountain economies need to focus more on their comparative advantages (e.g. tourism, quality mountain produce such as cheese, fruit and honey) (Seznec 1992).

A recent study on production support in Morocco in terms of producer subsidy equivalent (PSE) shows that price policy has provided much less support to traditional farm produce from the foothills and mountain areas (barley, durum wheat, olives and sheep: PSE = 0 to 0.1) than to modern irrigated production (sugar, soft wheat, rapeseed, beet, pure-bred cattle: PSE = 0.3 to 1.5).

CONCLUSION: LINES OF RESEARCH TO BE DEVELOPED

- Improve knowledge of land-use systems in mountain regions.
- Calculate erosion economics in terms of yield losses/cumulative erosion.
- Effect of agricultural policies on integrated watershed development.

CONCLUSION: NEED FOR A SOCIOLOGICAL AND ECONOMIC ANALYSIS OF EROSION CRISES AND FARMERS' EXPECTATIONS

In world terms, soil degradation is worrying, but has not yet reached disastrous proportions.

However, in local terms, losses in yields and potential production wipe out the profits of smallholders and/or heighten the risk of famine. And famines are reappearing in many places in semi-arid Africa in the wake of strong demographic pressure, lower rainfall and political instability. Adults are migrating from certain regions (e.g. south of the Sahel) to secure additional income to feed their families. This factor must be taken into account, for these migrants will not be on hand for village-based land-use planning programmes that require a large local labour force.

Erosion affects soil productivity to varying degrees, depending, for example, on whether it concerns a deep homogenous soil or a soil in which fertility is confined to the surface horizons. Research is now underway to determine which soils are the most economically viable for investments in erosion control.

The first results clearly indicate that it is more profitable for farmers to invest the limited sums at their command to manage land that has not yet suffered too heavily. However, to date RML and SPR have intervened mainly in heavily degraded areas abandoned by farmers, in order to reduce sediment transport ... and - at a very high price - maintain the quality of the water needed for large-scale irrigation schemes and urban expansion.

If the intention is to enlist farmers' participation, their perspective must obviously be taken into account (which means rapid improvement in land and labour productivity); otherwise the State must provide them with incentives and compensation for their efforts to achieve the national objectives of land stability and/or water quality.

Further study is still needed on the effectiveness, feasibility and comparative costs of the different erosion-control methods and to model the most economic structures for each region.

PART TWO

Erosion control as a response to various erosion processes

State of research, analysis and application to land husbandry

Part Two will take account of the various types of erosion that have been observed, in order to adapt erosion control as closely as possible to the «ecological niches» and functional segments of each slope. The forms of erosion reflect the local efficiency of various processes – processes using a variety of energy sources, and subject to a variety of modifying factors (Table 8).

Although one type of erosion can sometimes develop into another as degradation advances (e.g. sheet erosion developing into rill and then gully erosion), each series (comprising type, cause, factors and method) will be allotted a separate chapter of varying length. Given the aim of the present work – to develop the management of water and soil fertility – sheet erosion – the initial phase of the erosive process – will be treated in greater detail, using various experimental findings. The basic principles and the results of some recent trials on methods of controlling the other erosion processes are highlighted, with reference to more specialized manuals.

TABLE 8

Degradation and erosion, their causes, environmental resistance factors, and their consequences are very diverse

Degradation and erosion processes and their forms	Causes: various energy sources	Environmental resistance factors	Consequences: selectivity of erosion and deposits
Degradation: loss of structure Form: appearance of thin slaking crusts	Numerous: - mineralization of organic matter - compaction - etc.	1. structural resistance depends on organic matter, iron, aluminium, flocculated clay, absorbed cations and soils 2. it depends also on drainage or groundwater recharge 3. compaction depends on the weight of implements used, the pressure of tractor tyres and the number of passages	Degradation involves little sediment transport, but rather reorganization and deposition
Wind erosion Forms: ripple marks, mounds at the base of clumps. dunes, dust clouds	Wind energy	1. wind speed and air turbulence 2. direction of the prevailing wind 3. environmental resistance depends on soil roughness and plant cover 4. soil resistance depends on the structure of clods, texture, and organic matter	Selectivity Erosion : + + Deposition: + +
Dry mechanical erosion Form: creep	Through gravity, and pressure from tillage implements	1. depends on intensity of tillage, i.e., frequency and type of implement 2. depends on slope and cohesion of the soil	Selectivity Erosion : 0 Deposition: 0
Sheet erosion Form: sheet of sand, thin slaking or sedimentation crusts, small pedestals, microcliffs	Impact of raindrops	1. plant cover 2. slope 3. soil 4. erosion control techniques and structures	Selectivity Erosion : + + Deposition: + +
Linear erosion Forms : grooves, rills, gullies	Runoff energy depends on the volume of runoff and its squared speed	1. speed of runoff depends on slope and roughness 2. volume of runoff depends on size of watershed and infiltration capacity 3. resistance of soil profile and roots	Selectivity Erosion : 0 Deposition: + +
Mass movement Forms: creep, landslides, mudflows	Gravity, slope imbalance	1. weight of soil cover + water + plants 2. wetting of slide bed-plane 3. the terrain: a. lithology and dip parallel to the slope b. impervious levels and mica c. drainage, slope and thin soil over the impervious level	Selectivity Erosion : 0 Deposition: 0

Chapter 4

Dry mechanical erosion

DEFINITION, FORMS, DYNAMICS

This type of «tillage» erosion is a process (removal + transport + deposition) that takes place without the action of water. Little is known about it, or its extent in quantitative terms. Through gravity and the simple pressure of farm implements, the top horizons are stripped from the upper slopes and from areas where the slope surface is irregular, and this mass of soil is then pushed down to the bottom of the toposequence, where it banks up along the edges of plots or in concave colluvial deposits whose texture is very like that of the original horizon.

Each tillage carries off a slice of earth (about 10 t/ha on a 100 x 100 m plot) and each hoeing sends several clods of earth downhill. When all this is added up, in two years time it produces a small wall 1.30 metres high (i.e. about 40 t/ha/yr) (Ecuador - De Noni and Viennot 1991) building 1-metre banks in four to five years, i.e. a rise of 20 cm per year (Côte d'Ivoire, Rwanda and Burundi - Roose and Bertrand 1971, Roose 1990).

An orchard was planted in about 1960 near Ouzera in Algeria on a hillside with a 35% slope on red fersialitic soil. Thirty years later the trees were perched on pedestals, for 30 cm of earth had been stripped away from between them. Even adding up cumulative erosion over 30 years on a bare plot (15 t/ha/yr = 1 mm), it amounts to no more than 3 cm, while creeping of the soil cover from tillage would come to 27 cm, i.e. 135 t/ha/yr (Roose 1991), as a result of two criss-cross tillages (in autumn and spring) to keep the soil bare and cloddy.

CAUSATIVE FACTORS

The degree of soil displacement depends on:

- **the type of implement:** a mouldboard plough displaces more earth than a chisel (Revel *et al.* 1989), a disc plough, a cultivator or a harrow;

- **the frequency of passes:** in a humid zone with two rainy seasons, land is ploughed twice and hoed twice; in a tropical humid zone with one season, it is ploughed once and hoed twice; in a semi-humid Mediterranean zone, it is often rough-ploughed twice and hoed twice; in a semi-arid zone, it is ploughed once and hoed once; and in a temperate zone, it is ploughed once and harrowed two or three times;

- **the direction of tillage:** the soil may be tilled along the contour with the mouldboard oriented downhill or uphill; it can be done from the top to the bottom of the hill (the usual case with tractors on slopes steeper than

15%); or, lastly, it can be done from the bottom to the top of the plot (usually the case with manual tilling in developing countries); it is very rare for implements to push soil uphill, and in mountain areas or where earth is scarce, soil is in fact collected mechanically or in small baskets on the level ground and carried upslope (as with vineyards); it is also noted that the repeated passage of farm machinery can significantly slow the rate of stripping by dry mechanical erosion (Revel *et al.* 1989);

- **the slope:** the steeper the slope, the more the clods dislodged by the hoe will roll downhill; in mountain areas, upper slopes and hilltops are often stripped, indicating not only sheet erosion (which has not been offset) but above all large-scale dry mechanical erosion.

Slope irregularities are also weathered, with the soil surface being lighter in colour there and the surface horizon thinner. Scouring must thus speed up where the slope is steeper, and slow down – possibly with colluvial deposition – where the slope is gentler, especially on embankments or the lower slope. On plots in the Belgian Brabant, a soil loss of 30 t/ha/yr through sheet and rill erosion has been recorded. Harvesting sugar beet or potatoes on slightly moist loamy land displaces 15-50 t/ha/yr of soil, i.e. 1-3 mm/yr. The two processes of sheet erosion and dry mechanical erosion have often been confused, with the white patches on upper slopes and breaks in slopes being taken as evidence of sheet erosion, whereas dry mechanical erosion by implements has probably two to ten times the effect of sheet erosion (Wassmer 1981, Nyamulinda 1989).

EROSION CONTROL METHODS

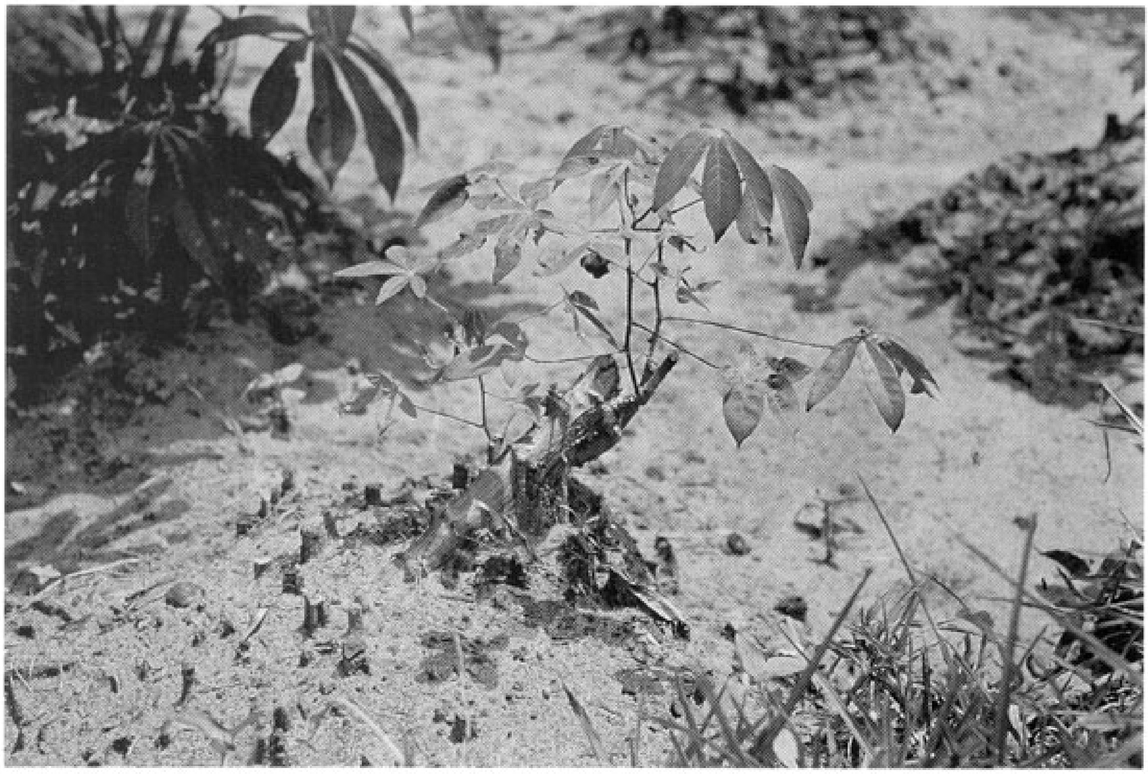
Control of sheet erosion and of dry mechanical erosion has often been taken as the same thing because the causative factors and control methods tend to overlap.

- **Reducing the number of passes by implements and also the amount of tillage.** There is a trend toward minimum tillage, with crop residues being left on the surface, and spring cultivation being confined to rows covering 10% of the soil surface. This most effective method has been studied in the Lauragais region in southwestern France (Roose and Cavalié 1986).

- **The energy spent on tillage must be reduced.** The soil does not always need to be turned with a plough. Simply breaking it up with the teeth of a chisel or cultivator aërates it in depth, increases macroporosity, water-storage capacity and rooting, and keeps organic matter and crop residues on the surface. In its most extreme form, minimum tillage can be reduced to a simple line while the rest of the soil is covered with a stubble mulch. Preparing the soil in this way cuts the risk of dry mechanical erosion from implements by 90%.

- **The direction of tillage is important.** If the slope is less than 14%, the soil may be worked mechanically, alternating from one direction to the other, which evens out the effect or restricts sediment transport (Revel *et al.* 1989). If the slope is steeper than 14%, however, tractors risk turning over, so that the land must either be divided up into cultivated strips between banks, reducing the slope sufficiently, or planted with perennial crops requiring no tillage or cover plants or mulch, or else tilled and hoed in the direction of the maximum slope but sown across the slope, with small dams, risers and bunds installed every 10 metres, or with localized hand-planted crops staggered as much as possible throughout the season.

- **Banks should be built** in such a way as to create horizons of run-on, fertility and soil on each level of the slope, which will in due course develop into progressive terraces. This will work only if the soil is deep enough; otherwise the banks have to be less than 5 metres apart, with some slope being kept on the cultivated terraces, tilling the land in beds or large ridges perpendicular to the slope when it is steeper than 40% (an example from the Comoros Islands).



Chapter 5

Sheet erosion: the initial phase of water erosion

The term sheet erosion refers to the way the energy of raindrops affects the whole of the soil surface, and dislodged matter is carried away by sheet runoff. This is the initial stage of soil degradation from erosion [Plate 1].

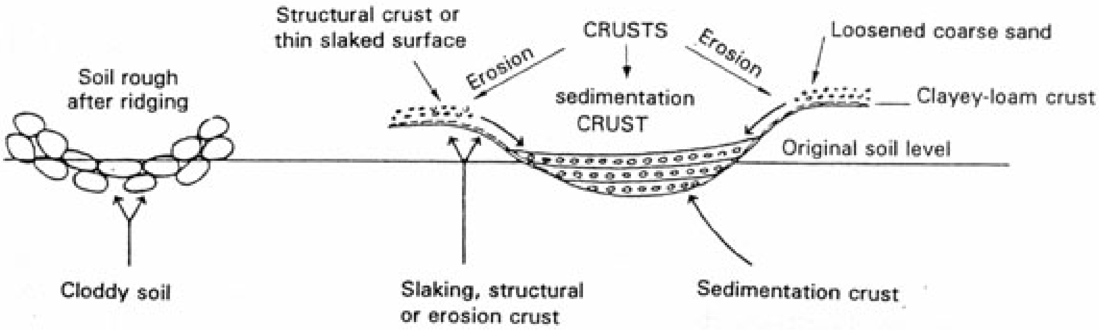
FORMS AND SYMPTOMS OF SHEET EROSION

Sheet erosion leads to degradation of the whole soil surface. This means that it is hardly detectable from one year to the next, since a significant erosion of 15-30 t/ha/yr corresponds to a 1-2 mm loss in depth – insignificant when compared with the expansion of soil, the roughness of soil after tillage (Difference in height [dH] = 2-10 cm) or the respiration of swelling clay soils simply from rewetting (dH of several centimetres). However, when combined with dry mechanical erosion (and with deterioration of macroporosity following accelerated mineralization of organic matter, or simply compacting by implements), sheet erosion can lead to **removal of most of the surface horizon** in a few decades (10-20 cm dH in comparison with the neighbouring profile still under forest). The most widely recognized sign of sheet erosion, then, is the presence of **pale patches** at the most scoured and severely affected points in fields (hilltops and breaks in slope gradient).

The second symptom is that **stones are brought up to the surface** by tilling implements. Farmers say that «stones grow», but what really happens is that the surface horizon melts away and deep tillage brings pebbles to the surface. After several showers, the fine soil is carried away by the rain either through deep drainage or selective erosion, while pebbles too heavy to be carried away collect on the surface (Roose 1973, Poesen 1987). If there is sand in the soil, the impact of raindrops will dislodge particles from the clods, planing them, and turning them, on the one hand, into erosion-induced or slaking surface layers (superficial rearrangement of clods) and sedimentation crusts and, on the other hand (Figure 15), into:

- **veils of washed sand**, white in an acid environment, pink or red if the sand is ferruginous;
- **dark craters** in these pale sandy veils (left by the last heavy drops of the last storm); and
- **small columns** that form under large leaves which protect the soil from rain splash.

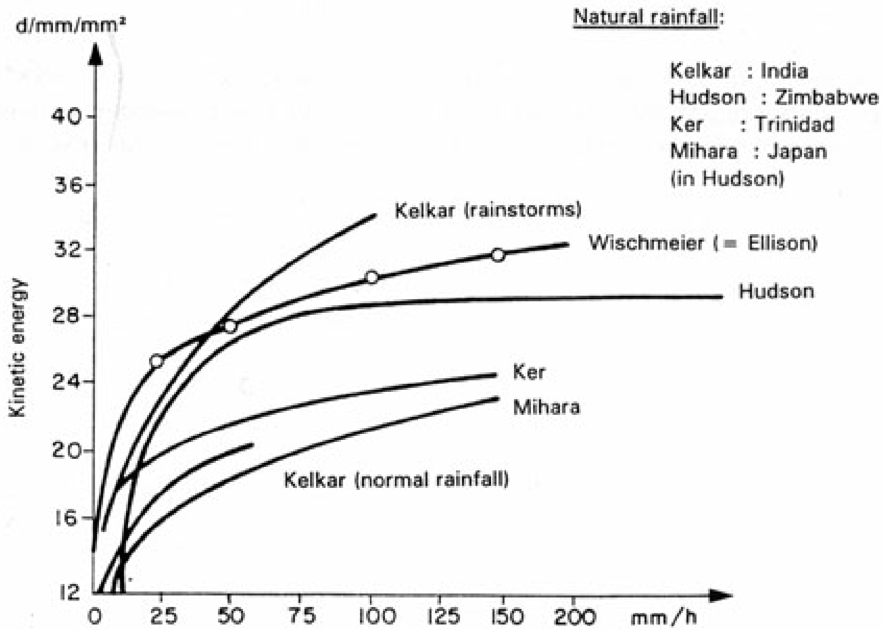
FIGURE 15
Diagram of erosion, structural and sedimentation crusts (after Valentin 1979)



Final infiltration > 100 mm/h	5 to 15 mm/h	1 to 5 mm/h
Depth	1 to 2 mm	5 to 30 mm
Random succession	1 loosened sand on 2 C-L layer	1 C + L + OM layer on 2 loosened coarse sand

C = clay L = loam OM = organic matter

FIGURE 16
Kinetic energy of rain as a function of rainfall intensity and regions where observed



However, the most dramatic forms are the **small pedestals** topped with a hard object (seeds, roots, leaves, pebbles or simply crusted earth protected by lichen) which resist the onslaught of raindrops. They are higher (0.5-15 cm) when erosion is more severe, that is, on bare, relatively unhomogenous soil and on steep slopes. These little columns are proof that raindrop energy attacks the soil surface and that runoff carries off fine, light particles but that it does not have the force to cut away the bases of the columns. As soon as there is abundant runoff, it stratifies and develops enough energy of its own to attack the base and edges of its bed, and will cut down the **small pedestals** and leave **microcliffs** in their place (dH = 1-10 cm). Sheet erosion will then combine with linear erosion to form rill and interrill erosion, which can develop into **grooves** (Height = a few cm), **rills** (H = 10-50 cm) and **gullies** (H = more than 50 cm) if no steps are taken to correct this process of nascent erosion (= dry mechanical erosion + sheet erosion + grooves and rills) (Roose 1967; 1977a).

The consequences of sheet erosion are:

- **levelling of the soil surface** by degradation of clods and filling up of troughs; this leads to various smooth, whitened crusts;
- **skeletonization of surface horizons** through the selective loss of organic matter and clay, leaving behind a layer of sand and gravel paler than the underlying surface horizon;
- **scouring of the surface horizon**, leaving pale patches where the underlying mineral horizon is exposed.

CAUSE AND DYNAMICS OF SHEET EROSION

Sheet erosion is caused by the force of raindrops impacting on bare soil (Ellison 1944) and dislodging particles of earth. This force is dependent on the speed of fall (a function of the length of fall and the wind-speed) and the weight (a function of the diameter of drops). After falling for 10 metres raindrops reach 90% of their final speed, which is determined by the balance between gravity and the air resistance of the bearing surface of the drop (Laws and Parson 1943). Wind can increase the force of raindrops by 20-50% (Lal 1976), but turbulence reduces the diameter of drops to 3-5 mm. The force is often stronger under the crowns of tall trees than on cultivated plots because the drops come together on the leaf sheathes, forming larger drops (Valentin 1981). Raindrop diameter in storms of varying intensity can be observed for each region, resulting in regressions such as: energy of a storm = energy of each segment of rain falling at a given intensity multiplied by the number of millimetres fallen at this intensity. Such proportions (Figure 16) vary considerably from one region to another, and in the absence of regional data on rainfall energy, those of Wischmeier and Smith (1978) can be used.

This impact energy is dissipated in four ways:

- **compression of the soil** under the rain’s impact, following rapid moistening of the soil surface;
- **crushing and shearing stress:** separation of aggregated particles;
- **projection of elementary particles** in a crown formation on flat soil and transport in all directions but most effectively downhill on slopes;
- **noise of the impact of the drops** on resistant material.

TABLE 9
Influence of season, maximum intensity in 30 minutes, and rainfall over the previous decade (R 10 days = index of soil moisture) on erosion and runoff from rainfall of similar proportions on bare soil and covered soil (cf. Roose, 1973)

Dates	Rainfall			Runoff (%)		Erosion (kg/ha)	
	R (mm)	R 10 days (mm)	Max. intensity 30 min	Bare soil	*Panicum*	Bare soil	*Panicum*
13.2.72	28	58	33	47	0	548	0
18.3.72	33	1	59	52	0.1	1 104	0
27.3.72	32	45	23	26	0	327	0
21.5.72	34	20	28	26	0	1 518	0
9.6.72	33	131	35	48	32	3 833	21
11.6.72	34	164	26	44	11	2 191	26
13.6.72	38	230	37	63	22	3 264	31
2.7.72	32	212	43	73	0.1	6 025	0.2
31.7.72	30	0	15	9	0	412	0
19.10.72	31	88	14	39	0.1	1 501	0.1
23.11.72	28	18	43	71	0	1 827	0

This rain energy meets opposition in the cohesion or **resistance of soil matter**, which may already be to some extent degraded:

- **by breaking up** on contact of drops with dried clods;
- **by wetting** followed by drying, creating small cracked clods;
- **by compression** by tyres or rollers, creating small broken clods;
- **by dispersion of colloids**, either through prolonged wetting or through salinization or the presence of exchangeable sodium.

The resistance of the soil material will depend on the presence of pebbles, the percentage of silt and fine sand (10-100 ì), organic matter and clay, the presence of gypsum or limestone, iron hydroxides and free aluminium, and again the structural stability and permeability of the profile (see «Soil erodibility», page 91).

Particles are initially carried a short distance by the splash effect and then by sheet runoff. The impact of raindrops sends droplets and particles in all directions, but on slopes the distance covered uphill is less than that downhill, so that on the whole particles move downhill in jumps. Christoï's experiments (1961) at the Niangoloko IRHO station in southern Burkina Faso showed that soil particles can jump up to 50 cm into the air and travel more than 2 m at a time during heavy storms at the end of the dry season. Sheet runoff starts only after puddles have formed and water that has not infiltrated overflows from one puddle to another. As the runoff spreads over the surface, it moves slowly even on 5-10% slopes because of the roughness of the soil surface (clods, grass, leaves, roots, pebbles, etc.) which keeps the speed below 25 cm/s. Faster than that, runoff will not only carry fine particles but can also attack the soil, digging out stratified channels in which speed quickly builds up, and thus becoming linear erosion (grooves, rills and gullies). See the Hulström curves (Figure 19).

Sedimentation. As raindrops fall, particles or even aggregates (especially if large stormdrops fall on dry clods) will become detached from clods, filling in any hollows and forming sedimentation crusts which allow very little infiltration (Figure 15).

Sheet erosion observed on an erosion plot depends (Table 9) on:

- **the maximum intensity** (I) of the rain that triggers runoff (max I in 15 minutes on steep slopes, or max I in 30 minutes on average slopes);
- **the energy** of the rain (E C) which dislodges particles then easily carried away;
- **the duration** of the rain and/or the soil moisture level before the rain.

Hudson (1965 and 1973) working in Zimbabwe, and Elwell and Stocking (1975) working on well-structured ferralitic soils (oxisols), have found the best relation between erosion and raindrop energy above a certain intensity threshold (I > 25 mm/h) (E = **K E [kinetic energy] if I > 25 mm/h**). These authors have observed that only intense rain leads to erosion. However, it is likely that any rain will have some ill effect on the soil surface, for even if not all rains produce runoff, they do foster the development of a fairly impermeable crust and accelerate runoff in future storms.

If there really is **a rain intensity threshold** below which runoff does not occur, it will vary according to the moisture level of the soil and the degradation of its surface before the rain starts (cf. the work of Lafforgue 1977, Raheliarisoa 1986, Casenave and Valentin 1989). Lal (1976) argues that a sudden peak intensity in 7 or 15 minutes is even better correlated with erosion than intensity for 30 minutes. This may be true in certain places (De Noni, Nouvelot and Trujillo 1984 on volcanic soil in Ecuador), but not necessarily everywhere. Roose (1973) has shown that on the sandy ferralitic soils of southern Côte d'Ivoire the longer the rain's maximum intensity lasts, the higher the regression coefficient, while Lal (1976) has shown that wind can increase the energy of raindrops – although it is difficult to take this into account, since both rain intensity and wind intensity rarely exist at the same time.

Wischmeier (1959) combined the kinetic energy of each rainstorm multiplied by the greatest amount of rain in any 30-minute period (mm/h) into **a single erosivity index (EI_{30})**, which takes full account of the three conditions of **rain energy, peak intensity and duration**, as described above.

Inasmuch as processing a rain-gauge printout for each rainstorm is a finicky and tedious operation, and not all the necessary information on rain intensity is always available, many authors have tried to simplify the task of estimating the rainfall erosivity index.

In West Africa, Charreau (1970), Delwaulle (1973), and Galabert and Millogo (1973) found a direct relation between kinetic energy and rainfall:

$$R' = (a + b\ H)\ .\ I_{30}$$

In Nigeria, Lal proposes:

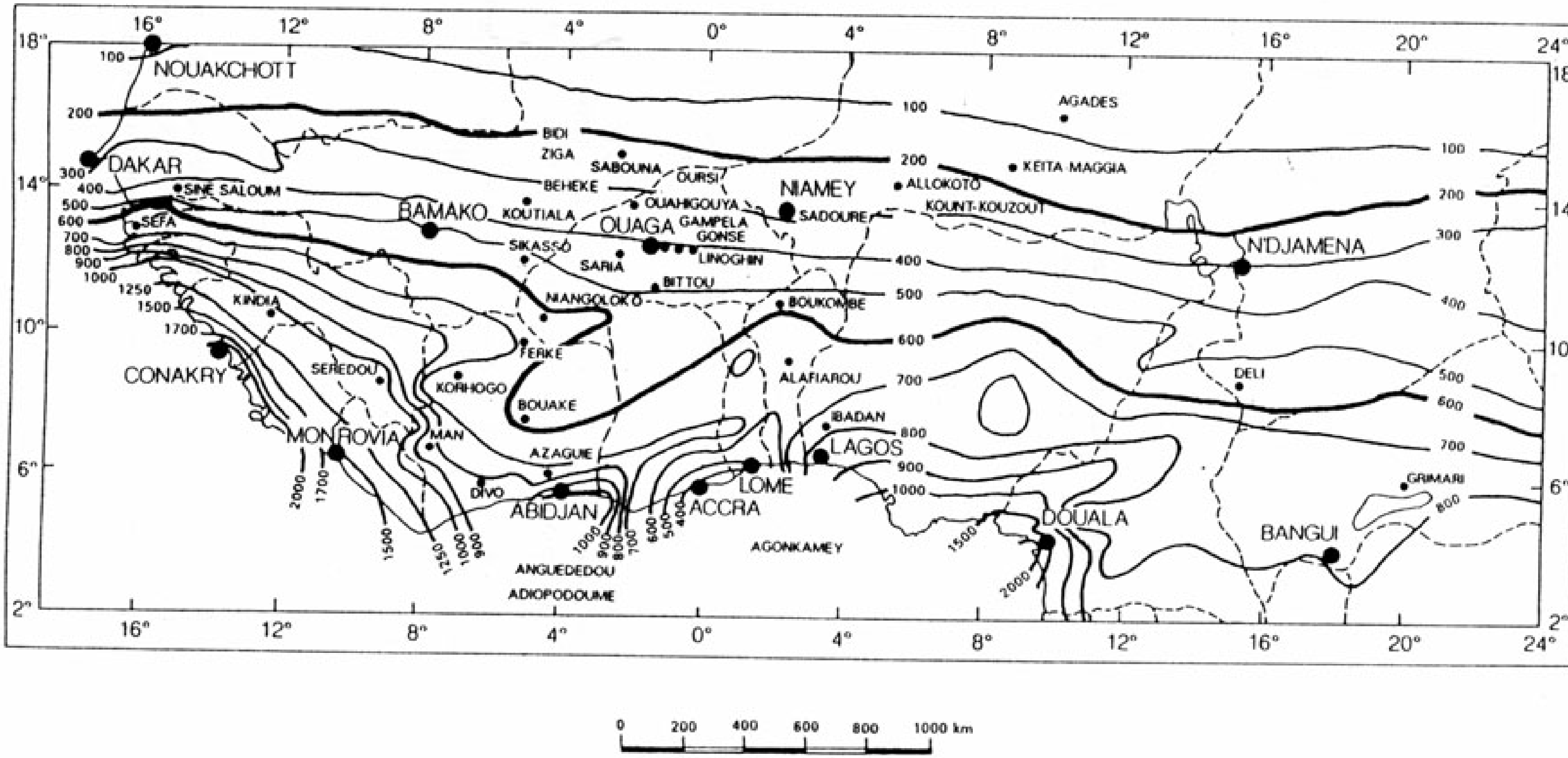
$$R' = \text{precipitation in cm x max I 7'.}$$

Roose (1977a) analysed readings from 20 stations between Séfa in Senegal and Deli in Chad and between Abidjan in southern Côte d'Ivoire and Allokoto in Niger, and showed that in West Africa there is a direct relation between **the mean annual aggressiveness index and the mean annual rainfall** over the same period (over more than ten years).

m a R = m a R x   0.5 + 0.05 in West Africa,

FIGURE 17

Sketch map showing mean annual climatic aggressiveness (Wischmeier's R_{USA}) in West and Central Africa: condition of erosion plots (from rainfall data collected by the Hydrology Department of ORSTOM up to 1975)



0.6 on a coastal strip 40 km wide,
0.3-0.2 in mountains in Cameroon (Roose), Rwanda, Burundi and Madagascar (Sarrailh),
0.1 in the Mediterranean area of Algeria (Arabi 1991),
less than 0.01 in the oceanic temperate zone.

It is, however, interesting to study the extent of erosion phenomena in relation to different levels of precipitation. During the 1965 season at Adiopodoumé (maize grown on ridges following the slope) there was no runoff for showers of less than 15 mm, nor serious erosion for those of less than 30 mm. At least 30 mm were needed for runoff to occur in any given shower, and more than 90 mm to be certain of sediment transport. On the basis of the nature of the soil, but also plant cover and cropping methods, each plot therefore has its own trigger point below which there is no sign of erosion (Roose 1973). In reality precipitation levels are not totally independent of rainfall intensity – or at least intensity for 30 minutes and more.

Figure 17 is a diagram showing the distribution of the Wischmeier index, R, for West and Central Africa based simply on average isohyets adjusted on the basis of different coefficients. This was possible because there are good correlations in this part of Africa between peak intensity and annual rainfall: 1/10 frequency (Brunet-Moret 1963; 1967; Roose 1977b).

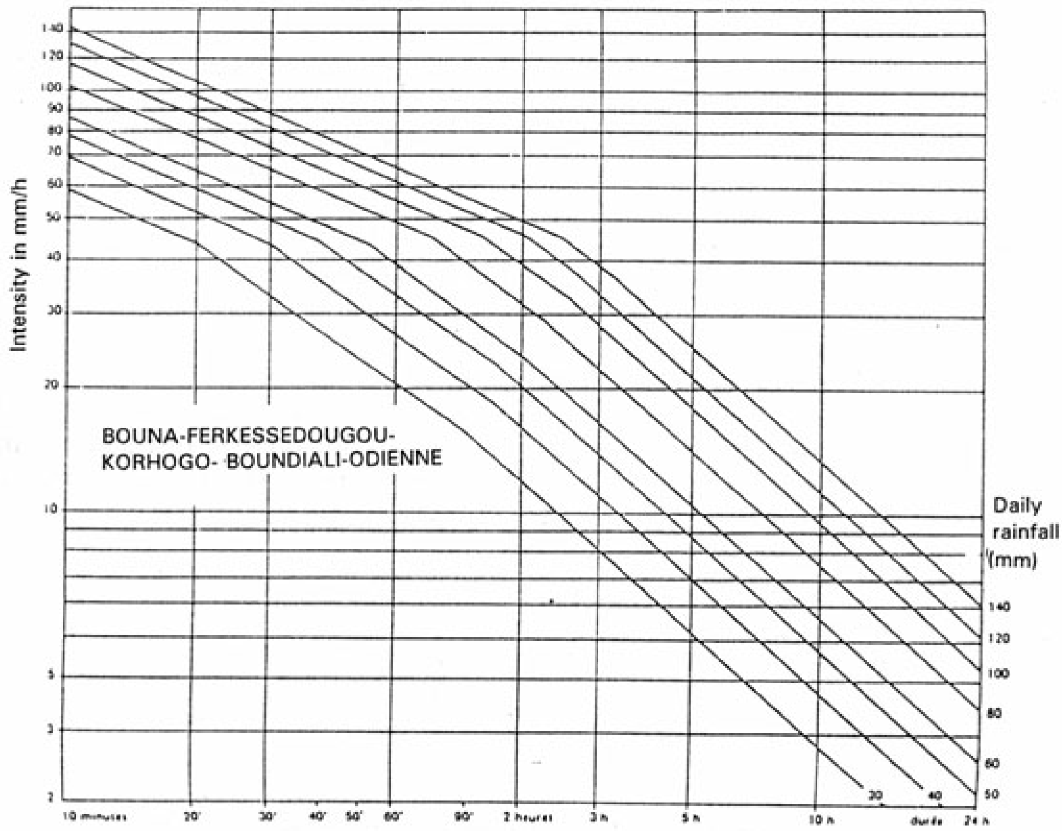
Note the curves: intensity, duration, as functions of rainfall (Figure 18).

In the United States, Wischmeier's index varies from 20 to 650 units. In Europe the index varies from 20 to 150. In the Mediterranean region, R_{USA} = 50-350 (Tunisia, Morocco, Algeria). In dry tropical zones, R_{USA} = 100-450, and in humid tropical zones, 500-1 200 (Roose 1973).

It should be noted, however, that serious disparities have been observed between sheet erosion in certain regions and rainfall aggressiveness according to Wischmeier's equation. The point is that aggressive rain can take the form of storms at the onset of the rainy season as in West Africa, or summer storms as in Europe, or long showers of fine, drenching rain with little force, falling on soaked soil, at the end of winter or beginning of spring as in France or Algeria. In the latter case, erosion is caused more by runoff energy, hence taking the form of linear erosion, than by the energy of the raindrops themselves. (It may also develop into massive earth movements if the slope is steep enough.)

For watersheds of over 2 000 km^2, Fournier showed in 1960 that sediment transport was essentially dependent on two factors: topography and aggressiveness, or what he called the «indice de continentalité» (rainfall continentality index) (c). This index is equal to the relation between the square of the rainfall in the wettest month divided by the mean annual rainfall. In this form it applies only to sediment transport in large watersheds, and cannot be applied directly to sheet erosion on plots, which depends too much on plant cover and tilling techniques. However, attempts have been made to estimate Wischmeier's index of rain aggressiveness, working from the total of Fournier's monthly indices, and good regional correlations have emerged between Wischmeier's index and Fournier's modified, monthly index (Arnoldus 1980).

FIGURE 18
Intensity/duration curves for storms of known frequency at each point in West Africa (cf. Brunet-Moret 1967)



WISCHMEIER AND SMITH’S EMPIRICAL SOIL LOSS MODEL (USLE)

After 20 years of erosion trials on plots in at least 10 states in the USA, a large amount of data was waiting to be processed. In 1958, Wischmeier, a statistician with the Soil Conservation Service, was put in charge of analysing and collating over 10 000 annual records of erosion on plots and small catchments at 46 stations on the Great Plains. Wischmeier and Smith’s aim (1960 and 1978) was to establish an empirical model for predicting erosion on a cultivated field so that erosion control specialists could choose the kind of measures needed in order to keep erosion within acceptable limits given the climate, slope and production factors.

ANALYSIS OF THE PRINCIPLES OF THE EQUATION

Erosion is seen as **a multiplier of rainfall erosivity** (the R factor, which equals the potential energy); **this multiplies the resistance of the environment**, which comprises K (soil erodibility), SL (the topographical factor), C (plant cover and farming techniques) and P (erosion control practices). Since it is a multiplier, if one factor tends toward zero, erosion will tend toward zero.

This erosion prediction equation is composed of **five sub-equations:**

$$E = R \times K \times SL \times C \times P$$

1. First, **R, the rainfall erosivity index**, equals E, the kinetic energy of rainfall, multiplied by I_{30} (maximum intensity of rain in 30 minutes expressed in cm per hour). This index corresponds to the potential erosion risk in a given region where sheet erosion appears on a bare plot with a 9% slope.

2. **Soil erodibility, K**, depends on the organic matter and texture of the soil, its permeability and profile structure. It varies from $^{70}/_{100}$ for the most fragile soil to $^{1}/_{100}$ for the most stable soil. It is measured on bare reference plots 22.2 m long on 9% slopes, tilled in the direction of the slope and having received no organic matter for three years.

3. **SL, the topographical factor**, depends on both the length and gradient of the slope. It varies from 0.1 to 5 in the most frequent farming contexts in West Africa, and may reach 20 in mountainous areas.

4. **C, the plant cover factor**, is a simple relation between erosion on bare soil and erosion observed under a cropping system. The C factor combines plant cover, its production level and the associated cropping techniques. It varies from 1 on bare soil to $^{1}/_{1000}$ under forest, $^{1}/_{100}$ under grasslands and cover plants, and 1 to $^{9}/_{10}$ under root and tuber crops.

5. Finally, **P** is a factor that takes account of **specific erosion control practices** such as contour tilling or mounding, or contour ridging. It varies from 1 on bare soil with no erosion control to about $^{1}/_{10}$ with tied ridging on a gentle slope.

Each of these factors will be studied in detail in the following paragraphs. In practice, in order to work out the production systems and erosion control measures to be set up in a given region the first step is to determine the risk of erosion from rainfall, then the degree of erodibility. A series of trials then follow to determine a factor C on the basis of desired rotations, farming techniques and erosion control practices; finally, the length and gradient are calculated for the slope to be obtained through erosion control structures in order to reduce land loss to a tolerable level (1-12 t/ha/yr). It is thus a practical model for an engineer with few data to use as a less empirical basis for finding **rational solutions to practical problems.**

INTRINSIC LIMITATIONS OF THE USLE MODEL

1. **The model applies only to sheet erosion** since the source of energy is rain; so it never applies to linear or mass erosion.

2. The type of countryside: **the model has been tested and verified in peneplain and hilly country** with 1-20% slopes, and excludes young mountains, especially slopes steeper than 40%, where runoff is a greater source of energy than rain and where there are significant mass movements of earth.

CALCULATING THE R INDEX OF RAINFALL AGGRESSIVENESS
(cf. Wischmeier and Smith 1978)

For each rainfall, define the periods of uniform intensity.

Each intensity has a corresponding kinetic energy, according to the equation:

$$E = 210 + 89 \log_{10} I$$

E = kinetic energy of rainfall expressed in metric tonnes x m/ha/cm of rainfall.

Intensity cm/h	.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0,9
0	0	121	148	163	175	184	191	197	202	206
1	210	214	217	220	223	226	228	231	233	235
2	237	239	241	242	244	246	247	249	250	251
3	253	254	255	256	258	259	260	261	262	263
4	264	265	266	267	268	268	269	270	271	272
5	273	273	274	275	275	276	277	278	278	279
6	280	280	281	281	282	283	283	284	284	285
7	286	286	287	287	288	288	289			

The value 289 can be applied to all intensities above 76 mm/h.

Construct a table as follows:

Shower Date	Total rainfall mm	Duration in minutes	Rainfall of equal intensity	Partial intensity mm/h	Unit energy per cm see table	Total E	I_{30} mm/h
19.7.67	30.5	10	5.0	30	253		
		33	5.5	10.0	210		
		32	12.5	23.4	242		23.0
		177	7.5	2.5	157		
			30.5			6622.5	23.0
		R index = $\frac{6622.5 \times 23}{17356}$ = 8.78					

Cumulative values of R per month/season/year.

To rainfall energy must be added the energy from snow, irrigation and/or runoff.

Although the annual R index is not directly linked to annual rainfall, in West Africa Roose has shown that the mean annual R over 10 years = mean annual rainfall x a

a =
- 0.5 in most cases ± 0.05
- 0.6 near the sea (< 40 km)
- 0.3 to 0.2 in tropical mountain areas
- 0.1 in Mediterranean mountain areas

3. The type of rainfall: **the relations between kinetic energy and rainfall intensity generally used in this model apply only to the American Great Plains**, and not to mountainous regions although different sub-models can be developed for the index of rainfall erosivity, R.

4. **The model applies only for average data over 20 years and is not valid for individual storms.** A MUSLE model has been developed for estimating the sediment load produced by each storm, which takes into account not rainfall erosivity but **the volume of runoff** (Williams 1975).

5. Lastly, a major limitation of the model is that **it neglects certain interactions** between factors in order to distinguish more easily the individual effect of each. For example, it does not take into account the effect on erosion of slope **combined** with plant cover, nor the effect of soil type on the effect of slope.

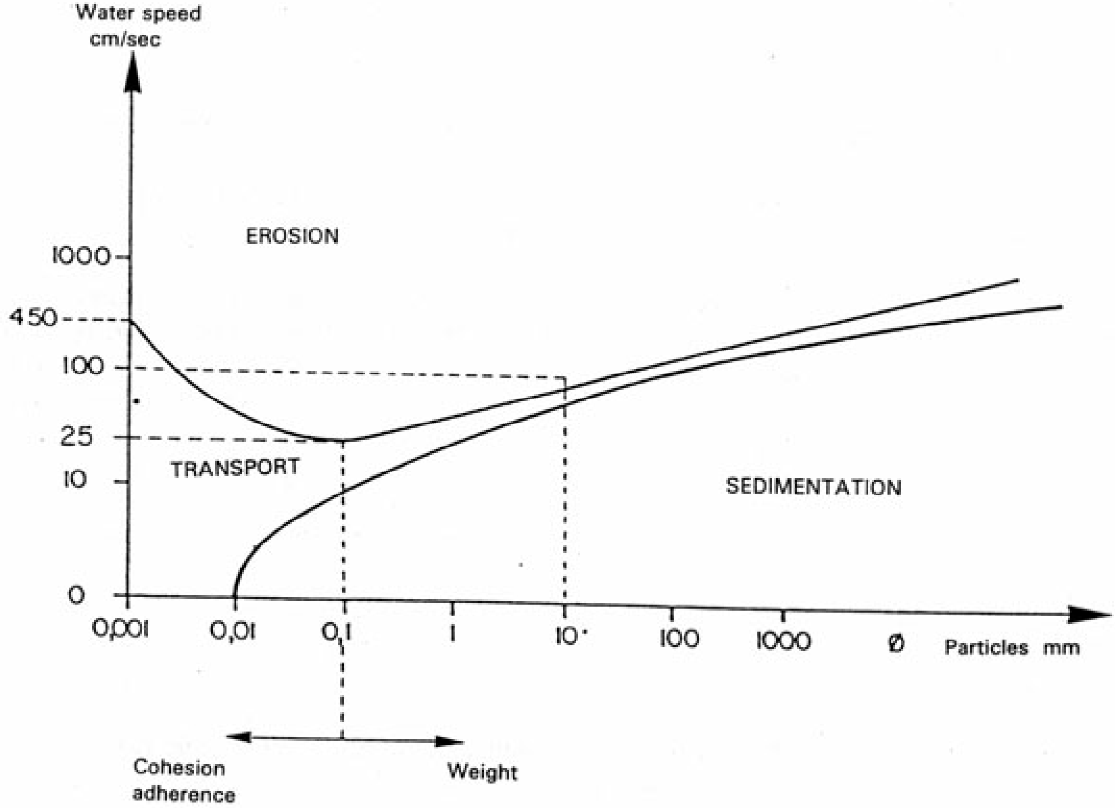
At present this empirical model is being used as **a practical guide for engineers** and is still being developed in several countries. However, **it does not always satisfy scientists** who are looking for physical models based on the primary erosion processes and also hope to identify the processes occurring in isolated rainstorms instead of average values collected over 20 years. One must avoid trying to derive more from the model than the initial hypotheses permit – and, above all, more than the authors actually incorporated in their empirical model. In Zimbabwe a model valid for the region – SLEMSA – has been developed (Elwell 1981). Other models are based on Wischmeier's equation, such as EPIC (Williams 1982) or on physical processes, such as the RILL AND INTER-RILL MODEL or EUROSEL, the new European model for predicting erosion. It should be noted that at present only the USLE model is widely used in many countries. A good ten years must pass before other models can be used on a daily basis in the field. Moreover, it is not certain that such physical models will be more effective than the best locally adapted versions of present empirical models (Renard *et al.* 1991) – a point confirmed at the Merida Seminar in Venezuela (May 1993).

SOIL ERODIBILITY

The erodibility of a soil [Plate 2] as a material with a greater or lesser degree of coherence is defined by its resistance to two energy sources: the impact of raindrops on the soil surface, and the shearing action of runoff between clods in grooves or rills. The first studies on the erodibility of materials were done by Hjulström in canals (Figure 19). **Hjulström's diagram** shows that there are three sectors, depending on water velocity and the diameter of soil particles. Analysis of the erosion sector shows that the diameter of the particles of the most fragile matter is about 100 microns, i.e. fine sand. With finer matter, cohesion develops simply as the surfaces of the clays rub together, while coarser clumps become increasingly heavy and therefore harder to transport. This kind of trial is concerned with **resistance to the erosive force of river or runoff in a wet environment**.

Soil scientists have long realized that soils react at varying speeds to raindrop attack and structural degradation. A whole series of laboratory and field tests has been set up to try to define **structural stability** with respect to water – for example, **Ellison's capsules** (1944) where sifted aggregates are exposed to raindrop energy, **Hénin's structural stability test** (Hénin and Monnier 1956) where aggregates are submerged and sifted under water, the **waterdrop test** where graded clods (30 gr) are exposed to drops of water falling from

FIGURE 19
Hjulström's diagram



This diagram provides some very important information.

1. The material most easily dislodged by runoff has a texture close to that of fine (100 μ) sand. More clayey material is stickier. The coarser material has heavy particles which can only be moved at higher fluid speed. It is interesting to note that for Wischmeier the most erodible soils are those rich in loam and fine sand.

2. As long as the flow is slow (25 cm/sec), it cannot erode. Measures will therefore have to be taken to spread and slow down the flow, in order to prevent linear erosion. This is the basis of the theory of dissipation of runoff energy.

3. Fine clay and loam particles are easily transported, even at low speeds, but in the case of anything coarser than fine sand, it is a short distance from erosion site to sedimentation site. This explains why ditches to channel runoff water either erode if they are too narrow or steep, or silt up with coarse material which cannot be moved. This is one of the reasons why diversion ditches are unpopular in developing countries, for such ditches and channel terraces have to be regularly cleared and maintained.

a specific height (McCalla 1944) or **Middleton's dispersion test** (1930) which seeks to compare the content of particles naturally dispersed in water with and without dispersant.

Quantin and Combeau's work (1962) on ten erosion plots at Grimari in the Central African Republic showed that a higher Hénin's instability index will also increase both erosion and the average sediment load, and that the products carried away are finer.

$$E\ (t/ha) = 4.9 \log 10\ I_S - 0.5 \qquad R = 0.902$$
$$C\ (g/l) = 2.47\ I_S - 0.1 \qquad R = 0.904$$

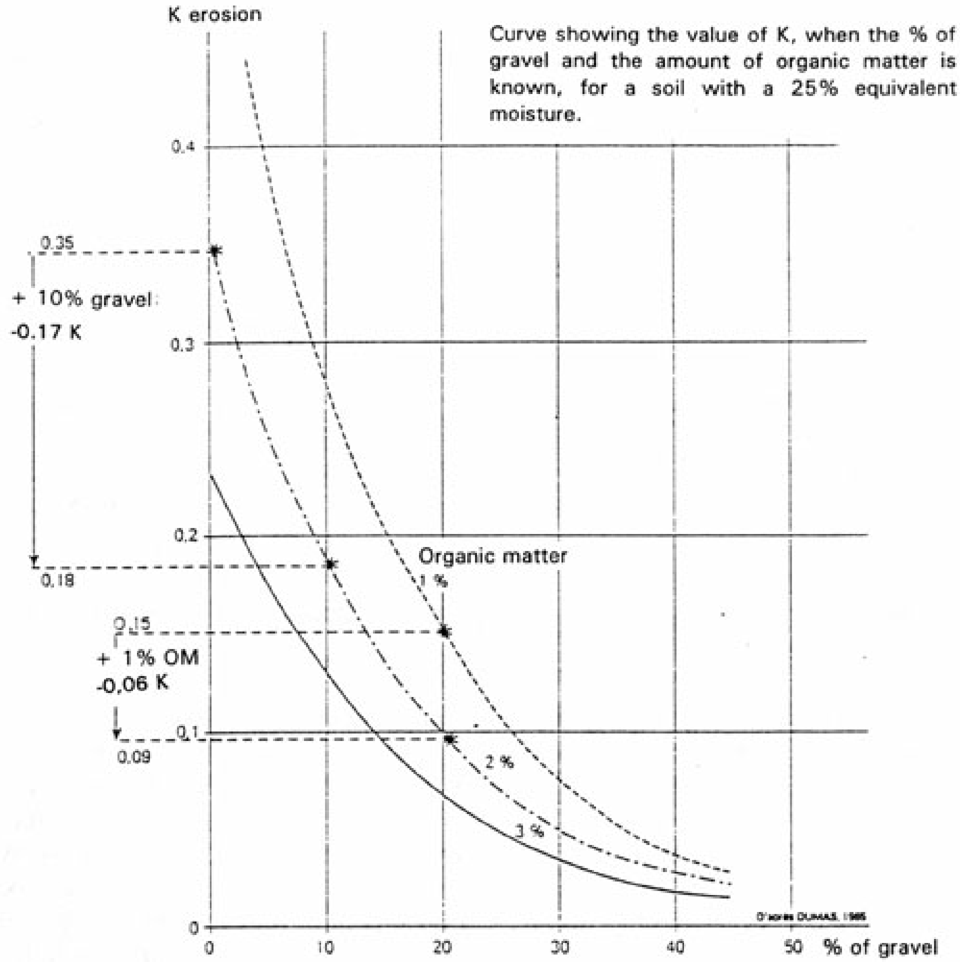
These authors noted that the instability index, I_S, varies according to season, plant cover and time elapsed since clearing. Tropical soils would thus be less sensitive towards the end of the dry season when plant cover decreases, and more sensitive on old cleared land – as has been tested under cotton in northern Cameroon (Boli, Bep and Roose 1991).

In order to approximate natural conditions, many authors have taken populations of aggregates from tilled horizons and exposed them to simulated rainfall in the laboratory in order to classify soils according to their resistance to erosion (Madagascar, Zimbabwe, Canada, United States, and many others). In a comparative study, Bryan (1981) showed that soils were classified differently according to type of simulator and procedures used in experiments. Recently, Le Bissonnais (1988) has clearly shown that in fact different processes of soil degradation were involved, and that these were dependent on the different programmes of simulated rainfall.

Many tests have been carried out **in the field, under simulated rain**. For example, Swanson and Dedrick (1965) in the United States, Dumas (1965) in Tunisia, Pontanier *et al*. in Cameroon (1984) and Tunisia, Lelong, Roose and Darthout (1992), Masson (1992) and Gril (1982) in France, Roose and Asseline (1978), Collinet and Valentin (1979 and 1984), Valentin and Janeau (1989) in West Africa, and Delhoume *et al.* (1989) in Mexico. Working on calcareous soils on 50 m^2 plots in Tunisia, Dumas showed that soil erodibility depends on the amount of pebbles, the amount of organic matter, and the equivalent humidity of the soil, which depends in turn on its texture (Figure 20). From this figure, it can be seen that in the case of Mediterranean calcareous soil an increase of 1% in the amount of organic matter reduces soil erodibility by a mere 5%, whereas a 10% presence of pebbles in the surface horizon will reduce its erodibility by over 15%. When the percentage of pebbles exceeds 40%, there is a decrease in the reduction in soil erodibility. In the young calcareous Mediterranean countryside, **the percentage of pebbles is therefore a sign of good resistance to soil erosion**.

In the United States Wischmeier and Smith have defined **the standard bare reference plot** as having a 9% slope, 22.2 m in length, cultivated in the direction of the slope, and having had no organic matter ploughed in for three years. On these reference plots, under both natural and simulated rainfall, Wischmeier and his colleagues calculated multiple regressions between soil erodibility and 23 different soil parameters. Simplifying, it turns out that erodibility depends essentially on the amount of **organic matter** in the soil, the **texture of the soil**, especially sand of 100-2 000 microns and silt of **2-100 microns**, and lastly the profile, the **structure** of the surface horizon and **permeability** (Figure 21). Several years later, Singer, Blackard and Janitsky (1978) showed that some supplementary factors have to be added in the case of Californian soil, in particular **iron and free aluminium**, the **type of clay** and the **salinity of the matter**. Today, if the texture of the surface horizons, their

FIGURE 20
Erodibility of Tunisian soils under a rain simulator (cf. Dumas 1965)



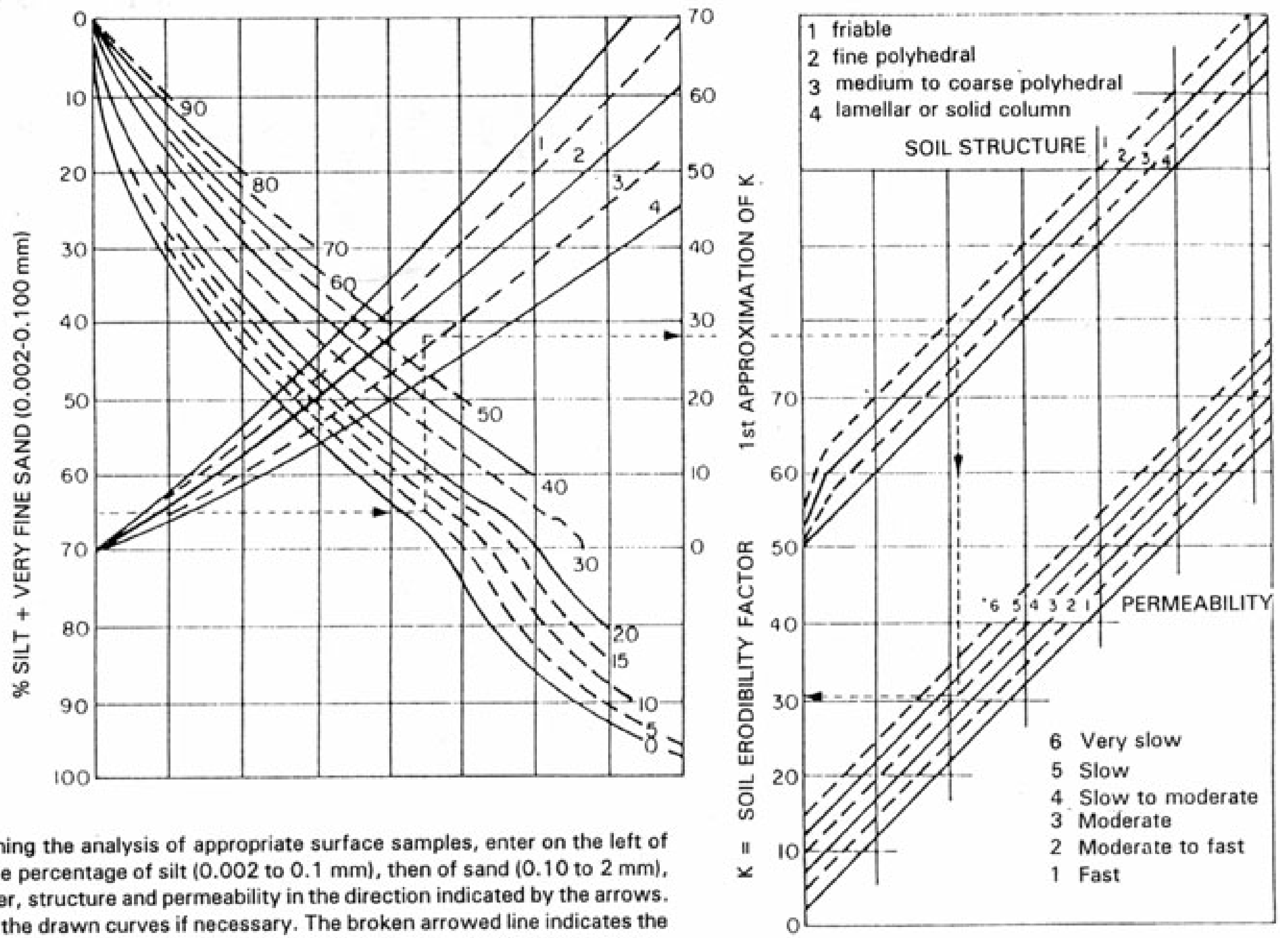
$\log 100\,K = 3.4623 - 0.1695\,X_2 - 0.0214\,X_3 - 0.0282\,X_1 \quad y^2 = 88\%$

where = X_1 = amount of gravel in % of weight in first 5 cm
X_2 = organic matter
X_3 = equivalent moisture

level of organic matter, iron and free aluminium are known, and the type of clay, plus some observations on the profile, an initial estimate of the soil's resistance to sheet and rill erosion can be given.

Since the highest-level soil classifications do not take these parameters into account, there is **no clear relation between erodibility and currently recognized soil types**. However, the K erodibility index varies in the United States between 0.7 for the most fragile soils, 0.3 for brown leached soils, and 0.02 for the most resistant soils. In Africa, scientists (Roose 1980, Roose and Sarrailh 1989) have found values from 0.12 for ferralitic soils on granite, 0.2 for ferralitic soils on schist, and up to 0.4 if the ferralitic soils are covered by volcanic deposits. They found 0.2-0.3 on tropical ferruginous soils, 0.01-0.1 on vertisols, and 0.01-0.05 on soils which were gravelly even on the surface. Overall measurements using a rain simulator, even on 50 m^2 plots, give

FIGURE 21
Nomograph allowing a quick assessment of the "K" factor of soil erodibility (cf. Wischmeier, Johnson and Cross 1971)



Procedure: in examining the analysis of appropriate surface samples, enter on the left of the graph and plot the percentage of silt (0.002 to 0.1 mm), then of sand (0.10 to 2 mm), then of organic matter, structure and permeability in the direction indicated by the arrows. Interpolate between the drawn curves if necessary. The broken arrowed line indicates the procedure for a sample having 65% silt + very fine sans, 5% sand, 2.8% organic matter, 2 of structure and 4 of permeability. Erodibility factor K = 0,31.

TABLE 10

Effect of slope on runoff (KR %) and erosion (t/ha/yr) at Séfa, Senegal: root and tuber crops 1955-1962, tropical ferruginous soil leached in patches and concretions (cf. Roose 1967)

Slope %	Average erosion and t/ha/yr	Average annual runoff %
1.25	5.0	7
1.50	8.6	22
2.00	12.0	30

lower readings than long-term measurements on plots under natural rainfall, since rills develop more easily on the latter. In reality there is no one erodibility index per soil type, for the index changes over time according to the soil's moisture and roughness, plant cover, slope, and soil organic matter content.

There are two possible approaches to improving soil resistance **in order to control erosion**. The first is to **choose the most resistant soils in the area** for those crops that provide the least cover, leaving the most fragile soils permanently under plant cover. The second solution is to control the organic matter in the soil. Ploughing organic matter into the entire tilled horizon will rarely achieve even a 1% improvement in the level of organic matter. Also, a 1% improvement in organic matter will not reduce erodibility by more than 5% (see Dumas's graph and Wischmeier's nomograph). This means that either **organic matter must be controlled on the soil surface** - i.e. mulching - or it must be ploughed only into the very top horizon. Marls. i.e. clay and calcium carbonate, can also be introduced, improving soil resistance to rainfall aggressiveness by 5-10%.

In conclusion, it is clear that **the methodological problem of estimating soil resistance to erosion and the way this resistance develops is still awaiting solution**. At present, attempts are being made to classify soils according to a variety of tests based on the different processes that may be met in different circumstances. Valentin (1979) has shown that Hénin's index of structural instability bore a good relation to soil resistance to erosion if the drops fall on dry soil, i.e. at the start of the rainy season (C = breaking of aggregates), whereas on wet soil at the end of the rainy season there are better correlations between soil loss and Atterberg's liquidity limits. De Ploey (1971) developed a similar index for brown leached soils in Europe. Infiltration capacity and the resistance of the material to gullying (the shearing force) must also be evaluated in cases where the soil is very prone to runoff (see the ORSTOM Soil Science Journal, 1989, no. 1, special issue devoted to soil erodibility).

THE TOPOGRAPHICAL FACTOR

Although slope has a powerful influence on erosion, the presence of erosion and heavy runoff on gentle slopes (2% in the Sahel or on European uplands) indicates that this phenomenon can occur without any need for a steep slope: the action of rain is enough (Fauck 1956, Fournier 1967).

The influence of slope on the development of hillsides is well known to geomorphologists, so that some of them would even specify the age of the landscape in terms of the gradient and shape of its slopes. Steep slopes and deep valleys are found in a young landform such as the Alps, whereas in an adult and senile landform – as on the old African continent – there are plateaux, gentle slopes, pediments and vast peneplains.

Slope intervenes in erosion in terms of its form, gradient, length and position.

THE FORM OF SLOPES

Estimating the influence of the concavity, convexity, regularity or warp of a slope is a very delicate procedure. This factor is too often neglected, which in large part explains why authors come up with such divergent results. As eroding plots age and are exposed to severe erosion, they become more and more concave, since the base of the plot stays fixed (the runoff channel) and the middle of the plot erodes more quickly than the top. This means that each year the slope of the plots must be readjusted so that the results are not falsified by default. According to Wischmeier (1974), with a smooth average slope, sediment transport is reduced on a warped or concave slope (due to localized sedimentation), but increased on a convex slope due to the gradient of the steepest portion. The presence of concave slopes in a landscape indicates that there must be trapping, siltation and colluvial deposit in the valley. In general, erosion on the hillside exceeds the sediment transport in the river – although this is not the case in the Mediterranean area, where the main cause of sediment transport is the energy and volume of runoff (Heusch 1971; Arabi and Roose 1989).

SLOPE GRADIENT

As the gradient increases, the kinetic energy of rainfall remains constant, but transport accelerates toward the foot as the **kinetic energy of the runoff increases** and outweighs the kinetic energy of the rainfall when the slope (S) exceeds 15%. In 1940 Zingg showed that soil loss increases exponentially with the slope gradient. In the United States the exponent is 1.4:

$$E = K\ S^{1.4}$$

Hudson and Jackson (1959) emphasized that in **Central Africa** aggressiveness of climate increases the effect of slope over what is found in the United States, so that they obtained exponents averaging about 1.63 on complete rotations (including grassland and fallow periods), and up to 2.02 on clayey soil and 2.17 on sandy soil under extensive maize cropping. An exponent in the region of 2 would seem more likely under African conditions (Hudson 1973).

At Séfa in **Senegal**, Roose (1967) found that erosion and runoff increase very quickly with minor variations in slope (0.5%) (see Table 10).

In **Côte d'Ivoire** on food crops between 1964 and 1976, Roose (1980a) obtained an exponent higher than 2 for extensive crops that provide little cover, such as groundnut, maize and cassava.

On the other hand, in **Nigeria** Lal (1976) found that erosion increases with slope according to an exponential curve of 1.2 on modified ferralitic soil enriched with gravel (alfisol) when the soil is bare, but that soil loss is independent of slope (from 1 to 15%) if crop residues are left on the surface. Runoff as such would depend more on the hydrodynamic properties of the soil than on the slope itself.

TABLE 11

Runoff (KR %) and erosion (t/ha) on bare soil and under pineapple as a function of crop residues (cf. Roose, 1980a)

Adiopodoumé : 12 cases of erosion under natural rainfall 1975-1977: 16-month cycle, ferralitic soil, slopes 4, 7, 20%

RUNOFF (KR % of rainfall)					
1st cycle : 3 337 mm rainfall	Bare soil	Burnt off	Dug in	Mulch	Average/ slope
Slope 4 % 7 % 20 %	44.6 34.7 29.3	7.3 4.4 7.5	1.7 1.0 3.4	0.9 0 0.1	13.6 10.0 10.3
Average/ treatment	36.2	6.4	2.0	0.6	11.3
Notes : Runoff does not necessarily increase with slope. Strong influence of crop residues if planting date is close to critical periods (cycles).					
EROSION (t/ha)					
	Bare soil	Burnt off	Dug in	Mulch	Average/ slope
Slope 4 % 7 % 20 %	45 136 410	1.2 4.1 69	0.7 0.45 33.2	0.1 0 1	11.8 35.2 128.3
Average/ treatment	197	24.8	11.5	0.38	58.4
Notes : Planting in August; pineapples provide good soil cover before the June rains – little erosion, regardless of type of treatment. Slope has a strong effect on erosion					

TABLE 12

Erosion (t/ha/yr) and runoff (KR %) as a function of slope under forest, crops and bare soil at the ORSTOM centre at Adiopodoumé in southern Côte d'Ivoire (cf. Roose 1973)

Adiopodoumé 1956-1972.
Ferralitic soil on clayey-sandy tertiary material.
Mean rainfall: 2 100 mm.

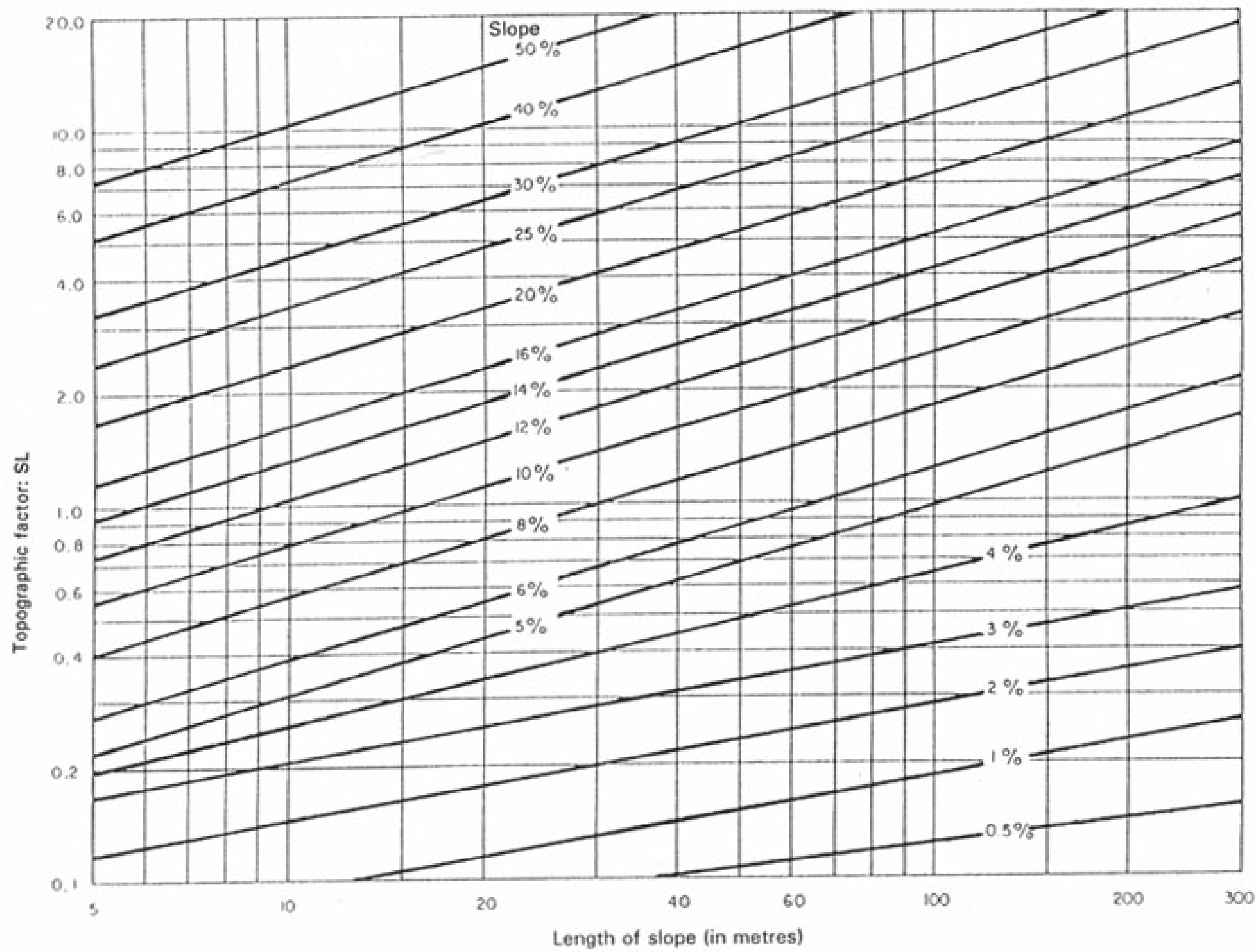
Slope %	Erosion t/ha/yr			Runoff KR %		
	forest	bare soil	crop	forest	bare soil	crop
4.5	-	60	19	-	35	16
7	0.03	138	75	0.14	33	24
23	0.1	570	195	0.6	24	24
65	1.0	-	-	0.7	-	-

On erosion plots with slopes of 4, 7 and 20% at the ORSTOM centre at Adiopodoumé in **southern Côte d'Ivoire**, Roose (1980a) compared erosion on bare soils and on soils covered with pineapple plantations, residues having been burnt, ploughed in, or left on the surface. He recorded a more than proportional increase of erosion with the slope, but highlighted the existence of **gradient thresholds** below which erosion is small but above which it suddenly increases. For example, when residues are ploughed in, erosion is very slight on slopes of under 7%, but beyond 20% it quickly moves far above the tolerance level. If residues are left on the surface as a mulch, erosion is negligible even beyond 20%. Similarly, during the second cropping cycle, planting took place in August so that the pineapple plants provided good cover to the soil before the aggressive rains of the following June; very little erosion was recorded, whatever the slope and the way crop residues were handled. These results clearly indicate the existence of **interaction between the effect of slope, plant cover and treatment of crop residues** (Table 11). It has been noted in West Africa that natural vegetation that has survived fires protects landforms very well (Roose 1971, Avenard and Roose 1972). The same can be seen in southern Côte d'Ivoire, where there are slopes of over 65% on sandy-clayey ferralitic soil protected by dense secondary forest. If forest is cleared manually without destroying the root network that provides cohesion to the topsoil, the soil can resist the aggressiveness of rainfall for one or two years. However, if forest or savannah is cleared mechanically, scouring the fertile topsoil, erosion and runoff assume catastrophic proportions, further aggravated on steep slopes.

Adiopodoumé has three plots under closed secondary forest, and three cultivated in 1966/67, maintained under bare fallow, and tilled before the rainy season from 1968 to 1972. Slopes varied from 4.5 to 65%. Table 12 shows average soil losses (in t/ha/yr) and runoff (as a percentage of annual rainfall) recorded during the period 1956 to 1972 (Roose, 1973).

Erosion is seen to increase proportionately faster than slope, and faster under crops than on bare soil. Under crops (cassava followed by groundnut), if the average erosion on a 4.5% slope is taken as the basis (E = 18.8 t/ha/yr), soil loss increases fourfold when the slope rises to 7% (i.e. 1.5 times steeper) and another fourfold when it rises to 23% (i.e. 5.1 times steeper than the control plot). Erosion increases more slowly on a bare plot, but starts higher (E = 60 t/ha/yr). It seems clear that **on a steep slope there is an interaction between the effects of slope and the decrease in plant cover** resulting from water stress and mineral deficiency in plants growing on steep eroded slopes. Alongside this quantitative aspect, the forms of erosion change with the slope and the soil profile. On a gentle slope (4%) raindrop energy dislodges aggregates and releases fine particles. Stable suspensions of colloids may travel long distances through the drainage system. Sand, on the other hand, collects on the soil surface, giving it a striped appearance with alternating dark bands (from stripped soil in relief) and yellow streaks (from sand in the grooves). The soil surface is almost flat on 4% slopes, but on a 7% slope, these lower areas deepen into widened rills into which sand in the washload settles. Microcliffs and small pedestals (2-4 cm) appear, which clearly show the extent of the scouring damage caused by sheet erosion. Lastly, on slopes of more than 20%, the runoff evacuation system removes particles of all sizes (up to 5 or 10 mm in diameter) and digs out grooves, so that the soil surface becomes extremely uneven, with deep rills (5-20 cm) and numerous humps chiselled by rain and runoff and protected by objects such as seeds, roots, leaves, bits of pottery and even hardened or crusted clods. In the United States Smith and Wischmeier (1957) have shown that on plots with a slope of 3 to 18% exposed to natural rainfall for 17 years, a second-degree equation works better than the logarithmic functions proposed by other American scientists, though these are in fact very close. This equation is:

FIGURE 22
Topographical factor (cf. Wischmeier and Smith 1978)



$$E = L/100\ (0.76 + 0.53\ S + 0.076\ S^2)$$

where E, erosion, is expressed in t/ha, S, slope gradient, in %, and L, slope length, in feet (Figure 22).

Wischmeier (1966) has shown that runoff usually increases with the slope on small plots, but that the increase varies with soil surface roughness and water-retention capacity (type of crop and saturation level before the rain).

In Côte d'Ivoire, the runoff/erosion duo behaves in a very different manner with respect to slope. At Adiopodoumé under crops, the runoff coefficient reaches 16% on a 4.5% slope, and stabilizes at around 24% on plots with a 7 or 23% slope. On bare fallow ground, runoff decreases noticeably (35, 33, 24%) when the slope increases from 4 to 7 and 23%, and this phenomenon has been confirmed over years of trials. **This decrease in runoff as the slope increases** is seen not only with average runoff coefficients, but also with maximum coefficients when the soil is saturated (KR_{max} = 98, 95, 76%). These trends were confirmed in subsequent years (1975-1977) under pineapple (Table 11). On bare soil runoff dropped from 44 to 35 and 29% as the slope increased from 4 to 7 and 20%. Under pineapple, runoff increased slightly or even decreased depending on how crop residues were handled. Here again, there is **interaction between the slope and the condition of the soil surface as these affect runoff**.

Hudson (1957) had already noted these phenomena in what was then Rhodesia, where he observed that erosion increases exponentially with slope, but that runoff increases rapidly at first (up to roughly 2% of slope) and then stabilizes.

In Nigeria too, Lal (1975) observed that runoff stabilized above a certain gradient depending on the way crop residues were used and on soil type.

The decrease in the runoff coefficient on bare soil may be explained, at least partially, by the following factors (Roose 1973):

- The sloping surface exposed to the rain increases as the slope grows steeper. In other words, if the area of the plot is field-measured without taking account of the vertical component, there will be an error of 0.3% for a 4.5% slope, 0.7% for a 7% slope, and 2% for a 20% slope.

- As the slope increases, **the type of erosion changes**, chiselling the ground into different shapes and thereby increasing the surface area – and hence the number of pores that can absorb water, at least in the initial phase.

- When the slope is gentle, runoff energy is too weak to carry relatively coarse sandy particles very far. When it rains, these are released by the splash effect and then slowly carried downhill. As they move they may be drawn in by pores and block them. They also go to form microstrata – the phenomenon of glazing familiar to agronomists. On a steep slope, however, all particles detached by the rain's force are carried off the plot, and it may be surmised that more pores stay open, for erosion scours the soil surface heavily. In any case, it has been observed in the field that **crust formation occurs much more slowly on steep slopes** and that hoeing has much longer-lasting effects than on gentle slopes.

- Lastly, **the hydraulic gradient** increases in line with the topography; i.e. steep slopes drain faster than gentle ones.

If erosion increases exponentially with slope despite a decrease in runoff, this is because the total sediment transport (suspended load + bedload) increases substantially with the slope.

As early as 1948, Woodruff in the United States showed that while the contribution of the kinetic energy of raindrops is of primary importance on a gentle slope, it is secondary to runoff energy over a 16% gradient. Heusch (1969, 1970, 1971) then showed that on pre-Rif marls in Morocco, **erosion and runoff are sometimes affected more by position in the toposequence than by gradient.** On the **vertisol** toposequence on marl, erosion and runoff readings increase at the foot of the slope, where the gradient decreases. This would be due to very marked phenomena of oblique drainage in these soils that are fissured down to the weathering level of the nearly impermeable marly rock. On a steep slope at the top of the hill (concave slope), rain infiltrates directly as far as the impermeable level, and then drains quickly down to the foot of the hill (gentle slope), where it re-emerges (Roose 1971). And this is where the gullies start that then climb back up to attack hills in regressive (headward) erosion. As Heusch (1971) has rightly pointed out, the steeper the topography, the steeper the hydraulic gradient. This means that water circulates quickly inside the soil, thus allowing the soil to reabsorb a certain amount of water before saturation. The soil on steep slopes and hilltops will dry out quicker, thus producing less runoff. In marly landscapes with steep slopes, erosion consists mainly of undermined banks, wandering wadis, gullying and landslides (Heusch 1971).

Somewhat similar processes have been described and studied on the Sudanian savannahs of central and western Côte d'Ivoire by a multi-disciplinary ORSTOM team (Valentin, Fritsch and Planchon 1987). The red gravelly ferralitic soils at the top of the toposequence are resistant and permeable so that only rarely are any significant traces of erosion found here. Ferruginous tropical hillsides are already more fragile, with small, discontinuous gullies, while larger gullies form on the sandy hydromorphic lowlands, growing in size as they move back up the landscape. Although these sequences in a Sudanian region operate very differently from those of marls in a Mediterranean region, topographical position often seems significant in explaining the development of erosion.

SLOPE LENGTH

In theory, the longer the slope, the more runoff will accumulate, gathering speed and gaining its own energy, causing rill erosion and then more serious gullying. Thus, Zingg (1940) found that erosion increases exponentially (exponent = 0.6) with the length of the slope. Hudson (1957 and 1973) considered that a higher exponent value is more appropriate in tropical regions. Wischmeier, Smith and Uhland (1958) examined 532 annual results on erosion plots, and concluded that **the ratio between erosion and length of slope varies more from year to year than from one site to another**; the value of the exponent (from 0.1 to 0.9) is strongly affected by changes in soil, plant cover, use of crop residues, etc. Then in 1956 a research team from Purdue University, Nebraska, USA, decided to adopt an exponent of 0.5 to express the average influence of length of slope on soil loss for current field work. **The influence of slope length on runoff is still less clear, being sometimes positive, sometimes negative, sometimes nil, depending on the prior moisture and condition of the soil surface** (Wischmeier 1966).

At Séfa in Senegal (Roose 1967) three plots with a 1.25% slope were compared. On one plot, twice as long as the others, the crops of the other two plots were alternated (strip cropping in the direction of the slope). In general, runoff was weaker on the long plot (KR = 19% as against 21%), while erosion was higher (E = 6.08 as against 5.55 t/ha/yr) than on the two short plots, but the difference in behaviour was barely significant.

At Agonkamé in southern Benin (Verney, Volkoff and Willaime 1967, Roose 1976), conclusions from two neighbouring plots (slope = 4.5%) also failed to clearly confirm any increase in erosion with length of slope. Under natural thicket, erosion and runoff were weaker on the long slope (60 m), while the following year, on cleared land with stumps removed, runoff on the two plots was similar, while erosion on the shorter plot (30 m) was much greater than on the longer plot (E = 27.5 as against 17 t/ha/yr). **At Boukombé in northern Benin** (Willaime 1962), observations on three plots under millet 21, 32 and 41 metres long with a 3.7% slope showed scarcely any difference in runoff (KR = 4%) or erosion (E = 0.8, 1 and 0.7 t/ha). The influence of length of slope is therefore neither consistent nor particularly strong.

In Côte d'Ivoire, Lafforgue and Naah (1976) simulated 12 rainfalls totalling 652 mm for an aggressiveness index of 1161 on four plots with a 6% slope on former grassland. The soil was sandy-clayey and all plant débris was carefully removed from the land. When length increased from 1 to 2 to 5 and 10 metres, runoff changed from 27 to 29 to 23 to 20%, but erosion increased from 8 to 8.6 to 11.3 to 13.7 t/ha/yr – because turbidity (the solids suspended in the water) increased from 5 to 27 g/l. On these relatively short slopes, runoff decreased, while erosion and sediment load increased as the slope lengthened. **However, there is no proof that there will be a proportionate increase in erosion when the length of the slope is increased to 50, 100 or 150 metres.**

In the United States, Meyer, Decoursay and Romkens (1976) studied the effect of slope length on three sites with varying susceptibility to rill erosion. They showed that the effect of slope length was felt after a certain distance and that the speed of increase in erosion varied depending on soil susceptibility to rill erosion. Here again there is an **interaction between the effect of slope length and soil sensitivity to rill erosion** (Figure 23).

Ramser's equation was developed to calculate the gap between two erosion control structures. In practice, soil conservation engineers have adapted Ramser's equation, linking the difference in height between two erosion control structures (H in metres) directly to the gradient of the slope (S in %) while ignoring any interaction with soil cover and production system.

$$\text{Ramser's equation: } H \text{ (metres)} = 0.305\,(a + [S\%/b]) \quad (1)$$

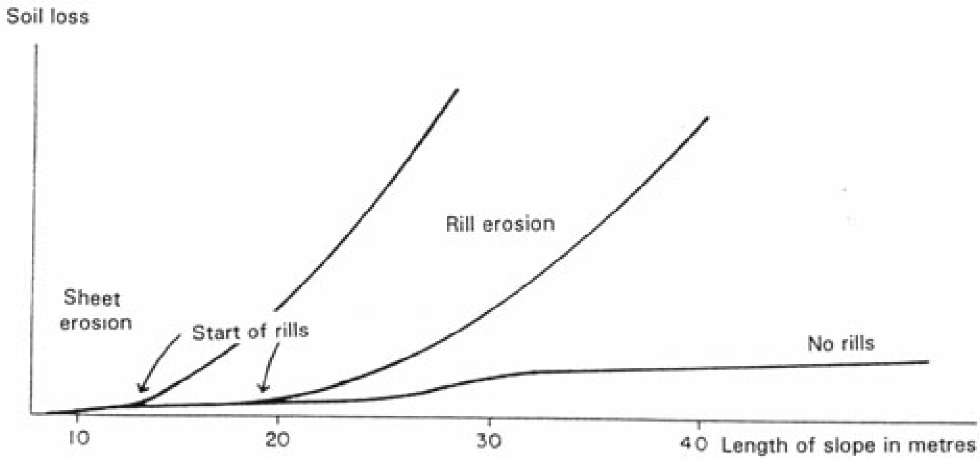
a = 2   b varies from 2 to 4 if the climate is more aggressive

where a and b are parameters made to vary empirically by 25% depending on climatic aggressiveness or specific erosion risks (see Figure 24).

According to Figure 24 (taken from Combeau 1977), on a 10% slope:

- in Guinea, aggressive climate, H = 1.37 m, and gap = 14 m

FIGURE 23
Effect of length of slope on three sites of varying susceptibility to rill erosion (cf. Meyer, Decoursay and Romkens 1976)



Rillability may be estimated by measuring:

- resistance to shearing stress
- volume of overland flow
- variations according to the drop test.

The structural stability of clods maintains:

+ a high degree of roughness
+ a high degree of turbulence

hence a higher untiary load.

Ramser's equation is far from complete, since it takes account only of slope as a percentage (see Figure 24).

- in Burkina Faso, less aggressive, H = 1.62 m, and gap = 16 m
- in Tunisia, H = 3 m, and gap = 30 m.

Ramser's equation is in fact far from complete, since it takes no account of possible interactions between the effects of slope, soil type, condition of surface and topographical position. It has even been seen that slope length has no apparent effect on erosion at certain stations in Africa.

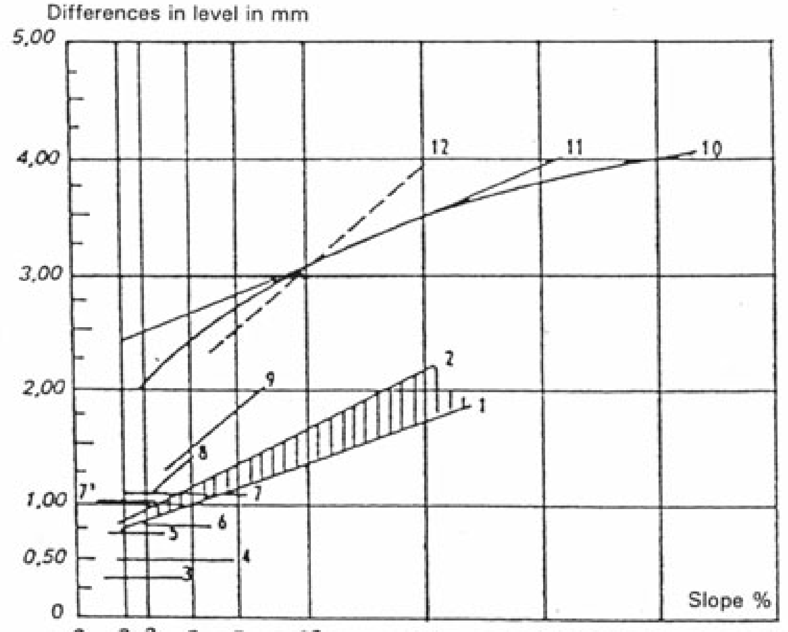
There is little point in developing models that take account of slope length. Advice on field observation of the birth of rills would be preferable, allowing farmers to build erosion control structures at intervals reasonable from the technical standpoint and affordable for the farmer (5-50 m).

In Algeria, Saccardy (1950) used an assessment of peak rainfall intensity of about 3 mm/min over half an hour, and proposed for slopes of

$< 25\%\ H^3 = 260\ S$ (2)
$> 25\%\ H^2 = 64\ S$ (3)

where H is the difference in altitude between two bunds (in metres), and S is the slope of the land (as a percentage).

FIGURE 24
Various formulae linking the gap between erosion control structures and slope gradient (%) depending on country where applied (cf. Combeau 1977)



Differences in level of various structures

1. Application of Ramser's equation H = 0.305 (2 + [S/4]) in Congo and Guinea.
2. Application of Ramser's equation H = 0.305 (2 + [S/3]) in less dangerous conditions.
3. Highly eroded soil very much reduced spacing, Burkina Faso (Ouahigouya), Mali (Sikasso).
4. Another proposal for Burkina Faso (Ouahigouya).
5. Another proposal for Burkina Faso (Boulbi).

6/7/8. Various proposals for Boukombé (Benin).

7. Dabou terraces (Côte d'Ivoire) and contour hedges.
9. Ramser's equation modified (South Africa).
10. Saccardy's equation (Algeria) $H^3 = 260\ S + 10$.
11. Bugeat's equation (Tunisia) H = 2,20 + 8 S.
12. Washington State equation (USA) H = 0,305 (0,58 + [S/1,7]).

Distances between erosion control structures according to Saccardy's equations (cf. Heusch 1986)

if slope	<	25%	H^3	=	260 S
if slope	>	25%	H^2	=	64 S

S %	0.03	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
dH (m)	1.98	2.35	2.96	3.39	3.73	4.01	4.38	4.73	5.06	5.37	5.66
dist. (m)	66.0	47.10	29.80	22.90	19.00	16.50	15.20	14.30	13.6	13.1	12.7

According to Heusch (1986), «There is no theoretical or practical justification for these formulae». Wischmeier's SL factor for the distance given by Saccardy's equation is not constant, but increases progressively from 0.4 for a 3% slope 66 m long, to 11 for a 50% slope and a gap of 12.7 m. At the very most, it can be agreed that Formula 3 can also be written:

$$H.C = 64$$

where C is a coefficient depending on local conditions, particularly climate,

which is the same as saying that the energy comes from the runoff if the slope is 25% or more.

This uncertainty over the influence of slope length on sheet and rill erosion throws fresh doubt on the generalized use of erosion control techniques such as terracing, bunds and diversion channels which are too often indiscriminately applied in very different climates. While terracing is justified in a sub-desert environment where rainfall is below 400 mm/yr, it may be best replaced by biological methods in regions where vegetation can cover the soil and intercept the rain (Roose 1974). From a scientific viewpoint, the topographical factor and its multiple interactions should be further investigated and more clearly defined, for the influence of slope is not independent of plant cover, cropping techniques, soil type and probably climate (Roose 1973; 1977). However, until sufficient data are available, Wischmeier's topographical index or an exponential equation such as $SL = C \times L^{0.5} \times S^{1.2\text{-}2}$, where L is length of slope in metres, and S the gradient in percent, can be relied upon. It should be satisfactory in most cases (Hudson 1973; Roose 1977).

In practice, rather than systematically applying models developed to some extent for other physical and human circumstances, the best approach seems to be a compromise between (a) field observation on the distance after which rill erosion develops, and (b) how many obstacles the farmers can accept on their land.

Consequences for erosion control

Reduction of gradient was generally more effective than reduction of length of slope in controlling sheet and rill erosion. However, it does appear that under major crops **the land must be partitioned** with linear structures - semi-pervious microdams - which allow **a reduction in runoff energy** while encouraging the evacuation of water to the bottom of well-protected banks. This means that the ill effects of slope length can all be countered by building erosion control structures; **all interactions of factors concerning the condition of the surface must be brought into play**, especially encouraging roughness of soil and plant cover on cultivated fields between semi-pervious filtering structures. This will reduce the effect of slope length and gradient on erosion. It should be noted that slope length has little effect on sheet erosion because the speed of sheet runoff is kept down by the roughness of the soil, whereas it may have a significant effect on rill erosion.

EFFECTS OF PLANT COVER

Plant cover is effective in preventing erosion to the extent that it absorbs the kinetic energy of raindrops, covers a large proportion of the soil during periods of the year when rainfall is most aggressive, slows down runoff, and keeps the soil surface porous. However, it is difficult to assess the protective action of plant cover without a close look at the farming techniques involved.

Plant cover is certainly the most important factor for erosion, inasmuch as erosion goes from 1 to over 1 000 tonnes when, all else being equal, plant cover on a plot falls from 100% to 0% (compare the plots under pineapple and harvest residues left on the surface, with the bare plots in Table 13).

INFLUENCE OF TYPES OF PLANT COVER

Table 13 shows three types of plant cover.

Full cover year-round

This category encompasses closed forest, but also secondary shrub forest, unburnt tree savannah, natural fallow, grasslands with grasses more than one year old, and shrub crops with cover plants or mulching. Erosion is always negligible under such thick cover (E = 0.01 to 1.5 t/ha/yr) and runoff very slight (KR % = 0.5-5% on average, 10-25% at most in the case of exceptional rainfall). Erosion and runoff are generally very slight under forest, although there are some exceptions: a forest on a 65% slope on tertiary sand near Abidjan, a plot with a 20% slope on schist-engendered soil at Azaguie, a forest plot in Guyana on Bonidoro schist (Blancaneaux 1979), and a forest plot in a very high-rainfall area in Gabon (Collinet 1971). The maximum runoff observed in these often very moist forests can rise to over 35% for a single rainstorm. On the most usual types of slope, it seems that runoff is considerably stronger on ferralitic schist-engendered soil than on soil resulting from granite or tertiary sediment. With their foliage distributed over several levels, their bushes and their litter of dead leaves, forests provide year-round cover to the soil, protecting it against the energy of falling rain.

Mesofauna (termites and earthworms) keep the soil porous, and infiltration speed remains high throughout the rainy season. The only problem that may arise is saturation of the soil above a relatively impervious horizon with low macroporosity, for example the base of the gravel sheet at Azaguie, and also laterally drained soils in Guyana. Similar results – in other words, very little erosion or runoff – have been observed on three plots under closed degraded forest thickets on the Agonkamé station in southern Benin (Verney, Volkoff and Willaime 1967; Roose 1976b). As in forest areas, runoff travels between the soil and the litter and is constantly slowed down by unevenness in the soil and trapped by the holes left by rotted roots and mesofauna. Its flow is broken and its volume reduced in the sequences studied.

Under savannah or old fallows that have been protected for some years, average runoff (Kaar = 0.02-5%) and maximum runoff coefficients are very little higher than under forest. On the other hand, as seen below, if fires occur each year, particularly late in the season, conditions are radically different.

Bare soils, bare fallows or fallows providing little cover during the most aggressive months

Erosion is greater the steeper the slope and the more aggressive the climate. At Adiopodoumé, erosion rises from an average of 60 to 138 and 570 t/ha/yr with a slope increase from 4-7 to 23%, and runoff is very heavy (average KR = 25-40% with maximum KR = 70-90%). In principle, farmers never leave their soil uncovered during the

TABLE 13
Erosion and runoff at Adiopodoumé (Côte d'Ivoire) as a function of plant cover, cropping practices and slope (1956 to 1972) (cf. Roose 1973)

Plant cover and cropping practices	Annual erosion (t/ha)		Average annual runoff (%)	Maximum runoff* (%)	
	Extremes	Average			
Secondary forest (23.3% slope)	0.01 to 0.2	0.1	0.7	6	(12)
Bare soil (S = 4.5)	34 to 74	60	37	71	(98)
(S = 7)	69 to 150	138	33	66	(87)
(S = 20-23.3)	266 to 622	570	25	65	(73)
Cover or forage plants (s = 7%)					
. 1st year					
- early planting, strong growth starting in 1st year, *Pennisetum purpureum, Guatemala grass, Panicum maximum, Cynodon dactylon, Setaria*	0.1 to 1.9	0.5	4	25	(29)
- late planting, thin density, poor growth in 1st year, *Crotalaria, Flemingia congesta, Mimosa invisa, Panicum maximum, Digitaria umfolozi, Centrosema, Titonia diversifolia, Stylosanthes*	23 to 89	40	20	62	(87)
. 2nd year					
- all cover plants - 2nd year	0.05 to 0.7	0.3	1	8	(12)
Natural fallow (S = 4.5%)	-	0.6	8	64	
Coffee, oil palm or cacao (S = 7%)					
- with a good cover plant	0.01 to 0.5	0.3	2	8	(16)
- with a fairly undeveloped cover plant	5 to 143	-	30	60	(87)
Banana trees with mulch (S = 7%)	0.04 to 0.05	0.04	0.5	4	
Pineapple 1st year) flat planted 7%	8 to 20	12	14	51	
Pineapple 1st year) on mounds 4.5 %	-	1.5	9	5	
Pineapple 2nd year	0.1 to 0.3	0.2	3	12	
Cassava and yam (S = 7%)					
. on mounds 1st year	22 to 93	32	22	53	(82)
. on mounds 2nd year	-	2	7	24	
Maize 20 x 100 cm (S = 7%) ridged parallel with the slope	(35)** to 131	92	30	75	(86)
Groundnut 20 x 40 cm flat planted (s = 7%)	59 to 120	82	27	73	(87)

* The first column is the probable maximum each year per rainstorm; the second column igure refers to an axceptional rainstorm occurring once every ten years.

** Exceptional rainfall.

rainy season, but grow some crop; otherwise the ground is invaded by weeds. However, if for some reason they sow their crops too late, the soil will be left without cover during the first months of the rainy season and will behave like that on bare plots. Erosion on a late-sown plot is thus roughly 80% that of a bare plot.

Incomplete cover for part of the year

Some food, industrial, cover or forage crops are planted late or simply need time to thrive. Erosion phenomena are clearly intermediate, but depend very much on the planting date, crop spacing, slope and cropping techniques.

Table 13 shows that food crops are among those offering the least soil protection. Erosion under cassava or yam amounts to 22 to 93 t/ha/yr on a 7% slope, whereas under maize and groundnut it varies between 35 and 131 t/ha/yr. This is with no erosion control measures, late planting, and widely spaced crops on poor soil. In any case, 80% cover only developed after two to five months, in other words after the heaviest rains. This does not happen on traditionally farmed fields, since farmers often plant very soon after the first rains and almost always combine various crops providing complementary cover and succeeding one another in time and space. Under intensive cropping, the risk of having to resow if dry periods follow the first storms is too great, so that planting necessarily follows relatively late after tillage, often two to three weeks after the sowing date in the traditional system. However, tillage does encourage deep rooting, and fertilizer applications make it possible to catch up for the growth lag and to space plants more closely.

Table 13 also shows that erosion – and to a lesser degree runoff – depends largely on **the proportion of soil not covered by plants before the heaviest rains**. It is not simply a question of the green matter produced on the field, but more specifically of the vertical – or, better, slightly oblique – projection of cover provided. During major rainstorms, the angle of incidence of drops is generally less than 25°, except in the case of certain tornadoes, when it can be as much as 45°. It also depends on the architecture of the plant structure: i.e., the height of foliage above the soil and whether plants are funnel-like and thus concentrate water (e.g. pineapple and maize), or umbrella-like and scatter the drops (e.g. cassava).

There has been little general study of the dynamics of the cover provided by different crops, and there is no reliable technique for measuring every type of plant. Different procedures have therefore been used to assess plant cover on erosion plots (Roose 1973):

- the average diameter of the circle covered by groundnut rosettes, the proportion of surface covered by the circle circumscribed by a tuft of cassava (on a vertical photo);

- the number and surface area of maize leaves;

- the covered or bare geometric areas between rows of *Stylosanthes* or groundnut or under savannah;

- the quartile points (needles touching the cover or not) for grasses, weeds, stubble and pineapple.

Figure 25 shows that the growth dynamics of plant cover varies considerably depending on the type of plant but also on cropping techniques (spacing, date of planting, fertilizer applications) and climate (rainfall and light). If heavy rainstorms occur one month prior to sowing, erosion will therefore depend as much on the type of plants as on cropping techniques. Hence the concept of «soil-degrading» or «protective» plants, according to the speed at which they cover the soil – a factor that must be tempered by appropriate cropping techniques. Grasses generally protect the soil better than pulses or cassava, although crop protective capacity can be improved a great deal by early planting in relation to the periods of heaviest rain. For example, *Stylosanthes* reaches the same covering capacity (95%) as *Panicum* but two months later. Some plants are described as soil-degrading because they cover the soil slowly, for example pineapple and cassava, which gain by only 10 to 20% of cover per month.

FIGURE 25

Development of plant cover of various crops in the course of the year (Adiopodoumé, runoff plots, 1966-1975) (cf. Roose 1977c)

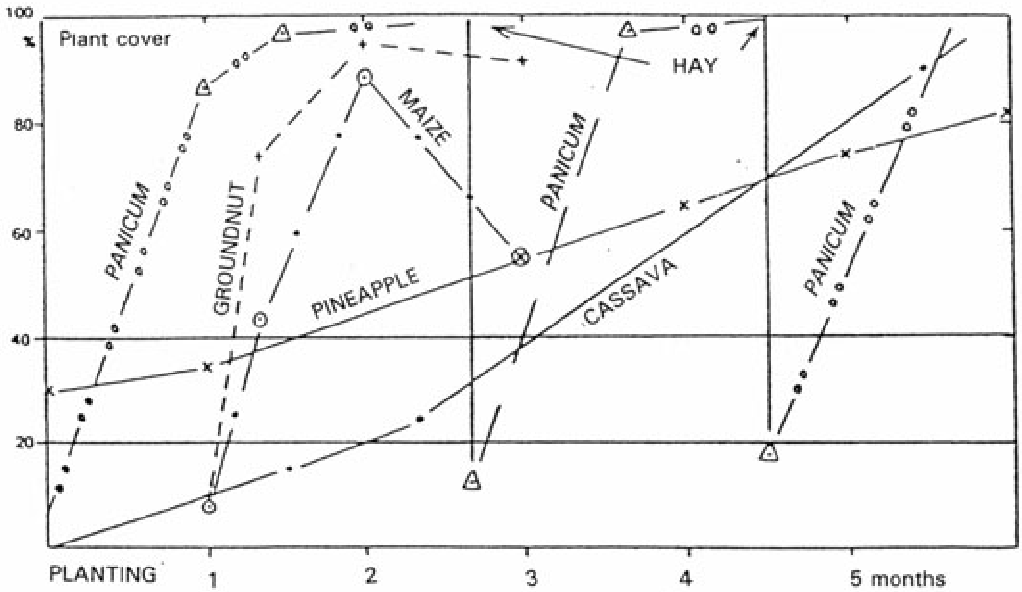


TABLE 14

Post-mowing protection by three forage crops (Adiopodoumé, 1970-1972)

	Rainfall		*Cynodon aethiopicus*		*Stylosanthes guyanensis*		*Panicum maximum*		Bare soil	
	Volume mm	Aggres-siveness R_{USA}	R%	E kg/ha	R%	E kg/ha	R%	E kg/ha	R%	E kg/ha
3.11.1970	41.5	13.8	3.6	47	19.6	10	0	0	39	1 843
4.11.1970	mowing									
5.11.1970	20.0	4.4	2.3	12	16.6	69	13.3	110	53	1 323
7.11.1970	22.0	7.3	2.6	2	14.9	87	25.0	175	74	1 111
22.9.1971	mowing									
27.9.1971	33.5	18.5	1.9	9	15.2	188	3.3	175	32	1 542
15.7.1972	mowing									
17.7.1972	65.0	42.3	3.4	10	6.1	16	21.8	335	77	9 710
Total after mowing	140.5	72.5	2.8	33	11	360	17	795	62	13 686
Plant cover after mowing on 17.7.1972			60 to 80%		42%		8 to 14%		0	

Some plants such as groundnut, maize and other cereals cover the soil very poorly in the first two months, reaching 80% only at the end of the third month, but since their cycle is fairly short (4 months), for the remainder of the year the bare soil is exposed to rain splash unless there are weeds to cover the soil and absorb raindrop energy. Other plants seen as degrading are simply grown in a way ill-suited to providing ground cover. This

TABLE 15

Effect on erosion control of development of a cover plant under bush crops (Adiopoumé, 1961 and 1962, on very desaturated, sandy ferralitic soil with a 7% slope)

Plant cover		Growth of the cover plant	E t/ha/yr	Average runoff %	Peak runoff %
1961	Rainfall: 2289 mm				
	Coffee + *Flemingia*	good	0.4	2.6	8
	Oil palm + *Centrosema*	almost nil	143.2	2.1	87
	Coffee + *Stylosanthes*	slow	5.2	1.8	75
1962	Rainfall: 2773 mm				
	Coffee + *Flemingia* 2nd yr	full	0.05	0.7	2
	Oil palm + *Centrosema* 2nd yr	average	0.08	1.4	4

applies, for example, to tobacco, which is widely spaced in order to produce more beautiful leaves. This problem can be solved by mulching the spaces between such poor cover crops. It is obviously not possible to use mulch under cotton, another notoriously degrading crop which takes at least two months to cover the soil, and also leaves no later trace of organic matter in the soil as its leaves are grazed and the stalks and roots carefully pulled up and burnt. It is in fact a combination of lack of plant cover and organic imbalance that leads to soil degradation under these different crops. Against this, *Panicum maximum* and other grasses that grow in large tufts can cover the soil in one month.

Table 14 shows the considerable amount of erosion protection provided by the stubble and superficial roots of three forage plants even after mowing:

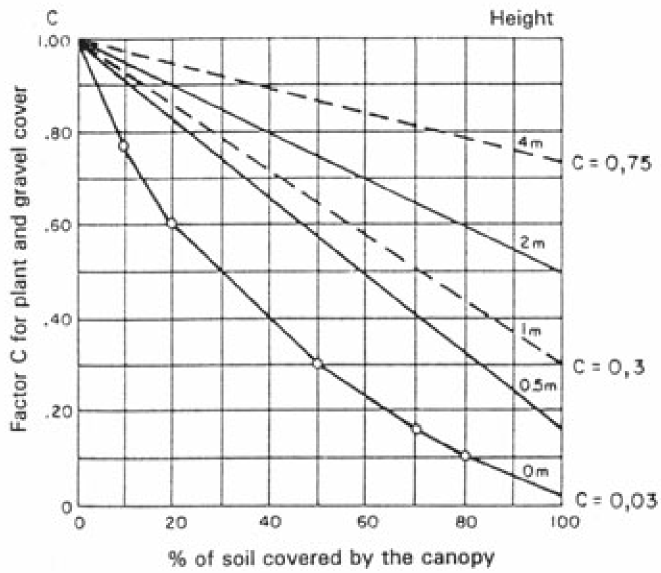
- runoff is reduced to ½ and erosion to $^1/_{17}$ and even $^1/_{415}$ of that observed on the bare plot;

- mown *Cynodon* is still much more effective than *Stylosanthes* (sown in rows) and especially *Panicum*, which grows in tufts; erosion depends on the areas of soil left uncovered after mowing, i.e. 20 to 40% under *Cynodon*, 60% under *Stylosanthes* in rows, and almost 90% under *Panicum*.

In Table 15 it should be noted that **results vary widely** for incomplete cover. This is fortunate for development experts, for the variability is a result not only of variations in rainfall and imperfections in measurement methods, but primarily of the way in which crops are planted and tended. Experts can therefore manipulate cropping techniques, using biological or mechanical approaches. The first method for soil and water conservation, the biological technique, aims at intensifying production on the best land by increasing plant cover. It entails early, close planting of vigorous species well suited to regional conditions, adequate soil preparation, balanced fertilizer applications, sufficient phytosanitary protection, the use of cover plants or mulching, crop rotation and alternating cover and root and tuber crops.

It is particularly important to ensure soil cover during the heaviest rains, particularly from 15 May to 15 July at Adiopodoumé. On two identical plots with a 7% slope, one month's delay in planting *Panicum maximum* led to an increase in erosion from 1 to 89 t/ha, and in runoff from 10 to 20% for the rainiest three months of the year.

FIGURE 26
Erosion varies according to the height of plant cover from the ground



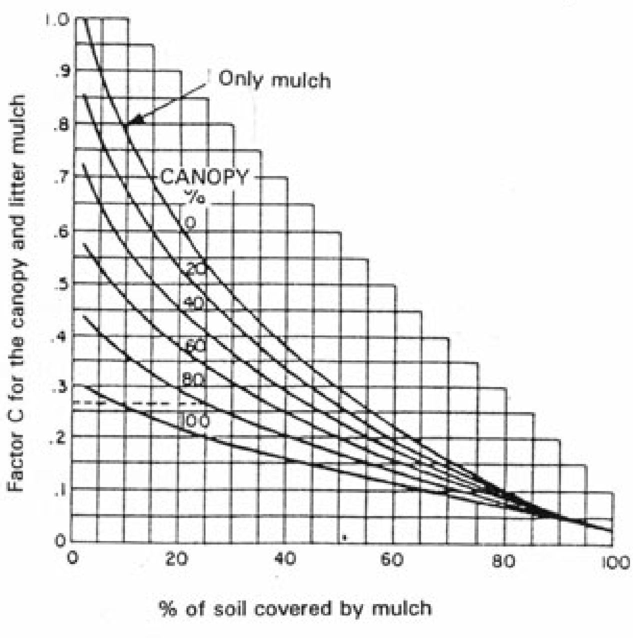
The higher the cover, the less effective it is, for drops pick up fresh energy.

If soil is 100% covered by a canopy at a height of 4 m.

If soil is 100% covered by a canopy at a height of 1 m.

With mulch in contact with the soil.

FIGURE 27
Combined effect of mulch plus canopy when raindrops fall from an average height of 1 metre or less (cf. Wischmeier and Smith 1978)



- the mulch absorbs

the energy of both → raindrops → runoff

- if the mulch cover is total (close to 100%):

  → the canopy makes little difference

- if the mulch is incomplete:

  → the canopy has a considerable effect

The choice of a very vigorous cassava variety and manure supplements reduced erosion from 93 to 30 t/ha/yr on neighbouring plots.

For shrub crops, planting a good cover crop generally solves erosion problems (see coffee, palm oil, cocoa and rubber plantations in Côte d'Ivoire) (Table 15).

INFLUENCE OF THE HEIGHT OF PLANT COVER (Figures 26 and 27)

Figure 26 shows that erosion is dependent not only on plant cover but also on plant height above the ground. For example, when plant cover is 100% but is 4 metres high, erosion will be about 75% of that on a bare plot; if the cover is 2 metres high, erosion will be about 50%; and if it is 50 cm high, erosion will still be about 18%. However, if there is a mulch, erosion will be reduced to 3%. If reduced erosion concerns the percentage of soil covered by mulch, a very fast reduction is seen for a relatively small area. For example, for 10% of soil cover, erosion is no more than 78%, for 20% it is no more than 60%, and for 50% it is only 30% of that found on the bare control plot.

This means that **litter has a very quick impact on erosion**. Mulching can be of use in erosion control even without covering the whole ground. If even as little as 20% is covered, erosion is reduced by 40%; if the mulch covers about 40%, erosion is reduced by 60%, and if 80% is covered, erosion is reduced by 90% from what would be found on bare soil.

Figure 27 shows **the combined effect of mulch and canopy**. If there is no canopy, the previous curve is seen for the effect of mulch on erosion, but if 20, 40, 60, 80 or 100% of the ground is also covered by canopy, there is a progressive increase in erosion control. Thus, with mulch covering 20%, erosion is about 60%, but if there is also 100 percent canopy cover, erosion will be no more than 30%. This means that if the mulch is not total, the leaf vault can have a considerable effect in reducing erosion.

Lastly, erosion can be reduced for a catchment if crops that provide poor soil protection (e.g. maize, groundnut, tobacco, cassava, yam) are alternated with grass leys or permanent grassland, or even buffer strips.

PLANT ARCHITECTURE

The architecture of plants can also affect the development of gullying and erosion, for trees with leaves that channel water toward the trunk operate as funnels, and water thus collected at the foot of the trunk can start to shear through the ridges, which will then drain off all the water contained in the furrows, giving rise to a gully. This occurs particularly with pineapple, but also – to a lesser extent – with maize. The other type of architecture is that of umbrella-like plants, which send drops of water outwards and thus scatter their energy; banana and cassava are examples here.

The influence of root formation must also be considered. Fasciculate surface roots hold the surface of the soil. Tap-roots grow in volume to start with, occupying the soil macropores and hence reducing infiltration, but they later rot, leaving tubes stabilized by organic matter, thus encouraging infiltration.

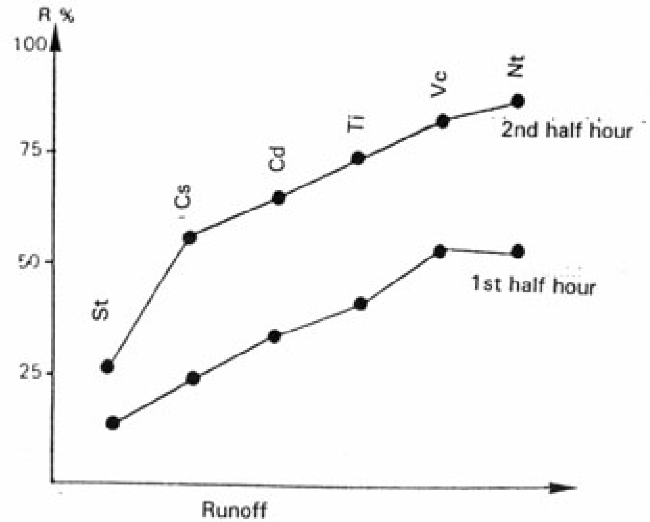
Intensified farming does not necessarily lead to increased soil degradation and erosion. Hudson (1973) indeed demonstrated that the production of one sack of maize caused 50 times more erosion when grown

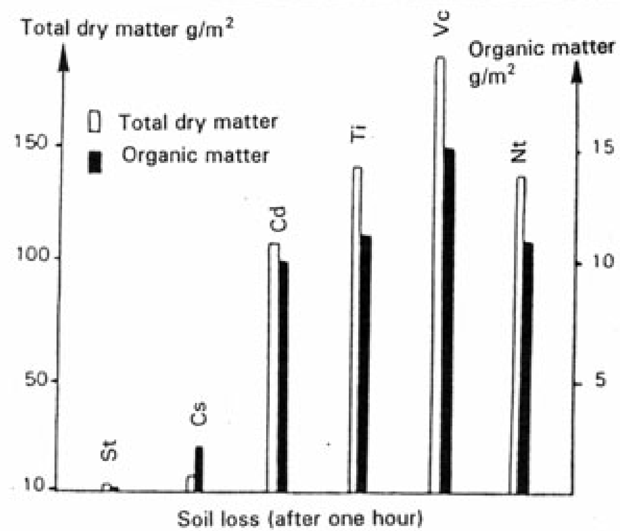
FIGURE 28

Effect of various erosion control treatments of Beaujolais grapevine plants (Pommier, France) on runoff, erosion and quality of wine (cf. Gril 1982)

Results obtained under simulated rainfall of 60 mm/h for 1 hour on 1 m².

Treatment		Runoff (%)		Erosion (g/m²) in 1 hour		Weight of harvest (g/vine plant)	Alcoholic strength	pH
		first half hour	second half hour	total dry matter	organic matter			
Straw	St	13	26	1.8	0.18	1573	8°33	6.59
Compost (surface)	Cs	24	57	6.9	2.2	1499	8°69	6.71
Compost (dug-in)	Cd	34	66	108	9.7	1514	8°63	6.76
Tillage	Ti	41	74	142	11	1565	8°38	6.50
Vine-shoots (crushed)	Vc	54	83	190	15	1546	8°33	6.58
Non-tillage	Nt	52	87	137	11	1481	8°38	6.50
Variation coefficient % Repetition = 4		41	13	60	44	9.30	2.80	3.65





extensively than when thickly planted and combined with fertilizer. This is not only because larger areas had to be cleared in order to produce the same amount of maize, but also because erosion is higher on sparsely planted fields than closely planted ones. Similarly, **fertilizers can have a significant protective effect against erosion** (Table 16).

TABLE 16
Efect of intensification of production on runoff and erosion (cf. Hudson 1973)

	KR%	Erosion in t/ha/yr
Maize without fertilizer	14	18
Maize with fertilizer	8	6.3

INFLUENCE OF CROP RESIDUE MANAGEMENT

Recall the test in Table 11 in which the presence of a cover of pineapple and burnt-off residues reduced erosion on bare soil from 200 t/ha to 25 t/ha and 11 t/ha if the residues are burnt or ploughed in, but 0.4 t/ha if left on the surface. Similarly, runoff fell from an average of 36% on bare, tilled soil to 6.4% under pineapple with burnt-off residues, 2% if the residues are ploughed in, and 0.6% if left on the ground. This clearly indicates that **residues left on the soil surface are much more effective in reducing erosion than residues ploughed into the soil** to improve its structure.

In France the best vineyards are often located on slopes. Since grapevines provide very little cover during the winter and spring storms (maximum plant cover = 40%), this crop poses serious problems for controlling runoff from steep slopes and preventing it from carrying away too much soil. This led Gril (1982) to set up tests on a Beaujolais grapevine, using an ORSTOM-type rain minisimulator, to assess the influence of six methods of soil preparation and organic matter management on the runoff coefficient (% of the rain), erosion ($g/m^2/h$) and quality of wine (Figure 28). The results clearly showed that:

- tillage reduces the runoff observed on untilled soil (by 15%), but makes little difference to erosion;
- the presence of crushed vine-shoots tends to increase runoff and erosion (+ 37%); curiously, this is the worst possible treatment;
- dug-in compost reduces runoff (by 11%) and erosion (by 24%) as against plain tillage;
- covering the soil with a compost – or, better still, a mulch – is the most effective method, reducing runoff by 65% and erosion by 98% as against the tilled control plot, with no ill-effects on the quantity, pH and alcoholic strength of the wine;
- the variation coefficient is high during the first half hour (13 to 54%), but falls as the rain continues: the condition of the surface is therefore very variable and important during short storms, but differences are really established during the second half hour.

EFFECT OF BUSH FIRES [Plate 4]

Under savannah or old fallow protected for several years, average runoff (Kaar = 0.02 to 5%) and maximum runoff are not much higher than under forest (Saria 1971-1974 and Korhogo 1967-1975: Roose 1979 and 1980a).

TABLE 17

Effect of bush fires on runoff from a plot (Gonse, 1967-1973) (cf. Roose 1979; Roose and Piot 1984)

		Full protection	Early fires	Late fires
Rainfall (mm)		674 and 799	759 and 810	553 to 691
Kaar	%	0.2	2.5	15
Max KR	%	1	10	50 to 70
Erosion	kg/ha/yr	40	140	400
Plant cover	%	85 to 95	50 to 85	10 to 55

TABLE 18

Influence on runoff of protection from grazing and fires measured under two fallows* (Saria, Burkina Faso) (cf. Roose, Arrivets and Poulain 1978)

Years		1971	1972	1973	1974
Rainfall	mm	602	724	672	714
Runoff:					
- on new fallow	Kaar %	20	5	6	8
	Max KR %	51	29	22	30
- on old fallow	Kaar %	10	0,4	0,3	3
	Max KR %	41	2	1	8
Erosion kg/ha :					
- on new fallow		700	43	19	720*
- on old fallow		17	9	10	35*

* In 1974, before the first storms, removal of the litter and all the stubble.

However, the situation is radically different **if fires take place each year**. Gonsé is a good example here (Table 17), for there is a sharp difference in soil cover if fire crosses a plot.

If the fire is early (one month after the last useful rain), it passes fast, burning the dried aërial parts, but destroying neither grass clumps nor major tree branches. On the other hand, it does wipe out the young seedlings, the litter of dead leaves, and a good number of insects and pests.

Late fires – as can happen in Sudanian and Sudano-Sahelian savannah in May, just before the rains – are disasters, for the vegetation is so dry that the fire lingers on each clump of grass, destroying every last stalk, the aërial parts of bushes, and sometimes even large trees. The soil is left practically bare, and will have little protection for at least a year. Rainstorms beat freely on the surface, forming a thin, almost totally impervious, slaking surface, giving rise to severe sheet runoff.

On the other hand, if the plot is totally protected from grazing and fires, tall plants and bushes thrive and young saplings take root, covering the land completely in two to four years and producing substantial litter to fully absorb rainfall energy and encourage the activity of the fauna that perforate the surface horizons.

Trials on fallow at Saria at the Mossi Plateau Centre clearly show the effect of stubble left on the soil since the end of 1971 (Table 18). In 1971, runoff was very high, as much as 40 and 50%, for the young fallow had almost no cover as yet, and the older fallow was grazed extensively. During the two years that the plots were protected from grazing and fires, runoff and erosion were kept down to a bare few percent of runoff. In April 1974, before the first storms, all the grass and dry leaves covering the ground on the plots was gathered. The average – and especially the peak – runoff immediately rose by several percent, although not returning to its initial level, for the clumps of grass quickly spread again as soon as the rains started, and the mesofauna did not suffer too much.

EFFECT OF FIRE CONTROL SYSTEMS ON THE NATURE OF PLANT COVER

A few kilometres from Bouaké in central Côte d'Ivoire the CTFT set up a very clear demonstration trial in the 1950s on the effect of fire on Guinean savannah (rainfall of 1 200 mm spread over four seasons) at the Kokondekro forestry station. On a sloping ferralitic soil, three one-hectare plots were isolated by fire-breaks and subjected each year either to late fire, early, running fire, or total protection from fire. After 30 years, the following observations could be made:

- on the plot subjected to fire (annual, late), the tree vegetation had practically vanished, giving place to a grass savannah;
- on the plot subjected to early, running fire one month after the last useful rainfall, tall plants shared the area with shrubby, fire-tolerant, stunted, misshapen, but fairly abundant shrub vegetation;
- on the plot totally protected from fire (a mere two accidental fires in 30 years), the grass had practically vanished, smothered by a very thick secondary forest rich in creepers and undergrowth, much more vigorous than the surrounding savannah, which was burnt almost every year, and composed of large, dominant trees (10 to 30 trees per hectare) and a mixture of tall plants and numerous shrubs.

Although unfortunately no information is available on changes in soil or on runoff, it is clear that fire has a decisive influence on the development of grasses and trees and on the variety of species present.

EFFECT OF TUFTS OF GRASS

In the absence of fire and grazing, infiltration recovers after a few years on old fallow. While double-ring infiltration tests (Müntz) have shown that infiltration is very slight between tufts of grass on denuded areas (1 to 20 mm/h), it is five to ten times greater under tufts of grass (over 100 mm/h). Such soil provides congenial shelter to termites and other small animals which build very temporary structures and hollow out passages; together with the passages left by rotted roots, these help infiltration (Roose 1979). This means that the better the young plants grow, the more extensively they cover the soil surface and the more they divert raindrops from their trajectory in order to lead them toward the base of the clumps, where they can infiltrate easily. Stalks and subaërial roots, but above all litter, also act as brakes on sheet runoff, slowing it down and thus increasing the time and volume of infiltration – although grass stalks are in fact more effective in trapping suspended solids than in reducing the volume of runoff.

CONCLUSION

Whatever the slope, cropping technique, extent of soil fragility or climatic aggressiveness, full plant cover (regardless of its architecture and botanical composition, so long as it reaches 80%) ensures a high level of soil and water conservation. The influence of plant cover is greater than that of any other factor. Biological methods that help increase plant cover should therefore have priority in any effort to improve water management, infiltration, biomass production and soil conservation. Elwell (1981) found that even if only 40% of the soil was covered by crops, this reduced erosion by 80% on oxisols in Zimbabwe, which are more resistant than the soils tested in West Africa. This clearly shows the possible interaction between plant cover and soil type with reference to erosion.

INFLUENCE OF CROPPING TECHNIQUES [Plate 17]

It is increasingly clear that the condition of the soil surface plays a major role in reducing runoff and soil loss.

There are two complementary approaches to improving surface condition. The first has been seen: **covering the soil**, planting early and densely, possibly using fertilizer, and also keeping the surface covered by stubble and other crop residues.

The second approach concerns tillage, and will be developed in the present subsection. It entails **keeping the soil surface rough**, increasing aëration and macroporosity, and improving root development, while working to control weeds and digging in organic residues to improve the organic status and structural stability of the soil. Lastly, contour cropping and ridging, if possible using tied ridges, can slow **or even halt runoff on the soil surface**. Although such techniques are mechanical means of reducing runoff, tilling the soil also encourages the development of roots and hence of plant cover, which means that **these methods combine both mechanical and biological aspects**.

EFFECT OF DEEP TILLAGE

Preliminary work on tropical ferruginous soil at Gampela in Burkina Faso (Birot *et al*. 1968) showed that tillage temporarily reduces runoff and erosion, but increases detachability and hence the long-term erosion risk, even on relatively gentle slopes.

Table 19 shows the effect of tillage with a cultivator on erosion at the ORSTOM Adiopodoumé Centre (7% slope, highly desaturated sandy ferralitic soil). Increased erosion and reduced runoff are observed on a bare tilled plot. Erosion increases despite a reduction in runoff after tillage (sandy ferralitic soil).

Tillage temporarily increases the porosity of the material but reduces its cohesiveness. Table 20 gives the various readings for erosion under rainfall for dates before and after tillage (tillage date 9 April 1971) on three bare plots with 4, 7 and 20% slopes.

Runoff is nil for three weeks when rainfall is 87 mm, increasing again sharply on the gentle slope wherever the surface has been smoothed, but much more gradually on the steep slope. Tillage slows down runoff for 50 days (corresponding to rainfall of 170 mm).

TABLE 19
Effect of tilling with a hoe (Adiopodoumé, 7% slope) (cf. Roose 1973)

Rainfall = 605 mm	E t/ha	Average KR %	Maximum KR %
Bare, flat, compacted soil	15.3	27	54
Bare soil, flat-filled to a depth of 15 cm	26.6	11	48

TABLE 20
Effect of tillage followed by harrowing on runoff (%), érosion (t/ha) and turbidity (g/m^3) on bare plots (Adiopodoumé, 1971 season) (cf. Roose 1973)

Date	Rainfall		Runoff %			Erosion kg/ha			Turbidity g/m^3		
	mm	Erosivity									
	Slope		4.5 %	7 %	20 %	4.5 %	7 %	20 %	4.5 %	7 %	20 %
30.3	31.0	30.5	**79.0**	**64.1**	**44.2**	**2494**	**4793**	**30 284**	273	664	1225
6.4	36.0	17.4	48.7	53.6	12.1	1003	2250	4795	**23**	**47**	**110**
9.4	tillage then levelling of all plots ended on 13 April										
10.4	37.0	16.6	0	0	0	0	0	0	0	0	0
19.4	5.5	-	0	0	0	0	0	0	0	0	0
22.4	12.5	1.4	0	0	0	0	0	0	0	0	0
26.4	5.5	-	0	0	0	0	0	0	0	0	0
3.5	27.0	12.0	0	0	0	0	0	0	0	0	0
4.5	17.0	8.1	**37.8**	**15.5**	**3.3**	946	145	383	**4281**	**5502**	**8562**
10.5	17.5	1.0	31.6	17.6	2.7	543	549	379	1492	1796	4320
15.5	24.0	12.2	37.8	20.3	6.4	878	676	2316	**624**	2719	2467
21.5	23.5	10.8	**53.8**	**30.1**	6.3	989	859	2031	678	1483	3992
29.5	35.0	17.3	46.9	34.8	**15.2**	**1708**	**3074**	**23 278**	810	**784**	**968**

Erosion cannot really be measured since runoff is nil, although rainfall impact clearly plays a short-term rôle inasmuch as the surface starts off cloddy and open but becomes smooth and sealed after four to six weeks (splash effect on clods and sedimentation in the lower parts). After 50 days erosion becomes exceptionally high, then falls after two months following compaction and crusting of the surface. It would seem that tillage has a longer-lasting effect on a steep slope than on a gentler slope, but when runoff does start up again, erosion becomes much greater on steep slopes because of the high energy of runoff.

Turbidity of runoff water (fine suspended load) is slight during the dry season (when the soil is crusted) but increases sharply when the first heavy rains come after tillage (the load is 10 to 100 times heavier), then gradually decreases as a smooth, sealed surface is re-formed. To sum up, **on this sandy ferralitic soil, since tillage with a cultivator to a depth of 15 cm leaves the surface cloddy, it can allow total absorption of rains of 45 to 80 mm, and its moderating action on erosion and runoff can be felt for three to five weeks (corresponding to 50 to 190 mm of rain) on a bare plot.**

TABLE 21

Reaction to rainfall as a function of the method of preparing a bare ferralitic gravelly soil (CIRAD, Bouaké) (cf. Kalms 1975)

Year	Rainfall		Runoff (annual %) from erosive rainfall				Erosion (t/ha/yr)				Turbidity (mg/l)			
	(mm)	R_{USA}	P	P+H	H	O	P	P+H	H	O	P	P+H	P	O
1971	1345	523	34	32	35	(41)	11.5	14.9	12.9	-	-	-	-	-
1972	965	329	37	34	37	42	19.7	11.0	25.0	17.9	-	-	-	-
1973	959	352	35	40	47	49	17.6	9.3	48.6	41.1	690	730	680	210
1974	1121	464	31	31	36	45	12.2	11.2	43.8	51.9	580	340	570	260

P = Ploughing H = Harrowing O = No-till

These results obtained in southern Côte d'Ivoire on ferralitic soils and bare plots would seem to militate against tillage, for the benefits in terms of infiltration last only one month, and at the end of the year soil losses are greater on tilled soil (25% more than on compacted soil). However, it is important to remember the interaction between the effects of tillage (temporary improvement of porosity) and plant growth (better rooting = better plant cover).

Another very instructive test on the effects of tillage was carried out by CIRAD at the central Côte d'Ivoire Bouaké Centre on plots of modified sandy ferralitic soil with a gravel horizon at a depth of about 30 cm (Kalms 1975). For four years comparisons were made of the reaction to rainfall of a bare gravelly soil worked twice a year in four different ways, although always in the same direction as the slope: tillage to 25 cm with a mouldboard plough (P), similar tillage followed by a light harrowing (P + H), surface harrowing to 5 to 10 cm (H) and no-till (O) (Table 21).

Tillage (deep or even shallow) improved infiltration: **runoff is always greatest on untilled, bare soil**, and the difference is even more marked when only the erosive rains that took place after tillage are considered. On the other hand, **erosion changes over time**, but from the third year onwards it is decidedly less on the bare ploughed and harrowed soil than on the bare soil that was tilled only shallowly or not at all. **Tillage clearly increases the fine suspended load in runoff**. The gravel turned up by tillage can be seen on the surface of the ground (gravel content: 10 to 13% without tillage, 22 to 28% with tillage). On such gravelly ferralitic soil in Bouaké, **tillage therefore increases infiltration and reduces erosion by bringing gravel up to the surface, which then acts as a mulch**, protecting the soil surface.

These two tests were carried out on bare soils, but what happens when the interactions between soil preparation and plant growth, and their effect on erosion are considered? Recall first the measurements of erosion and runoff under pineapple as a function of cropping techniques at Adiopodoumé on 4, 7 and 20% slopes (Table 11). Average runoff on bare soil was 36%. With plant cover of pineapple and burnt residues, it was cut to 6.4%. When residues were turned in, resulting in improved soil structure, runoff was no more than 2%, and when residues were left on the surface as a mulch, runoff was less than 1%. In this latter case, even on a soil that has not been tilled, infiltration is good because of the effect of mulching. So far as erosion was concerned, losses of 200 t/ha/yr were seen on bare soil, 25 t/ha/yr on burnt residues, 12 t/ha/yr on turned-in residues, and a mere 0.4 t/ha/yr when residues were left on the surface. This indicates that **tillage combined with pineapple cover considerably reduces erosion**; turning in residues improves soil structure, fosters infiltration and reduces erosion by another 50%, **but non-tillage, this time combined with a cover of crop residues, cuts runoff and erosion to negligible levels**.

In Nigeria (the IITA Ibadan Station), Lal (1975) considers erosion risks on bare soil after tillage to be so great – following structural degradation of the topsoil – that he recommends minimum tillage and even this confined to the planting line, while the space between is covered with residues from the previous crop. This method of minimum tillage combined with mulching can bring problems with weed- and pest-control, so that yields are not always the best in years with the right amounts of rainwater. However, when rainfall is insufficient or poorly distributed, more sustainable production is assured by improved infiltration, limitation of erosion loss, maintenance of structure at its original level, increased activity of mesofauna (especially earthworms) and an improved heat regime.

On the other hand, **on sandy tropical ferruginous soils in the dry tropical regions of Senegal**, Charreau and Nicou (1971a, b) showed that without deep tillage, yields are halved since water supplies are inadequate, the root network is not sufficiently developed, and rainwater infiltrates poorly into these soils which are sensitive to rain splash, which puts back the sowing date. Charreau (1969) observed that if organic matter is ploughed in during a rough tillage at the end of the cropping cycle, prior to the dry season, structural stability and infiltration are both improved, thus reducing erosion problems.

The numerous trials carried out since 1975 by Asseline, Collinet, Lafforgue, Roose and Valentin under simulated rainfall confirm:

- the very temporary improvement in infiltration as a result of tillage: after 120 mm of rain, there is practically no trace of this improvement on any of the soils tested at Adiopodoumé Centre and in Burkina Faso;

- the increase in the fine suspended load in runoff after tillage;

- the extremely beneficial and lasting effect for soil and water conservation of plant cover and of leaving crop residues on the surface;

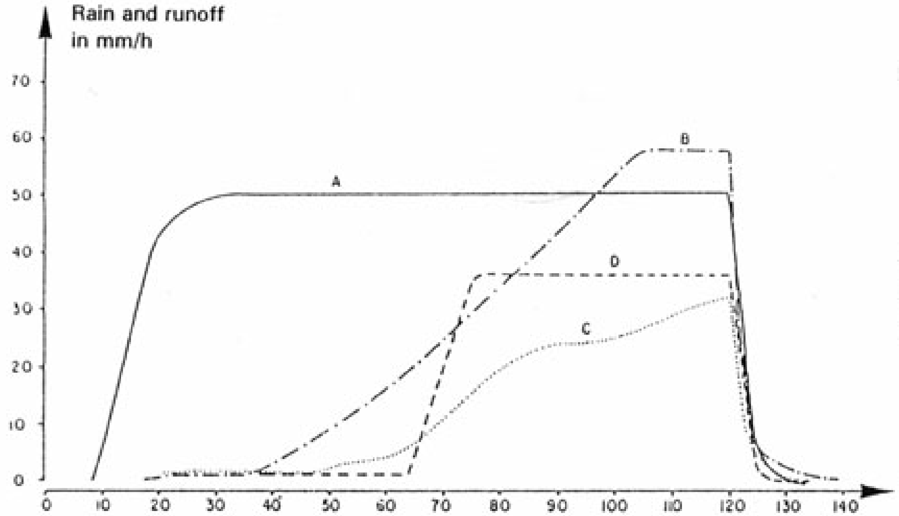
- the very marked but temporary effect of tied ridging and other methods aimed at increasing the roughness of the soil (Lafforgue and Naah 1976; Roose and Asseline 1978; Collinet and Lafforgue 1979; Collinet and Valentin 1979).

At Bidi, on sandy-clayey soil, tillage increases both infiltration and yields (+ 50 to 100%) in the first years, but quickly exhausts and weakens the soil, so that after three years erosion increases and yields fall.

Simulated rainfall experiments were conducted around Lake Bam in Burkina Faso comparing a slaking soil with a rough tilled soil, covered and not covered with a mulch, with tied ridging. Figure 29 gives the measurements under simulated rainfall of 62 mm/h for two hours on ferruginous soils in the dry tropical region north of Ouagadougou. These confirm:

- poor infiltration of end-of-dry-season storms falling on a crusted soil;
- infiltration reduced to 36 mm;
- the positive but temporary effect of tillage, which delays runoff and allows 82 mm of infiltration;
- the very positive effect of tillage followed by mulching, which allows 104 mm of infiltration;

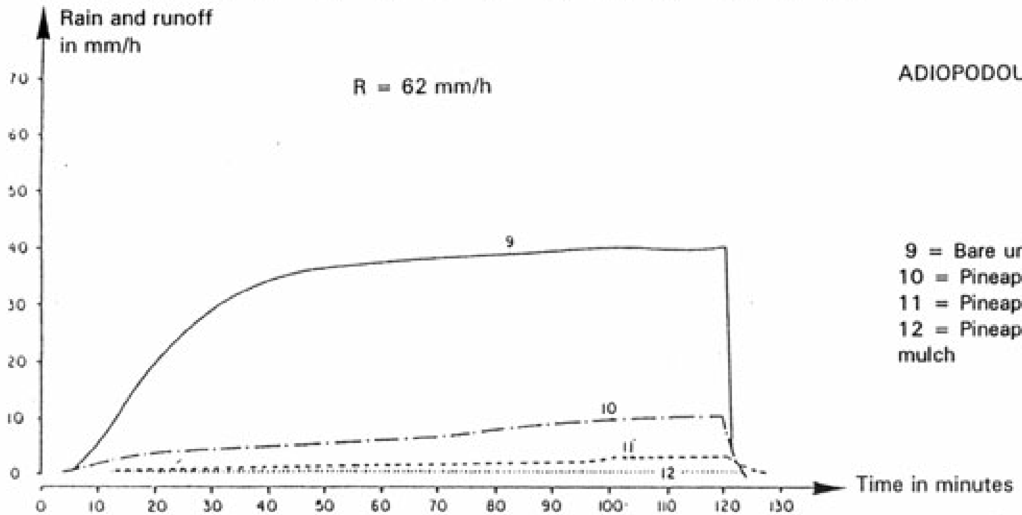
FIGURE 29
Runoff as a function of soil surface conditions and cropping techniques under a simulated rainstorm of 62 mm/h for two hours



POUNI (slope 1%)

A = Bare untilled soil
B = Bare tilled soil
C = Mulched tilled soil
D = Bare ridged tied soil

	Runoff coeff. %	Max. runoff mm/h	Infiltration mm
A	71	50	36
B	33.5	58	82
C	16	29	104
D	22	36	97



ADIOPODOUME (slope 20%)

9 = Bare untilled soil
10 = Pineapple, residue burnt
11 = Pineapple, residue dug in
12 = Pineapple, residue as mulch

	Runoff coeff. %	Max. runoff mm/h	Infiltration mm
9	51	39.5	61
10	9.65	9.9	11.2
11	2.2	39	121
12	02	06	124

TABLE 22
Influence of the number and type of seedbed preparations on a brown, slaking, alluvial, leached soil at Campagne/Hesdin, France (cf. Roose and Masson 1983)

Processes	Tillage + planting	Tillage + harrowing coupled with planting (4 km/hour)	Tillage + quick harrowing 8 km/h	Tillage + vibrating tooth cultivator + cultivator + planting	Tillage + 2 x vibro + 1 cultivator + planting
Number of passes	2	2	2 + quick	3 + deep	4 very fine
Number of germinated seeds per m^2	127	114	109	73	59
Runoff KR %	5	28	38	57	66

- Simulated rainfall is 33 mm in 1 hour (normally occurring once every 4 years).
- The difference in yields is 1000 kg/ha favouring the less tilled plots.
- This is an excellent example of land husbandry where the farmers realize that if runoff (and erosion) risks are to be reduced and production increased, they must reduce investments in inputs: fewer hours of tillage, less wear on the tractor, less energy. In this case, there is no need for extension services to point out insistently that their interests coincide with protection of the environment (reduction in downstream flooding and gullying.

- the very positive effect of tied ridging, which allows the first 60 mm of rain to infiltrate, and then maintains an overall level of penetration that is always higher than in any other case; whatever the technique proposed, it is effective only to the extent that it lastingly eliminates the thin slaked surface which to a large extent governs the water dynamics in the profile unless a warped horizon is found close to the surface (Collinet and Lafforgue 1979).

In the United States, Duley (1939) found the influence of surface crusting on runoff to be greater than that of soil type or the porosity of the different horizons. Burnell and Larson (1969) show that the delay in the start of runoff following tillage depends less on the depth of soil turned over than on the roughness of the surface. Harrold (pers. comm. 1967) considers that in regions where heavy but short summer storms are the greatest danger, deep contour tillage can considerably delay the onset of runoff by increasing both the roughness of the surface and its macroporosity (its sponge capacity). Dry subsoiling of soils with a hardened horizon close to the surface can also increase infiltration, so long as the whole of the hardened and compacted layer is broken up (Birot and Galabert 1967, Masson 1971).

Mannering, Meyer and Johnson (1968) report that when maize was grown for five years with minimum tillage, soil aggregation and infiltration increased by 24%, while erosion fell by 34% in comparison with the conventional treatment (full tillage). These authors emphasize the importance of not harrowing the soil surface in preparing the seedbed. Hence the idea of harrowing only the seed row and leaving the space between in large clods covered with crop refuse (Masson 1971, Shanholtz and Lilliard 1969).

In northern France (Tables 22 and 23), Roose and Masson conducted experiments on a farmer's field of leached, loamy, slaked, brown soil, to determine the effect of fine-tilling the seedbed on the emergence of wheat seeds

TABLE 23

Influence of cropping system on soil degradation and runoff during a winter storm with 33 mm of rain in one hour (cf. Roose and Masson 1983)

Treatment	Animal traction	Pasture	Broken up pasture	Tillage + subsoiling	Tillage, no subsoiling	Heavy machinery after harvest	
	winter wheat					endive	potatoes
Depth of tillage	17 cm	-	25 cm	25 cm	25 cm	30 cm	30 cm
Plough pan	0	0	+	+ intermittent	+ +	+ + +	+ + +
Surface condition	cloddy	compact for 15 cm	small clods	small clods	small clods	crusted	crusted
Plant cover %	80%	100%	7%	10% straw	10% straw	11% residue	11% residue
Runoff Time before onset	69'	16'	15'	15'	4'	1'	2'
In mm	0 mm	2 mm	9 mm	5 mm	14 mm	23 mm	28 mm
In %	0 %	6 %	27 %	15 %	42 %	85 %	85 %
Final runoff after 60 minutes	0 % *	24 %	48 % **	30 %**	73 %	91 %	98 %

* Runoff not yet started after 60 minutes.

** Runoff not stable after 1 hour's rain. Rainfall of 33 mm/h simulated on an acid brown soil on loess-covered uplands. The slope did not exceed 5%; runoff coefficient = runoff sheet/rainfall volume in %.

and on runoff and yields. When the soil is harrowed two to four times, with a faster tractor, the number of seeds germinating per square metre falls from 129 to 59. Runoff from a simulated rainfall of 33 mm/h rises from 5 to 66% when the ground is harrowed more times, and yields fall by about one tonne. Farmers have therefore realized that with less tillage they can improve infiltration, the productivity of their land, and net income, while reducing risks of erosion and environmental pollution (Roose and Masson 1983).

This survey shows the wide range of runoff risk (and hence of erosion) on slaked, loamy soils worked in different ways.

Animal traction entails much lower risk than mechanized traction (0 to 73%). Grassland leys temporarily protect the soil, but when broken up they rapidly become less effective (KR = 24 48 73%). Subsoiling can locally offer partial assistance (KR = 30 <-> 73%), but the highest risks were seen after harvesting endive and potato (deep tillage) with heavy machinery. On these soils, compacted by the repeated passage of tractors and trailers, 90% of all rainfall soon takes the form of runoff.

TABLE 24
Effect of cropping techniques on runoff and erosion (caused by simulated rainstorms of 40 mm in one hour) on maize seedbeds on *terrefort* soil on a hillside in the Lauragais region. Summarized data from the 1985/6/7 seasons in southwestern France (cf. Roose and Cavalié 1988)

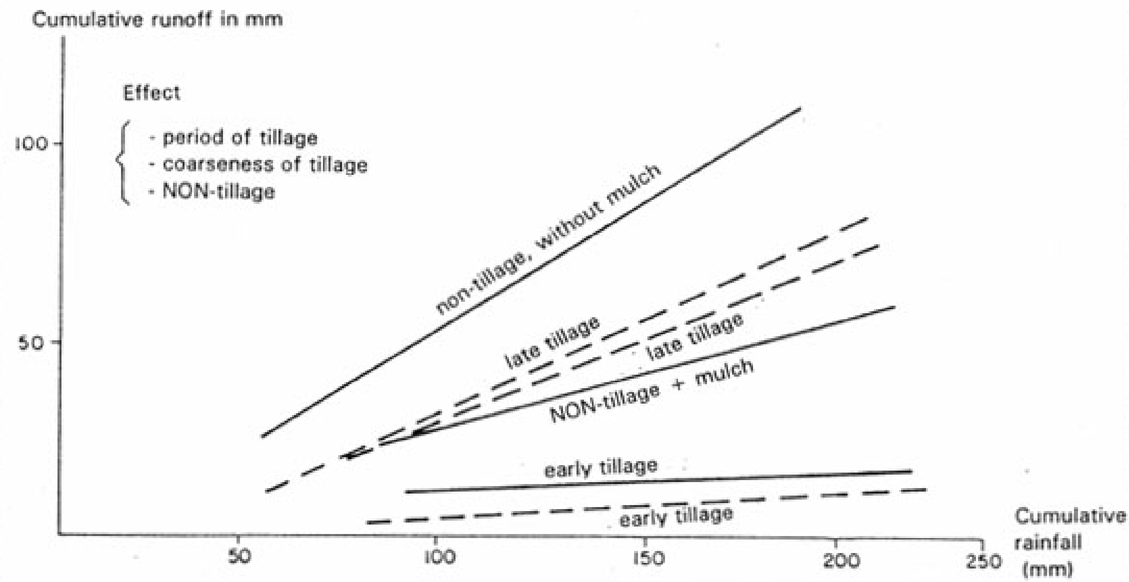
Treatment	Slope %	Runoff KR 40%	Ar mm	Si mm/h	AL g/l	Erosion g/m²	Repetition N
control = autumn tillage + re-tillage in spring	2-6 14-20 22-29	22 20 19	16 13 12	7 12 16	2 9 7	13 93 57	6 15 4
Idem + hoeing Idem + seed-bed + deep Idem + cultipacker (roller)	22-29 14-20 14-20	12 17 35	13 16 8	(20) 8 12	11 9 18	58 65 250	2 4 8
Idem + compaction once Idem + compaction twice wheel tracks	14-20 14-20 16	28 70 83	13 <u>3</u> <u>4</u>	8 <u>4</u> <u>1</u>	12 4 --	105 103 --	8 4 1
tillage + re-tillage in spring Plant cover = 30%	22-29	32	6	13	9	98	4
loosening + residues - stubble mulch tillage in autumn Plant cover 40%	22-29	17	4	21	5	35	5
loosening + surface residues + localized hoeing in spring	22-29	<u>7</u>	<u>20</u>	<u>23</u>	3,6	<u>26</u>	5

KR 40% = Runoff coefficient for a 40 mm rainfall.
Ar = Absorbed rainfall = point at which runoff starts.
Si = Stabilized infiltration capacity.
AL = Average load in g/l.
E 40 = Sediment load in g/m³ for a 40 mm rainstorm.
N = Number of repetititons.
<u>4</u> = Markedly different from the control treatment.

With the same ORSTOM-type simulator, the effects of various cropping techniques on runoff and erosion were tested on brown, clayey soils known as *terrefort* on a hillside in the Lauragais region near Toulouse in south-western France (Roose and Cavalié 1988) (Table 24). The experiment compared reactions to 44 mm/h of rainfall on three segments of the slope – the plateau of 2 to 6%, the lower slope of 14 to 20%, and the upper slope of 22 to 29%. The control plot was treated to rough autumn tillage with one or two extra passes in the spring, while a whole series of improved techniques proposed by the farmers were used on the experimental plots. In the first place, it was observed that overall runoff falls slightly from 22 to 19% as the slope gets steeper. With one extra hoeing, there is a further slight reduction in runoff from 19 to 12%. If, on the other hand, harrowing is followed by a cultipacker roller, runoff rises sharply from 20 to 35%, for the roller packs down the topsoil and breaks the clods into fine particles, which quickly re-form into a slaking crust. If the tractor is driven twice over the same place, runoff rises from 20 to 77%. Similarly, a runoff of 83% was recorded in wheel-ruts as a result not only of a reduction in the amount of soaking rain (i.e. that needed to trigger runoff), but also of a reduction in the final filtration rate, which falls from 12 to 4 or 1 mm per hour. In order to avoid such compaction in the spring, an attempt was made to prepare the seedbed in the autumn. This resulted in a rise in runoff from 19 to 32%, for throughout the winter the seedbed was degraded and formed slaking crusts. When ploughing was replaced by the use of teeth to loosen the soil and the stubble was ploughed in the autumn, runoff barely fell at all. On the other hand, with the stubble left in place after the autumn loosening, and the land tilled solely along the seed line, runoff fell from 19 to 7%, the rainwater retained rose to 20 mm, and the final infiltration rate remained at 23 mm/h.

FIGURE 30

Runoff depth as a function of the maize seedbed at Beaumont/Dème (after Rahéliarisoa 1986)



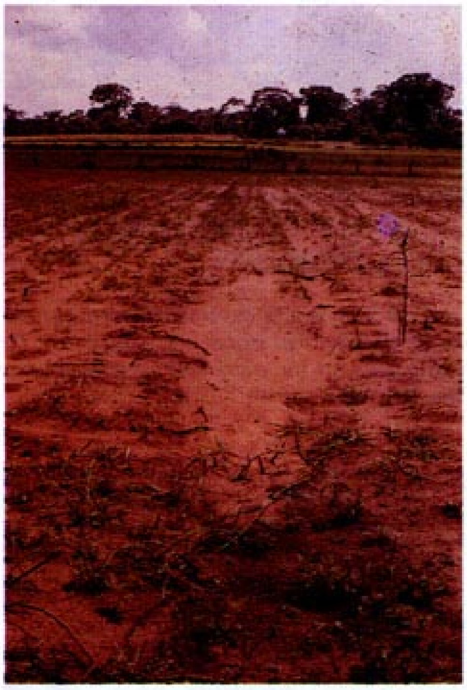
This experiment clearly shows how **compaction and the number of times machinery is driven over the soil affect runoff**, and also the positive effect of a rough autumn tillage (or else loosening the soil and leaving the stubble on the surface), followed in the spring by working the soil exclusively along the planting line.

A similar experiment under simulated rain was carried out in central France by a team of scientists from ORSTOM, the French Cereal and Forage Technical Institute, INRA, and Orleans University. The aim was to discover the risk of runoff as a function of the type of maize seedbed on a leached, loamy, very slaked, brown soil (Rahéliarisoa 1986, Lelong, Roose and Darthout 1992).

Six treatments allowed observation of the effects of date of tillage, fineness of tillage when preparing the seedbed, and presence of stubble in the case of no-till (Figure 30). It was seen firstly that no-till on a bare soil leads to the highest risks of runoff. However, if 50% of the soil surface is covered by stubble mulch, this method does not necessarily produce more runoff than late tilling just prior to sowing. On the other hand, early tilling, especially if followed by a long dry period, helps to maintain good structure and a good infiltration level. **The finer the tillage, the greater the risks of runoff**.

In the final analysis, the medium-term advantages of till or no-till in terms of water management and soil conservation depend to a large extent on soil type (i.e. its sensitivity to rain splash, compactness, amount of gravel, permeability, and initial amount of organic matter), slope, plant cover, the use of stubble, the date of tillage in relation to aggressive rains, and above all the type of tillage. Tillage is often a necessary evil for root development, weed control and breaking up the thin slaked surface that seals certain soils rich in loam and fine sand and poor in organic matter (particularly tropical ferruginous soils and leached, tempered brown soils). It is important to avoid overtilling steep slopes in humid tropical zones.

On grassland planted too late to Panicum maximum, *the first May storms beat down on the poorly covered soil and separated the humus and clay from the coarse sand. Sheet runoff carried away the light topsoil particles (coloured dark grey), leaving behind sheets of red sand as evidence of eroded soil. ORSTOM Station, Adiopodoumé, Côte d'Ivoire (5% slope).*

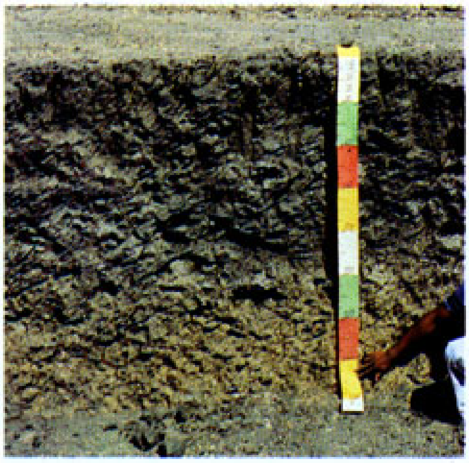


As (simulated) rain falls on the soil, it causes sheet runoff, which moves slowly. If the surface is rough, runoff quickly becomes organized (here after 3 minutes) into a network of thin, faster streams which carve small temporary grooves in which the water (artificially coloured) travels as in wadis. ORSTOM Station, Adiopodoumé, Côte d'Ivoire (7% slope).

Sheet erosion has been allowed to develop on this bare plot. It has left behind small pedestals of soil (2 to 10 cm high) protected by a hard body (crust, roots, seeds). Runoff tries to carve away the base of these pedesals, forming "micro-cliffs". It carries away the fine topsoil particles (grey), leaving a coating of red (ferruginous) grains of sand on the surface. Adiopodoumé, Côte d'Ivoire (7% slope).

A good mulch or a cover plant (here a pulse sown between rows of maize at the first hoeing) is enough to absorb the energy of raindrops, completely preventing sheet erosion and runoff. IITA Station, Ibadan, Nigeria.

Clayey vertisols rich in Ca are highly resistant to sheet erosion (K = 0.01 to 0.10). When waterlogged, they are prone to gullying. ICRISAT Station, Hyderabad, India



Brown-red, sub-arid, alluvial soils, poor in organic matter, are very sensitive to rainsplash. Heavy runoff develops, leading to widespread gullying as soon as such soils are placed under cultivation. Sabouna, Burkina Faso.

Deep ferralitic soils are highly resistant (K = 0.1 to 0.2), but in the weathering zone, runoff activates gullying and lavakas *which then develop through successive rock slides. Ambatomainty, Madagascar.*

These schists are too shallow and should never have been cleared. During a heavy rainstorm (of the kind that strikes every ten years), the channel overflowed and stripped away the entire soil cover, degrading the soil for centuries. Capetown, South Africa.

Andosols are highly resistant to rainsplash, but when ground fine, the surface horizon floats in the runoff water. In order to protect such soils, the aggregates must be enclosed in a network of roots. Honolulu, Hawaii.

In the foreground, the sandy ferruginous soil derived from a calcareous sandstone is very fragile, being rich in fine sand and poor in organic matter. In the background, black, clayey, humus-rich vertisols derived from diorite are extremely resistant. Crops grow faster on this kind of soil. East London, South Africa.

Fire and cropping quickly degrade the organic matter in these very poor, gravelly soils. A long fallow period is needed to re-establish the original vegetation. Koutiala, Mali.

Streambanks are often degraded by the continual passage of herds and flocks which come to drink and to graze the last green pasture in the dry season. Kaniko, Mali.

All cotton residues must be removed for pest reasons, causing organic imbalance in the soil and degradation of its productive potential, despite the good number of karité trees. Kaniko, Mali.

All the stumps had to be removed to allow mechanized tillage. After about ten years, the sandy topsoil horizon had been scoured, revealing the compacted impermeable crust of the plough pan. Runoff was then so heavy that it carried away seed and fertilizing organic residues, preventing any soil restoration. Baramandougou, Mali.

Fire can have five functions in Africa: clearing, hunting, parasite control, rangeland upkeep, and as an expression of dissatisfaction with government (particularly the forestry services). Korhogo, Côte d'Ivoire.

When fires are set earlier than usual, i.e. a month after the last useful rainfall, they spread quickly through the savannah, selecting for the fire-resistant tree species; this results in a shrub savannah made up exclusively of fire-loving species. Kokondekro Station, Côte d'Ivoire.

When this same area is closed to livestock for thirty years, the savannah develops into dry forest in which creepers and forest species replace the grasses that can transmit fire. Kokondekro Station, Côte d'Ivoire.

Fire is an essential instrument in animal husbandry, allowing regeneration of forage resources during the dry season. This picture shows the boundary between the area that has been burnt off late in the season for thirty years and the surrounding tree savannah. Kokondekro Station, Côte d'Ivoire.

A great deal of Africa that is at present under savannah would naturally revert to forest if it were protected from fire and grazing.

After the caterpillar ridger has overturned the trunks of the main trees, the rake then tears up the root network, separating it from the topsoil. The undergrowth, roots and trunks are all rolled along in a cloud of dust to the end of the plot, where the biomass and nutrients accumulated over the past 20 to 150 years are heaped up. Ibadan, Nigeria.

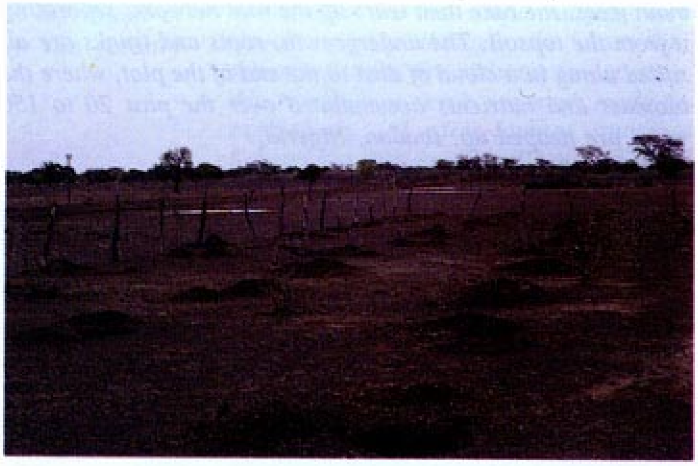
After the ridger and rake have done their work, the surface is level, but the litter and humus have vanished. The soil is bare, ready to suffer the onslaught of the rains and be turned into mire, for the root network has been pulled up and the soil pulverized by the caterpillar tracks.

When forest cannot be felled with a mechanical saw and progressively cleared, use of a special blade is recommended. This implement has a spur to split the stumps and a blade to saw them off at ground level.

After the special blade has been used, the soil surface is still covered with litter, and the stumps and root network are left in the soil, which suffers much less under this clearance method.

When branches cannot be left in place (since soil is tilled mechanically), it is better to burn the brushwood on the spot in order to release the mineral load rather than relegate it to the edges of the plot.

The local chief gave the worst piece of land to be used for a village woodlot. After the land was cleared and fenceposts put in to close the area off to livestock, seed holes were made. This gravelly soil is very poor and stores very little water, and so nothing actually grows, and the land is even more denuded than before. If by good fortune the young trees grow before the fenceposts are eaten away by termites and collapse, nobody bothers about upkeep of the stand or the necessary thinning, for nobody knows who owns the wood - the State or the farmers. Yatenga, Burkina Faso.



Reforestation on a half-moon on gravelly ironstone. In this example, the water has mainly benefited annual grasses, although some trees still survive after six years (acacia, neem, eucalyptus). Outside the gravel area, the half-moons disappear in one or two years on these very fragile, sandy soils. Gourga, Burkina Faso.

Reforestation along stone lines. After unbroken lines of stones had been arranged in semi-circles, the villagers planted various indigenous trees (barely visible in the foreground) and eucalyptus under wire netting. The women take care of weeding, and are allowed to grow a groundnut crop. The eucalyptus trees have profited considerably from runoff water. In the foreground, the posts supporting the netting have been destroyed by termites in three years. Cost of netting: 10 000 FF or $US 2 000/ha, obviating widespread use. Ilonga, Burkina Faso.

Trees growing around homes protected by a bundle of thorn branches, a woven basket or a small lattice wall of bricks. Yatenga, Burkina Faso.

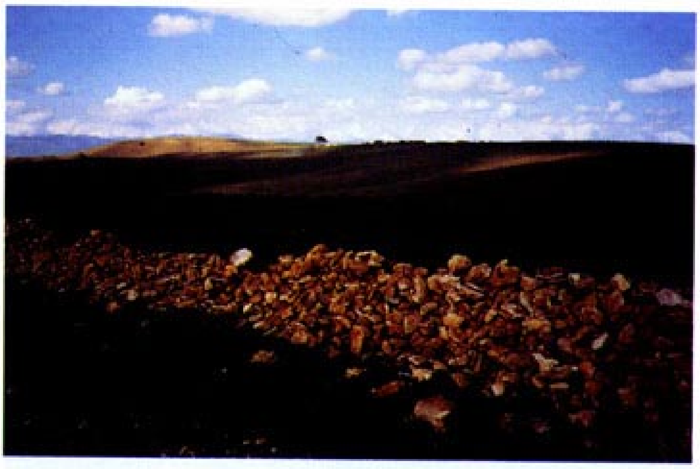
Some farmers have developed forest variations on the zaï method (see below). When hoeing, they leave some of the forest seedlings that spring from seeds contained in the dry corral dung that is dug into the zaï pit. When the first thinning is carried out after five years, some shoots are again left to create an acacia stand, while the rest are cut down for fuelwood. This system has a very positive effect on the restoration of soil fertility, runoff, and water and wind erosion, for the trees trap the leaves and alluvium blown by the dry harmattan *wind. Gourga, near Ouahigouya, Burkina Faso.*

Bocage of hedges. In a denuded area, a Regional Agricultural Centre (CRPA) project selected various hedge-forming species. Acacia nigritiana *proved effective not only in creating a livestock-resistant hedge, but also in reducing wind erosion. Under its protection grass cover developed naturally, slowing down runoff and sheet erosion. Elsewhere, farmers preferred* Ziziphus mauritiana, *for it is equally resistant but can also provide forage and fruit to sell at market. Ziga, near Ouahigouya, Burkina Faso.*

The Algerian diversion terrace was designed to evacuate runoff from fields made fragile by tillage to a protected spillway. To cope with the increased intake of water, the slope of the channel has to be increased from 0.2 to 0.4%, but here water collects at a low point, threatening to overflow, gullying the slope or causing landslides. Reforestation of communal lands with Aleppo pines by foresters is not respected: the best trees are removed before they reach maturity, and the pine litter does not improve the soil, or only very gradually. Milliana, Algeria.

Terraces have been built on the slopes of a calcareous plateau to encourage infiltration and the growth of fruit trees. There is no trace of runoff, either on the slope or in the spillway! The good condition of these terraces is insufficient justification for the investment. Is there a serious risk of runoff? Bel Mezioude, Algeria.

The calcareous crust of this brown soil was broken up by deep subsoiling. The stones were piled along the contour lines: not having prevented runoff, they were used to build new homes. It may be wondered whether such stones are more effective piled in rows or scattered over the ground where they intercept the energy of rainfall and runoff. Bel Mezioude, Algeria.



This completely gullied hill was reforested with Aleppo pines 15 years ago, but overgrazing has left the soil still almost bare. Is such an investment in badlands an economic proposition? Why do farmers not respect such government efforts to protect their environment? Probably because they see the planting of trees as an attempt at expropriation by the State. Oued Isser, Algeria.

Reforestation of badlands after terracing of a marly hillside. After 12 years, the Aleppo pines have reached a height of 3 m on the terraces, but cover less than half the soil surface (too little for erosion control) and suffer the ravages of processionary caterpillars. It would be wise to diversify the species and introduce a leafy under-storey. Seghouane, Algeria.

Reforestation of a semi-arid hillside (annual rainfall 250 to 350 mm) after building bench terraces. After 17 years, the pines are growing again satisfactorily, although their height and the ground cover provided are slight because of grazing and drought. The forceful intervention of the forestry services on these degraded common grazing lands is little appreciated by the "beneficiaries": if the dam is to be protected, other strategies must be sought, and compensation envisaged for poor farmers whose only resource is animal husbandry. Relizane, Algeria.

Farmers lay out lines of stones, branches or grass in order to slow down sheet runoff, stem peak flows, and trap organic matter and sand, while allowing excess water through. These lines can also be used as boundary markers for property. Yatenga, Burkina Faso.

Line of stones reinforced with a line of grass. Farmers can reinforce their stone lines by sowing Andropogon, *thus using 50% less stones, which can then be used for closer spacing of the lines, since the positive effects only extend 5 metres on 2% slopes.* Andropogon *fulfils a variety of functions: green forage in the dry season, straw for roofs, and various uses in artisanal crafts. Yatenga, Burkina Faso.*

In gullies and wherever gullying sheet runoff is too fast, a semi-pervious dam should be built with large blocks of laterite. This flat-topped structure will slow down peak flows, help recharge groundwater, and trap nutrient matter. Filtering bund in Yatenga, Burkina Faso.

These earth bunds have been built over an area of 45 000 ha in Yatenga province in the past 20 years. However, few are still functioning two years after construction. They act in fact as diversion bunds, leading runoff down into low-lying areas, particularly tracks! When farmers realize that the bunds waterlog upstream land while drying out downstream land, they break them and go back to irrigating their land with the water flowing down from the top of the hill. This method of diversion should be avoided in Sudano-Sahelian areas where stop-wash grass lines are more suitable. Ouahigouya, Burkina Faso.

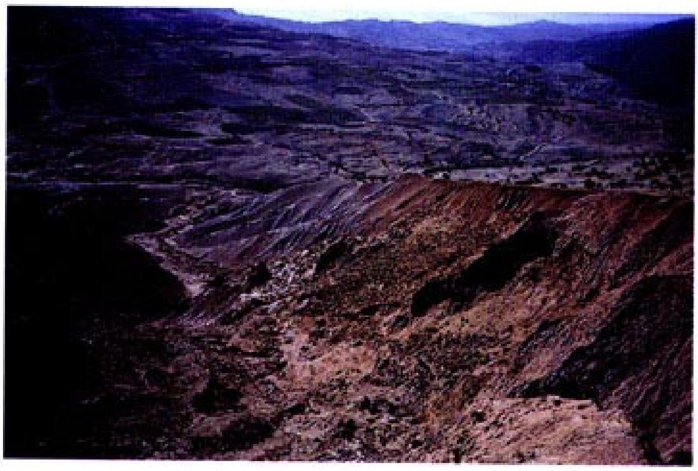
Bench or Mediterranean terraces built in the 14th century by the Incas, irrigable and still used to grow cereals. This method requires a huge investment in labour (600 to 1 200 days/ha) and upkeep (3 to 10 t/ha/3 yrs of manure + 2 to 5 t/ha/2 yrs of lime). It is acceptable only if land is scarce, labour abundant and cheap, and the crop economically viable. Machu-Pichu, Peru. [Photograph De Jaegher]

Stone risers in the valleys: systemas andenes *in Peru. In order to make the best use of the colluvial deposits trapped in the valleys, the farmers have built stone risers which allow control of runoff water and protection of cultivated land. Cuzco, Peru. [Photograph De Jaegher]*

In Nepal, slopes of up to 60% are converted in traditional style into narrow progressive terraces. The risers are grassed. Steeper slopes are covered with hay fields. Valley bottoms are irrigated and farmed intensively. Gulmi District, Nepal. [Photograph Ségala]

On the steep slopes around Lake Geneva, wine growers have built cemented stone risers as well as a network of stabilized roads which drain the whole slope. Lastly, the surface of the fields is protected by a bed of pebbles that absorb the energy of raindrops. The grapevines grow fast to start with, protected by this mulch of pebbles. Wine growing makes such large investments financially viable. Lake Geneva, Switzerland.

Sloughing in the form of a mudrock flow: a section of the hillside has collapsed into the gully during an exceptional rainstorm, forming a torrential red mud flow 1 km long. The gypseous marls of the hill had given rise to suffusion (tunnel erosion as the gypsum dissolved). Khef el Hamar, near Médéa, Algeria.

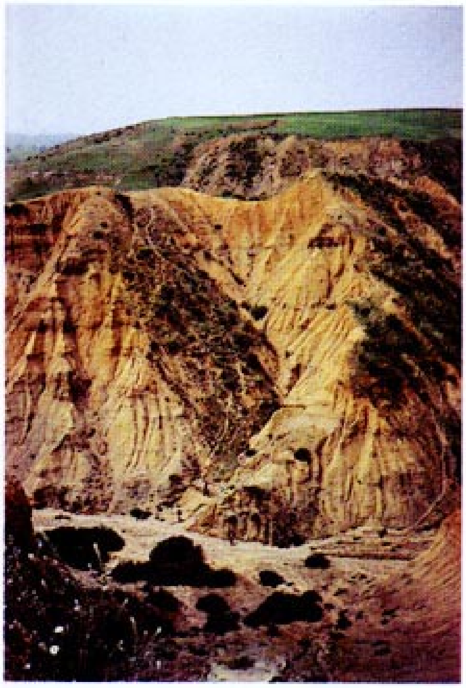


In a mountainous area, after a saturating downpour, gravity combined with runoff and alternations of frost and thaw to move huge boulders downhill. Ecuador. [Photograph De Noni]

Sloughing has produced a shell-shaped erosion scarp. On a steep schisty (or marly) slope, a section can break away, leaving a hollow with a reverse gradient. Water then collects at the bottom of the hollow and can give rise to a gully - which will remove any trace of the original slide. Biscuicuy, Venezuela.

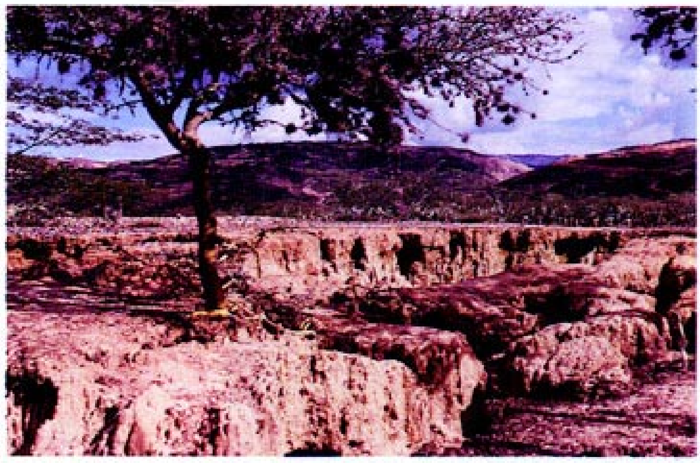
Such wholesale slides of soil cover over schist illustrate the dangers of working very steep slopes, which are further unbalanced by tracks and overgrazing. Gulmi District, Nepal. [Photograph Ségala]

Deep V-shaped gully in a marly hill. The slope that catches the moist winds is in balance and is covered with vegetation; the dry slope is steep, unstable, undermined at the bottom, and stripped bare. The slopes recede as the marl weathers and as runoff washes away the buildup of sediment in the bottom of the gully. A simple wire netting barrier is sometimes enough to stabilize such slopes. El Azizia, Oued Isser, Algeria.

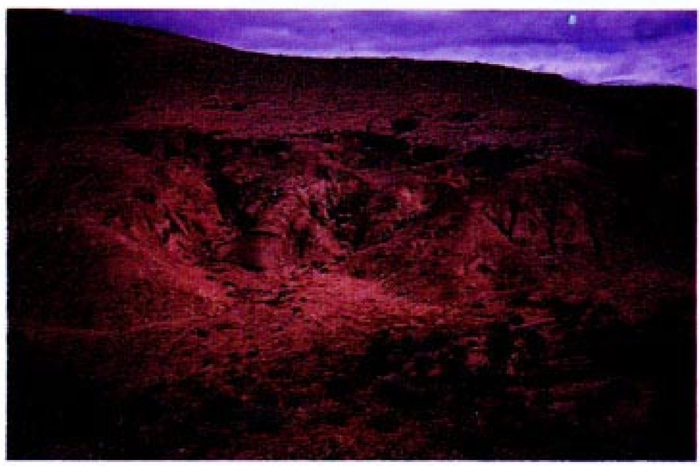


U-shaped gully. When the material sheared away by runoff lacks homogeneity, the gully develops vertical lips and grows as it caves in under pressure from the underlying water table. This is seen in the lavakas *of Madagascar, where runoff first penetrates the resistant horizons, which are rich in clay and iron, then the ferralitic alterites, which lack almost all cohesiveness.*

Trees do not stop gullying once it has started. Their roots can help to reinforce banks, but during the heaviest flood flows, the water swirls around the trunks, eroding the banks. Venezuela.



Tunnel gullying. In gypseous marls, water seeps through cracks, dissolves the soluble salts, and hollows out tunnels, giving rise to gullying that is difficult to control. Similar phenomena can be found in deeply fissured vertisols and where surface water penetrates via the tunnels made by burrowing animals. Oued Mina, Algeria.



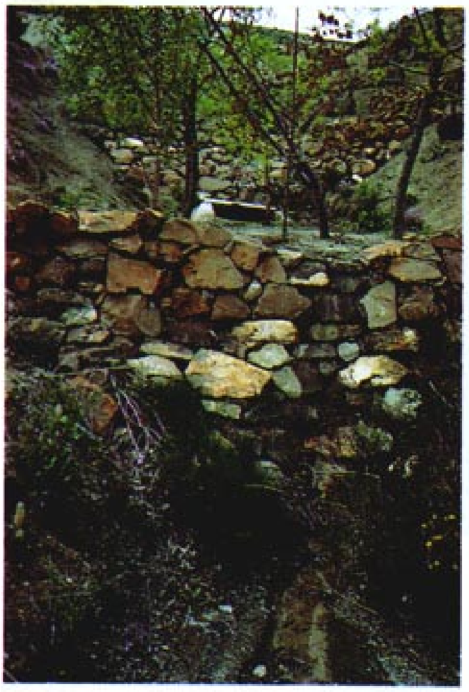
The ONTF built large gabion structures to control a gully on marl located not far from a dam. After five years, no sediment has yet been trapped, and it would appear that this huge investment was quite unnecessary. However, the weirs could perhaps fill during a particularly exceptional rainstorm. Oued Sikak, Algeria.

On the central uplands of Madagascar, farmers are very skilled at transforming gullies into rice paddies. They use clumps of grass to build earthen retaining walls to hold the water and mud eroded from banks and hills that have suffered bush fires; they then devote all available manure to these areas. The hillsides support only meagre, fairly undemanding crops (cassava and extensive grazing). Madagascar.

A gully garden. Since basaltic rocks weather fast, fine sediment can be trapped behind sills of earth-filled plastic bags (which must be protected from the sun). The terrace thus formed is then manured and planted to coconut, banana, mango, sugar cane and various forage species. Petite Valley, Nippe, Haiti.

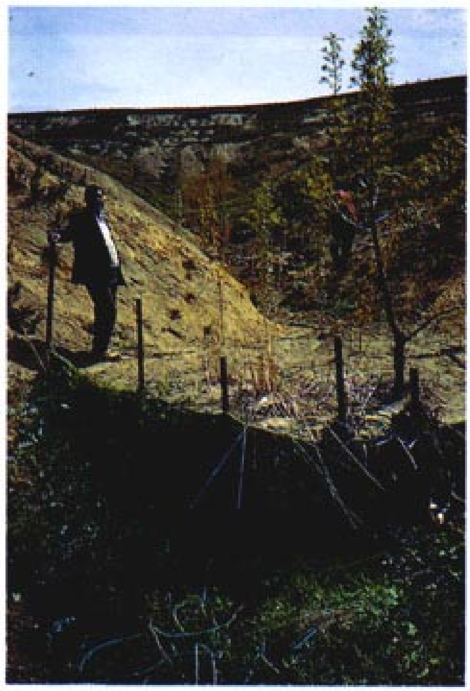
Runoff dug out a young gully in the soil cover starting at the ridge road. The farmer immediately planted banana, bamboo, sugar cane and various forage plants here. The runoff energy is absorbed by the plants, and the gully is stabilized. Jacmel, Haiti.

A series of gabion, dry stone or wire netting sills were built at the head of the gully. By the second year, the structures had been covered by sediment, and had to be raised again to reach the equilibrium that would allow natural vegetation to cover the slope. Souagui, Algeria.



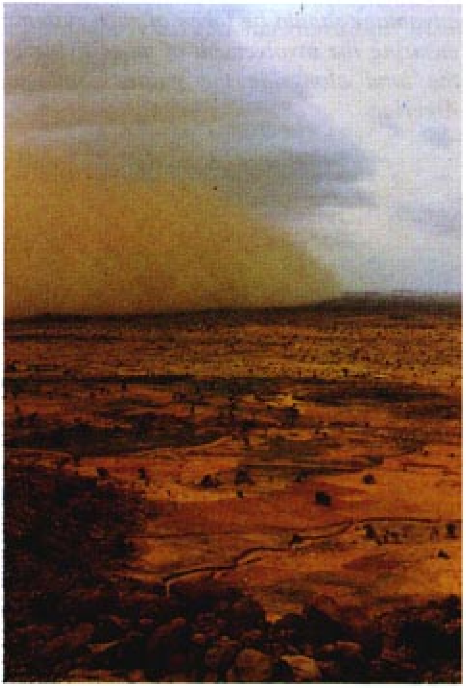
Several cubic metres of sediment have collected behind the dry stone sills. Water has infiltrated into the pores of this sediment, amounting to 20% of free water and a similar amount of absorbed water that can be used by plants. After two years, the mass of sediment gave birth to a spring, which was tapped to irrigate several trees. Souagui, Algeria.

A treated gully behaves like a linear oasis. Three years after the sills were built and trees planted in the silt, the gully was covered with natural vegetation, in contrast with the arid surrounding area. Given the considerable cost of treating gullies, full advantage should be taken of such systems, ensuring the involvement of those living on the land alongside the gullies. Souagui, Algeria.



Light sills made of wire or plastic netting (with 1-cm mesh) stretched between 2.5-metre angle irons stuck 50 cm into the soil, and held in place by galvanized bracing wires. They have proved at least as effective as gabion structures, which are more prone to piping under the sill that can evacuate all the accumulated sediment in just one peak flow. This type of sill costs 30 to 20% that of a gabion structure. Souagui, Algeria.

Cloud of fine dust (in suspension) raised by the approach of a "tornado" at Déou, north-eastern Burkina Faso. [Photograph Ségala]



*Formation of a small dune in the bed of an overflow basin. The soil is covered with a sedimentation crust, scored by the grains of sand sheeting over its surface. When grass manages to take root, the wind is slowed down and grains of sand are trapped. A small dune (*nebkra*) then forms, which will be the source of a recrudescence of vegetation (trapping seeds and water). Bani River, Mali.*

A Texas landscape invaded by sand dunes: saltation at Big Sprint. [Photograph Fryear]

Reg *on the surface of an eroded calcareous brown soil. These uplands of semi-arid calcareous brown soil are swept by wind and runoff which push fine particles down to the bottom of the slope and detach the calcareous crust, forming a* reg*. The olive is one of the last witnesses of the primary forest of this region, which was once the granary of the Romans. Darna, Cyrenaica Province, Libya.*

TABLE 25

Cropping systems (C) efficiency surveys and erosion control practices (P) in Brazil (cf. Leprun, da Silveira and Sobral, 1986)

	P	C
Cotton on contour lines (tillage + 2 conventional weedings)	0.41	
+ maize + contoured beans	0.75	
+ maize + contoured beans + buffer strips	0.48	
Maize on contour lines (tillage + 2 weedings)	0.87	
+ alternate hoeing	0.16	
+ alternate hoeing + perennial plant strips	0.08	
Tomato + bi-annual bean rotation		0.56
+ soil preparation		0.08
+ rotation with legumes as mulch		0.11
+ rotation with dug-in fallow		0.38
+ rotation with 2 years fallow as mulch		0.01
+ maize + green manure as mulch		0.07
+ rotation of green manure + grass strips	0.04	
Soybeans with no soil preparation		0.67
Wheat-soybeans + minimum preparation		0.37
Wheat-soybeans with no preparation or tillage		0.17
Wheat-soybeans with no preparation or tillage + mulch		0.09
Barley-soybeans + oats with no soil preparation		0.46
Wheat-maize with no tillage		0.14
Wheat-maize + fertilizer		0.31

One of the main focuses of present research on soil conservation is the use of crop residues and tillage, and there is as yet no real proof of **the long-term positive agricultural and economic effects** of such techniques as minimum tillage, localized tillage with the space between rows being protected by stubble, partial ploughing in of stubble (stubble mulching) and no-till, leaving stubble on the surface (mulch tillage) – techniques that all seem to have a positive effect on water management and soil conservation. In any case, there are still various practical obstacles in the way of using these methods in which organic residues are left on the surface: weed control (herbicides are expensive), machinery to break up the soil without turning it over (vibrating teeth in place of a plough), machinery to sow through a mulch, and pest-control problems (particularly grasshoppers and snails).

In Brazil, Leprun, da Silveira and Sobral (1986) collated the results of experiments on erosion plots in the north-eastern, central-western and southern regions (Table 25). These show the remarkable efficiency of simple farming and biological practices that are easy and inexpensive for farmers to apply, and that ensure long-term productivity. In the best situations, these biological practices allow control of erosion and a decided reduction in runoff.

The most effective mechanized cropping techniques are minimum tillage, sod seeding in the mulch made up of residues from the previous crop, or else contour cropping. The best biological techniques are crop rotation, cropping on a mulch of crop residues or green manure, and permanent contour buffer strips.

TABLE 26

Erosion, runoff and yields as a function of soil preparation techniques (Saria Station near Koudougou, Burkina Faso: tropical leached ferruginous soil on ironstone, 0.7% slope)

	Rain-fall	Bare soil	Shallow cultivation			Digger ploughing			Digger ploughing + tied mounding		
		E (t/ha)	E (t/ha)	KR %	Yield (t/ha)	E (t/ha)	KR %	Yield (t/ha)	E (t/ha)	KR %	Yield (t/ha)
1983	771	24.2	18.4	36	1.34	20.3	31	1.57	15.0	13	1.86
1984	700	9.3	7.3	31	0.82	6.3	27	1.73	3.5	14	2.46
1985	596	11.8	15.6	30	0.68	7.0	18	1.45	4.2	15	1.99
1986	933	23.5	19.6	32	1.40	20.8	18	2.89	11.1	10	2.88
1988	935	18.5	13.1	22	0.73	13.9	13	2.54	3.0	4	2.29
Average		17.5	14.8		0.99	13.6		2.04	7.4		2.30

TABLE 27

Effect of mounding on an almost bare soil (7% slope, Adiopodoumé, 1956) (cf. Roose 1973)

May-August: rainfall = 1534 mm	E t/ha	Average rainfall %	Max. rainfall %
Cassava planted late, almost bare soil on mounds	89.6	26.6	48
Cassava planted late, flat bare soil	79.0	28.2	52

In view of the difficulty of maintaining infiltration under major mechanized crops and reducing erosion through control structures on contour lines (Murundum in Brazil, the Monjauze embankment in Algeria), Séguy *et al*. (1989) worked with co-operatives to develop a holistic farming system that reduces tillage to a minimum and entails selection of disease-resistant seed, development of material for sod seeding plus fertilizer applications in stubble mulches (from manual planting canes to mechanized seeders), sowing legumes as catch crops under maize, dressings suited to the production level, a range of herbicides and pesticides compatible with mulch cropping, and a research and marketing network.

All these methods are at present being tested in Cameroon by IRA and CIRAD scientists within the framework of intensive cotton and cereal farming under Sudano-Sahelian conditions on typically fragile tropical ferruginous sandy soils.

SHALLOW TILLAGE (HOEING)

Since the formation of a thin slaked surface has a marked effect on infiltration, it might be hoped that shallow tillage would be enough to save both soil and water. And at Adiopodoumé (Roose 1973) it has been observed that the effects of hoeing a bare, sandy soil are similar to, though more ephemeral than, those of ploughing. Following a shallow scratching with the hoe, the soil can absorb only a single fairly gentle rainfall of 10 to 30 mm and erosion is contained for one to eight days after which it exceeds that on the control plots. While runoff is temporarily slowed, turbidity rises considerably, falling only with the formation of a new thin slaked surface.

The same conclusions could be drawn from cropping technique trials under simulated rainfall on steep-sloping loam-clay soil in the Lauragais region in south-western France. A rainfall of 40 mm in one hour produced a slight increase in infiltration, but the thin slaked surface then re-formed and with the higher turbidity soil loss in the end matched that on the control plot (Table 23).

At Bouaké (Table 21), shallow harrowing of bare soil barely reduced runoff compared to the untilled control plot but **increased erosion considerably** (Kalms 1975).

On the other hand, on **the broad, gently sloping, tropical ferruginous pediments of Burkina Faso**, Nicou, Ouattara and Somé (1987) showed that yields close to those obtained after tillage could be obtained so long as the surface was broken up each time the slaking crust re-formed (Table 26). The point is that in these semi-arid Sudano-Sahelian zones, tillage necessarily entails later sowing than that traditional among the Mossi farmers, while simply scratching the soil allows the plants to take root faster and the runoff to start later if the slaking crust is broken up regularly. In places where people have never adopted tillage, scratching the surface with a donkey-drawn implement is a fast and inexpensive operation within the reach of small farmers.

Shallow tillage unblocks the macropores of the soil surface, and can thus improve infiltration in semi-arid zones and even in temperate zones, so long as the soil is kept free of a thin slaked surface until plant cover can take over. On the other hand, **harrowing is a dangerous practice everywhere**, especially on steep slopes; it serves very little purpose and should be avoided during the period of major rainstorms.

MOUNDING AND RIDGING

These techniques are widely used in Africa to ensure good root development (cassava, yam), and good drainage in temporary wetlands (including Sudanian areas), and to collect fertile soil around plants grown on the most degraded soils. Ridging also facilitates weed-control by giving the crop an advantage of 10 to 20 cm in height over the weeds. However, mounding – and, to a slightly lesser degree, ridging – is a dangerous practice, for although it theoretically increases the infiltration surface (hence in principle reducing runoff), **it also increases the average slope of the land**, reduces soil cohesiveness, and concentrates runoff along specific lines. It also increases erosion, which rises exponentially with the slope of the land (Table 27) (Roose 1973).

Two temporary experiments carried out during the 1956, 1967, 1968 and 1969 seasons at Adiopodoumé suggest a slight reduction in runoff and an increase in erosion and turbidity on a ridged soil under cassava or maize. However, these phenomena are not always very clear.

It would be easy to reduce soil and water loss for crops grown on mounds and ridges by tying and mulching them. However, it would then be impossible to avoid the formation of **a very unfavourable surface structure in the furrows and pans they form** which would reduce soil infiltration capacity at the end of the rainy season. In semi-arid Sudano-Sahelian areas, level planting on unridged ground followed by hoeing and hoe-mounding at three-weekly intervals, then by tying, allow broad, tropical, ferruginous pediments to absorb rainstorms of 50 to 70 mm – the levels to be expected at the start of the rainy season when the cover has not yet taken over. Studies by Rodriguez (1986) in Burkina Faso have shown that tied mounding allows considerable improvements in infiltration -and also in

TABLE 28

Effects of tied contour ridging on a sandy soil in southern Côte d'Ivoire under pineapple (cf. Roose 1973)

1956 to 1958		E t/ha	Average KR %	Max. KR %
Pineapple flat-planted	1st yr	15.5	17	51
contour planted	2nd yr	0.2	1	5
Pineapple on tied ridges	1st yr	1.6	1	2
contour planted	2nd yr	0	0.2	1

crop yields (+ 500 to 1 000 kg/ha/yr for additional working days = 220 FF). Trials carried out by the CTFT at Gampela (Roose and Piot 1984) **on gravelly soils** have shown that **tied contour ridging is in fact the only way of appreciably reducing runoff and erosion** in Sudano-Sahelian areas. Unfortunately, on the relatively shallow **gravelly soils** on ironstone which are so common in the region, **the water storage capacity and soil fertility are so low that the additional infiltration rarely has much effect on crop yields**. Reference is made to the trials by Collinet and Lafforgue under simulated rain in the Lake Bam region (Figure 29), which showed that tied ridging on slopes of under 1% allows 60 mm/hr of rain to infiltrate, and more than 100 mm to be stored in the soil, i.e. three times more than if the soil had not been tilled.

The effect of contour tillage, but especially contour ridging, is difficult to test on such small erosion plots (5 x 20 m long) – and such tests could in any case give unreliable results. However, many authors do recognize that tilling the soil along the contours considerably reduces the erosion risk, at least on slopes of less than 10%. On steeper slopes, the sheet of water retained by the contour ridges decreases, correspondingly increasing the risk of a succession of breaks in the ridges all down the slope. It is therefore **vital to tie ridges** in order to keep water and sand in place, and to **set up spillways to lead off the excess** (Table 28) (Roose 1973).

Deep drainage can also have an effect on runoff and erosion. On loamy soils in central France, Trévisan (1986) used simulated rain to show the considerable effect of the proximity of drains, which reduce persistent moisture in the macropores, improve structure, and maintain infiltration. More rainwater is retained and the final infiltration capacity is greater. However, in a good number of these soils with a plough sole or a fairly impervious B horizon, the improvement from such drainage is confined to the immediate vicinity of the drains.

The major role of crop residue management should also be emphasized here. When pineapple residues are burned and ploughed in, erosion and runoff increase much faster than when residues are simply ploughed in (Table 11), whereas when they are left on the surface, erosion and runoff become negligible, whatever the slope (Roose 1980a). In a semi-arid region (where increasing seed density does not increase yields because soil water storage capacity is too low), the future lies in better management of the soil surface, partly by eliminating the thin slaked surface and increasing the depth reached by crop roots, and partly by keeping as many crop residues as possible on the surface.

On the very rich volcanic soils of **south-western Cameroon, the Bamiléké** traditionally multicrop half a dozen species on large ridges running perpendicular to the contour lines on steep slopes (Fotsing 1992a) (Figure 31). Inexperienced agricultural scientists felt that these large ridges should be perpendicular to the greatest slope, but then saw that in heavy rains, water would collect at certain points on the slope, overflow the ridges, and form more serious gullies than in the traditional system. It must be emphasized that **on slopes steeper than 25% the advantages are greatest if ridges are oriented in the direction of the greatest slope, which limits the catchment area and hence the volume of runoff between ridges**. In the case of small and medium rainstorms, damage will obviously be greater when mounding follows the direction of the slope and will certainly lead to quite considerable erosion in the course of the year, but **it does help to reduce the major risks of landslips or gullying**. Thus the contour ridging method is not universally applicable. One elegant solution might be large ridges on a gentle slope (under 1%) toward a prearranged spillway, with ties between these ridges every 1 to 5 metres. Such ties must be lower than the ridges themselves in order to allow progressive lateral drainage during exceptional rainstorms. However, the secret of the success of the Bamilékés' ridging method lies in keeping a very thick permanent cover thanks to the combination of a large number of different crops throughout the year (see Part III).

In mountainous areas, tillage entails some serious hazards:

- it temporarily improves infiltration but reduces soil cohesiveness, thus heightening the risks of erosion and sliding;
- it allows organic matter to be turned in, but exposes the subsurface, which is poorer in humus, to rainfall impact;
- above all, it accelerates dry mechanical creep, since the implements move the clods.

The following solutions have been put forward:

- rough tillage by two to four people working together turning large clods in order to dig in plants, grass and manure;
- mounding is dangerous, for it concentrates runoff into rivulets which soon carve channels on steep slopes;
- ridging is often used to dig in the fallow and crop residues:
    - it collects a great deal of well-drained, friable soil for tubers;
    - it stores water (60 to 22 mm if the slope increases from 2 to 40%) if it is perpendicular to the slope (a risk of landslips in the heaviest rains);
    - it drains slopes if it is oblique or follows the direction of the slope;
    - it gives crops an advantage in height over weeds.

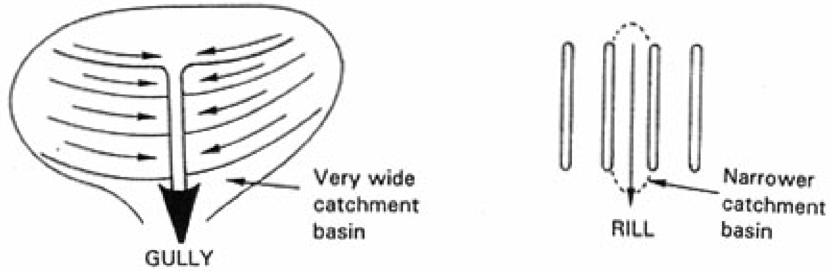
In Peru, depending on the season, the farmers may choose full tillage, ridging prior to sowing, ridging a considerable time after sowing, or tractor tillage (Figure 32). It has been seen that yields can be increased while reducing tillage time – and hence increasing the benefit for farmers. For tractor tillage, however, this obviously greatly increases the risk of degradation, for tillage has to follow the direction of the greatest slope if the tractor is not to overturn.

FIGURE 31
Direction of ridging in relation to slope

Gentle slope:	• tied ridging		P = 0.1	EROSION
	• contour ridging, slope up to	2 %	0.2	CONTROL
		8 %	0.3	PRACTICES
		16 %	0.4	EFFICIENCY
		25 %	0.6	RATE

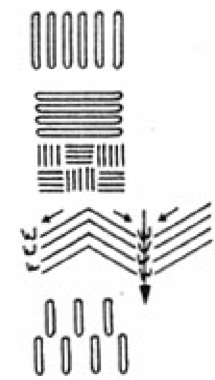
Steep slope > 25%, the effect of roughness on runoff quickly decreases,
due to the reduction in water storage capacity,
but risks of overspill and sliding increase

- during mild rainfall, erosion is less with contour ridging
- during heavy rainfall, there is a danger that runoff will spill over, causing a break: all the water held back by the ridge will then flow out at this point, forming a gully – which is much more difficult to eliminate than all the small rills that drain ridges set in the direction of the slope (smaller catchment basin).



▫ In PERU, at altitudes of 1 500 to 4 000 m, the farmers try to adapt their cropping methods to local conditions of season and climate: :

- if the season is:
  - late, ridging is partial
  - very wet, ridges are made parallel to the slope
  - very dry, or late ---------------- perpendicular to the slope
  - uncertain -------------------------------- patchwork-style
- if the slope is very steep and the soil poor, in a zig-zag arrangement



▫ In CAMEROON, in Bamiléké country, at between 1 000 and 2 000 m, the farmers make:

- large contour ridges on gentle slopes
- wide, short ridges on steep slopes, in the direction of the slope, or staggered

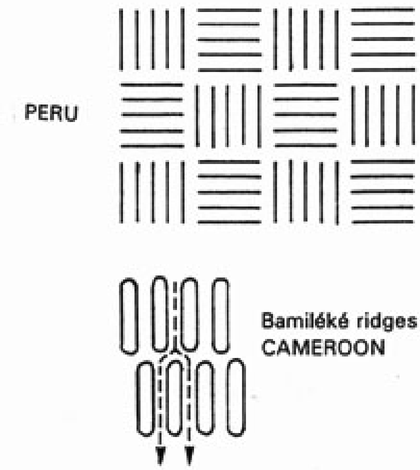
(effectiveness depends on the plant cover provided by mixed cropping)

IN CONCLUSION, giving advice on the orientation of ridges is a tricky matter!
On gentle slopes, ridging and tied mounding are very effective.
On steep slopes, depending on the greatest risks, there is a choice:

If draining is required	:	oblique ridges draining towards a grassed spillway
	:	well-covered, wide, short, staggered ridges
if landslides are likely	:	step microterraces or slanting ridges

Moreover, in dry years the farmers make their ridges perpendicular to the slope in order to store as much water as possible, whereas if it looks like a very wet year, they follow the direction of the greatest slope in order to facilitate drainage, and if the year looks uncertain, they make one square set perpendicular to the slope and the next in the direction of the slope, creating a patchwork of little plots that allows runoff to circulate slowly.

FIGURE 32
Direction of ridging in mountainous areas (Peru and Cameroon) as a function of rainfall risk



The C factor (influence of plant cover and cropping techniques in Wischmeier's equation)

In Wischmeier's equation, the C factor is the relationship between erosion measured on a bare fallow reference plot under a given crop. It expresses the interaction between the crop and cropping techniques and how this affects the reaction of a soil type to rainfall. The C factor changes as the plants grow and the state of the soil surface alters, and can be calculated for each of the main periods of the cropping cycle and the region under consideration: five periods are recognized in the United States, and up to nine in high-rainfall tropical areas with two cropping seasons. Taking account only of an annual overall measurement, the following figures have been obtained in West Africa (Roose 1973) (Table 29) and Tunisia (Table 30).

TABLE 29
Importance of plant cover and cropping techniques (C) for various crops in West Africa

	Annual average C	
	min.	max.
Bare soil		1
Forest, dense thicket, crop well-mulched		0.001
Savannah and pasture in good condition		0.01
Savannah, or burnt or overgrazed pasture		0.1
Slow-developing or late-planted plant cover, 1st year	0.3	0.8
Fast-developing or early-planted plant cover, 1st year	0.01	0.1
Slow-developing or late-planted plant cover, 2nd year	0.01	0.1
Maize, millet, sorghum (as a function of yields)	0.4	0.9
Intensively cropped upland rice	0.1	0.2
Cotton, second-cycle tobacco	0.5	0.7
Groundnut (in relation to yields and planting date)	0.4	0.8
Creeping cowpea		0.3
Cassava, 1st year, and yam (as a function of planting date)	0.2	0.8
Palm, rubber, coffee, cacao, with cover plants	0.001	0.3
Flat-planted pineapple (as a function of slope), planted early	0.001	0.3
- with burnt-off residue	0.2	0.5
- with dug-in residue	0.2	0.3
- with residue on the surface	0.001	0.01
Pineapple on tied ridges (7% slope), planted late		0.1

TABLE 30
Importance of plant cover (C) in Tunisia

	Average annual C
On bare soil bare fallow	1
Fruit trees	0.9
Winter wheat	0.7
Cereals in rotation	0.4
Forage crops	0.2
Cereals in rotation + forage crops	0.1 to 0.01
Improved pasture	0.01

CONCLUSIONS ON PLANT COVER AND CROPPING TECHNIQUES FOR DIFFERENT REGIONS

Whatever the slope gradient, the cropping techniques or the aggressiveness of the climate, full plant cover ensures a high level of soil and water conservation and has a greater influence than all the other factors. Plant architecture and botanical composition are fairly irrelevant, so long as cover is almost total. This means that biological methods encouraging such cover must have priority (to ensure water-saving, optimum productivity and soil conservation) over conventional erosion control measures (terracing), which are generally uneconomical and difficult to maintain, and often of dubious efficacity. If cover is not complete, the gradient of the slope exercises the next greatest influence on the amount of soil loss, but not necessarily on runoff, which is largely dependent on the hydrodynamic properties of the toposequence.

Mechanical cropping techniques can help reduce erosion risks in the short term. Tillage temporarily increases infiltration but also detachability and erodibility. However, it also has a positive effect on root establishment and speed of plant-growth – and in some regions on yields – so that it can in the final analysis reduce soil loss, at least in the case of certain soils. Nevertheless, a serious effort still has to be made to develop economically viable cropping techniques with reduced inputs that are truly suited to the crops and environmental conditions of high-rainfall tropical regions. **In the United States**, where farming has been very highly mechanized, efforts are now apparently being made to cut the number of passes of machinery across the land (minimum tillage or no-till) in order to conserve soil macrostructure.

In low-rainfall tropical regions (Charreau and Nicou 1971a, b), where there is a lack of water at the start of the season and soils are rich in fine sand and loam and poor in organic matter, and hence sensitive to rain splash, tillage seems helpful in order to allow good growth of the root system of crops. Hoeing and tied ridging can also improve water use and production.

In very high-rainfall tropical regions, mulching with crop residues could offer a tidy solution to erosion problems, but this still leaves the question of whether crops can take satisfactory root when hard rains heavily compact the soil – or alternatively what instrument would be best to turn mulched soil without disturbing it too much. Experiments in Brazil under high-rainfall tropical conditions on large-scale plantations of maize, soybean, rice and other cereals on ferralitic soil have shown that cover plants – generally deep-rooting pulses – can be combined with broadly spaced crops such as maize for on-site production of the plant cover needed to cover the soil and offset the rain splash factor, and also to increase organic matter and mesofauna activity in the surface horizon. The mesofauna, particularly earthworms, would thus be chiefly responsible for aerating the soil and perforating the megapores. This method has not been widely used in Africa to date, but is enjoying much success in the United States (Séguy *et al.* 1989).

The fundamental effect of plant cover and of the adaptation of cropping techniques to regional environmental conditions are subsumed under the C factor in the USLE model. Taking account only of an annual overall measurement, this factor varies from 0.9 to 0.1 for the main crops grown in West Africa. It can fall to 0.01 under a forest crop with cover plants and under grassland, and to 0.001 under a mulched crop and under forests of varying densities.

EROSION CONTROL STRATEGIES

Conventional erosion control generally recommends the application of erosion control structures and cropping techniques that have shown an ability to retain water and slow down erosion in some other place and under some other circumstances, so it is hardly surprising that most projects involving erosion control have met with failure over the past 50 years (Hudson 1990).

Here the effectiveness of erosion control practices and structures for surface water management, as well as the problems raised by certain production systems are briefly examined and analysed, and then an attempt is made to show how Wischmeier's empirical model can be put to practical use (Roose 1977a, 1987b and 1992b).

At the beginning of this work it was shown how governments have been led to approach erosion control from the off-site viewpoint, or that of **the general interest of their citizens**, focusing on protection of the quality of water (rural development strategies). Here, however, these problems are considered **from the on-site viewpoint**, in an effort to solve the farmer's problems of land degradation. Agricultural development strategies are discussed.

CAPITAL DEVELOPMENT STRATEGIES

In this perspective, the watershed is the natural physiographical unit for management, particularly erosion control, and the following procedure is adopted.

- First of all, **a map of land potential** is drawn up.

  The US Department of Agriculture (USDA) has defined eight categories of land on the basis of the constraints to large-scale farming.

  Classes 1 and 2 are slightly sloping (from 0 to 2%) and are fairly well drained. Such land is suitable for almost all crops without any special intervention, apart from drainage.

  Classes 3 to 6 cover arable slopes: the limitations on cropping increase in accordance with how shallow the soil is, to what extent pebbles and stones prevent mechanization, and how steep the slope is.

  Classes 7 and 8 must be kept under permanent plant cover, protective forests or extensive grassland. Cropping is not permitted.

  However, land potential must be classified in each individual case on the basis of local climate, landforms and soil. For example, in the semi-arid Sudano-Sahelian conditions of the Mossi Plateau, distinctions are traditionally made between (i) the steeply sloping ironstone or gravel top of the toposequence, which is reserved for animal husbandry and extensive rangelands, (ii) the broad, gently sloping pediment, which consists, first, of a shallow sandy area, limited in use, and, secondly, a clay-loam area on the lower part of the slope, which is where cropping will be concentrated, and (iii) the soil at the bottom of the slope, which is always to some extent hydromorphic.

Once the map of soil potential has been drawn up, **a map of present erosion risks and another of land use** are needed. When these 1:10 000 scale maps have been compared, **a map of intervention** and rural infrastructure for watershed management can be drawn up.

· **The permanent structures for this scheme are then decided.**

First comes the road network, the drainage network and the bridges to enable people to move around the catchment, particularly when transporting harvests. At this point an erosion control system can be decided, for example:

- gradual terraces defined by strips tilled downhill, based on grass buffer strips or banks;
- a system of beds developed by ICRISAT for vertisols on slopes of less than 2% (Pathak, Miranda and El-Swaïfy 1985);
- a system of level benches for areas where population pressure is strong;
- a system of stepped diversion terraces such as those found in North Africa, or a system of individual terraces for orchards.

· The last step is to plan **a production system** to take account of both environmental and human conditions (people's needs, economic viability of production, the local market and level of knowledge, and food self-sufficiency). Next come rotations and fertilizing and conditioning systems. Land to be set aside for forestry, used as pasture, and to be cropped must be identified, along with the areas to be irrigated or drained. A drainage system must then be planned, adequate outlets built, rivers and gullies stabilized, and the regional market and transport organized.

Within the framework of this strategy, the officially designated watershed manager will decide which areas are to be closed off and which are to be used as pasture for livestock, together with a whole set of conditions for production in the region.

AGRICULTURAL DEVELOPMENT STRATEGIES

In this approach to rural development, the expert will start by trying to meet the farmers' needs, a three-stage process.

· **The first stage is to establish dialogue with the local people and gain their confidence.** The expert will question the farmers to learn about the present land-use system and traditional production systems and to discover where, when and how environmental problems arise. He/she will then look for links between runoff and erosion problems and the local farming system, seeing how farmers perceive the problems and how they try to solve them. Lastly, he/she will work with them to find ways of increasing the infiltration of rainwater in order to increase biomass, yields, and the returns on the farmers' labour, as well as how to promote plant cover and thus reduce erosion risks. Once he/she has grasped the problems and observed the possible solutions already found by the farmers, he/she can propose more technical approaches for their consideration.

- **The second stage entails field trials on the farmers' own land**, where risks of runoff and erosion will be assessed for different types of rainfall. Various cropping techniques or erosion control structures will be compared, again on their land, so that the feasibility, effectiveness and economic viability of each element of a solution can be evaluated as precisely as possible. This stage will require between three and five years, ending with **an evaluation of results by both farmers and technicians**.

- **The third stage entails a land-use plan** no longer confined to individual farm units, but encompassing a slope, hillside or watershed, or the area occupied by a rural community. At this stage, the maps of potential land use, present damage and erosion risks, and current land use (a 1:10 000 scale aerial map) will be compared, and schemes acceptable to the farmers will be selected for each functional land segment starting with the cropped area, then the upper slopes, and lastly the valley bottoms.

This kind of land-use planning demands a more sophisticated approach to social and economic aspects: **the entire rural population must participate from the project design stage onwards** and be involved in the various phases of survey, demonstration and trial, and extension in the field. Observance of traditional water and fertility management methods will allow the methods best suited to the local environmental conditions and the socio-economic context of the local population.

Land husbandry is based on rational management of water and nutrients. Nutrient management **must** link fertilizer (organic and mineral) with erosion control. Water management must enable the available water to be used in such a way as to maximize soil productivity.

If a diagonal line is drawn through West Africa from the Sahara down to the subequatorial zone, four methods of water management can be distinguished, depending on climate and soil permeability. And each of these methods entails specific cropping techniques and erosion control structures.

EROSION CONTROL PRACTICES

This refers to cropping techniques used exclusively with a view to reducing runoff and erosion damage (Tables 31 and 33).

CONTOURING

This simply entails making sure that cropping techniques follow contour lines. Soil roughness (clods and small hollows) must be laid perpendicular to the slope, so that the eventual runoff sheet is slowed as much as possible. The method is effective only on gentle slopes: the P (or erosion control practices) factor will be 0.5 on slopes between 1 and 8%, 0.6 on 8 to 12% slopes, 0.8 on 17 to 20% slopes, and close to 1 on slopes steeper than 25% (Wischmeier and Smith 1978). In other words, the steeper the slope, the less soil roughness can hold back water. A variant consists of

TABLE 31

Cropping techniques and erosion control structures as a function of surface water management (cf. Roose, Ndayizigiyé and Sekayange 1992)

Water management methods	Structures	Cropping techniques
RUNOFF FARMING (water harvesting) Arid to semi-arid zone	Water harvesting, cistern Drain, bunds on wadis Discontinuous terraces	Tillage, basins Localized microcatchments Zaï
TOTAL INFILTRATION (absorption) Semi-arid (R < 400 mm) or humid zone on highly permeable soil	Blind ditches Radical terraces Bench terraces	Tillage + tied ridges Mulching
DIVERSION Semi-humid climate, very high-rainfall months, soil fairly impervious	Diversion ditches Algerian terraces Radical draining terraces	Ridges oblique or parallel to the slope
DISSIPATION OF RUNOFF ENERGY All climates, semi-pervious soils, slopes not too steep	Stone lines or walls Grass banks or lines Hedges	Agroforestry Cloddy ploughing Alternating crops/pasture Mulching

alternating crops in contour strips, thus combining the above effect with that of rotating crops with varying degrees of sensitivity to erosion.

CONTOUR RIDGING

It has been seen that tillage followed by ridging can increase erosion risks simply by increasing the slope. However, if the ridges are set perpendicular to the greatest slope, the furrows can hold a considerable amount of water containing suspended sandy or loamy solids. Contour ridging is twice as effective as simple contour tillage, reducing erosion to about 30% of that on the flat-tilled control plot for slopes of 1 to 8%. However, its effectiveness decreases as the slope increases, and on very steep slopes exceptionally heavy rain can cause breaks in ridges, thus giving rise to serious gullying or even landslides. This is all the more likely if the surface horizon is sandy and very permeable while the subsurface horizons are much less so. A first solution consists of setting the ridges at a slight slope, so that excess water can flow slowly – slowly enough to carry away very little solid matter – to a planned outlet (experiments by Hudson in Zimbabwe). Another solution is contour tied ridging, in which a series of pans and ties perpendicular to the ridges prevent the water behind the ridges from falling through a breach and creating a gully. Thirty to sixty millimetres of water will be trapped in the pans together with the heavier sediments, while the excess water can flow behind the ridges until it reaches designated outlets. To be effective, the ties must be 1 to 5 metres apart. The method has performed very well, reducing erosion to 10% of normal. Such methods are, however, suitable only for soils that are very permeable to a considerable depth.

On volcanic soil in Cameroon, the Bamiléké have developed an ingenious system of large, zigzag ridges set parallel to the slope and covered throughout the year by companion crops. This reduces the erosive force of runoff (Fotsing 1992b).

It is therefore difficult to advise on the orientation of ridges with a view to reducing erosion. **The decision will depend on interactions** between slope, cropping system and soil type. Only after local field trials can a decision be taken on the most effective and safest orientation for each cropping system.

BUFFER STRIPCROPPING

On slopes of less than 8%, erosion is thus cut to 30% of the control plot (P = 0.3). However, the effectiveness of buffer strips varies according to their width, the crop mixture, and the amount of concentrated runoff. While such strips are strikingly effective in the case of light to medium rainstorms, they can quickly become waterlogged under exceptional rainfall. They act as filters, slowing down the runoff flow, causing a fall in its competence – and hence the sedimentation of coarse sand and organic matter – and allowing its infiltration rate to rise. These filters are very effective when there is a mixture of pulses and grasses, and when the soil surface has a large number of stalks or roots per square metre (Roose and Bertrand [1971] in Côte d'Ivoire, and Delwaulle [1973] in Niger). In principle, ground-creeping plants with rhizomes and many scattered stalks are more effective than large tufts of grass. If the latter *is* used, a light mulch of cut tufts must be left on the soil-surface to prevent water from flowing between the tufts and digging channels. Live hedges staggered on alternate lines over a strip 50 to 100 cm wide act in a way similar to grassy strips, although they tend to be less effective, at least during the first years. In the semi-arid zones of Burkina Faso and even in southern Niger, when strips of *Andropogon gayanus* are sown on the edges of plots, or else about 20 metres from one another, a fair proportion of the sand carried off by wind erosion (Renard and Van den Beldt 1991) or water erosion (Roose and Rodriguez 1990) can be trapped. Erosion control strips have been tried out on erosion plots at Adiopodoumé and Bouaké in Côte d'Ivoire, and at Alokoto in Niger (Roose and Bertrand 1971, Delwaulle 1973), and it appears that once 0.5- to 4-metre strips of thick grass are established, they can reduce soil loss to one-tenth and runoff to about one-third compared to the control plot. The more aggressive the climate, the steeper the slope, the less crop cover there is and the more erosion-prone the soil, the wider the strips must be to ensure effectiveness. In any case, it is best to start with strips at least 5 metres wide, for they can always be narrowed later.

Any leafy plants provide good cover on erosion control strips, particularly natural fallow plants, but the presence of pulses with tap-roots and large, deep-rooting perennial grasses improves infiltration. In tropical areas, *Andropogon gayanus*, *Pennisetum purpureum*, *Paspalum notatum*, *Tripsacum laxum*, a mixture of various *Stilosanthes*, sugar cane and various forage plants can be used. *Setaria sphacelata* gives good results for the first two years, but is quickly exhausted on poor, acid soils.

However, plants whose seeds spread too easily into the fields should be avoided (unless the erosion control strips are mown before the plants flower). Spreading by suckers, runners or stolons (*Synodon dactylon*) is even worse. Plants with tightly packed roots and numerous stalks will slow runoff more effectively than free-standing trees.

Some experts have warmly recommended various vetivers, because they survive well in semi-arid regions where overgrazing is frequent. They produce siliceous, long-lasting mulch, but their forage quality is poor. The problem is that the strip has to be destroyed in order to extract the essence from their roots. Wherever possible, therefore, it is better to use forage plants and grasses that are suited to local conditions.

The buffer strip acts as a sponge, partially absorbing runoff waters, and also as a comb, slowing down runoff so it will deposit soil from the cropped field above. The runoff water infiltrates deeply or is at least slowed down, reducing its competence, so that it deposits the coarsest eroded sediments. This in turn maintains good porosity and leads to the formation of a small terrace at the rate of 5 to 20 cm per year, which as time passes transforms landscapes into a succession of gently sloping fields and banks protected by leafy growth.

This inexpensive method has been tested extensively and successfully on research stations, industrial plantations (rubber and pineapple) and modernized small-scale farms. It has some very decided advantages:

- it is easy and inexpensive for small farmers to launch;
- large areas can be treated fast without the costly, cumbersome intervention of surveying teams: after a one-day course in use of the water-tube level, most farmers are able to mark out the contours on their land;
- forage produced on the strips can be used to feed stock or to mulch the fields;
- this living network along contour lines can act as a reference for the orientation of cropping procedures;
- the land used to make buffer strips is not immobilized since they are also productive. Farmers who have no cows can be dissuaded from setting fire to the strips to destroy insects and other pests by planting trees – either fruit species, or trees that can produce kindling and posts – in the centre of the strips or on their lower side. The main problem with this method is to clearly and definitively separate the grass strips and the surrounding fields and fallow land. Particularly in arid zones, where it is hard to establish grass because of overgrazing, if rock débris is available this erosion control measure can be reinforced by arranging unbroken lines of stones inside the strips (Delwaulle 1973, Roose and Bertrand 1971, Roose and Rodriguez 1990). This combines contour cropping and buffer stripcropping, cutting the length of the slope and gradually reducing the gradient through the natural formation of grass banks. Such methods are already widely used in mountainous countries and are now being tested in semi-arid zones in Mali, Burkina Faso and Cameroon. They have been used for centuries in Europe, the Americas and Asia, where banks are protected by grass and bushes that can be as tall as 2 to 4 metres. The buffer strips develop spontaneously into banks, which act as boundaries between plots.

In the Sudano-Sahelian zone of southern Mali, the DRSPR suggested that grass strips 3 metres wide should be planted across cultivated fields at 50-metre intervals (thus covering 6% of the land). Six perennial species were compared in 1987/88. *Brachiaria ruzizensis* quickly covers the land even in the first year, but *Stylosanthes hamata* grows better in the second year. *Andropogon gaianus* is popular, although establishment need to be worked on. *Macroptilium lathyroides* and *atropurpureum*, *Clitoria ternatea* and *Pennisetum pedicellatum* proved disappointing. At present, the DRSPR is advising a mixture of *Brachiaria* and *Stylosanthes*. Some farmers toss the *Brachiaria* hay and mix it with molasses as feed for livestock.

At Yatenga (400 to 700 mm of rainfall), located north-east of this same zone but in Burkina Faso, Rodriguez has developed a method to be used by small farmers for harvesting *Andropogon* sp. and *Pennisetum pedicellatum* seeds in December. At the start of the rainy season in June, the seeds are pounded with damp sand to abrade them, then moistened for 12 hours. They are sown on a 50-cm-wide, shallow-tilled strip uphill of lines of stones, or between two plough furrows, every 20 to 25 metres. Farmers like these *Andropogon* hedges, not only because they help to control sheet runoff, but also because they produce the long straw needed for roofs and artisanal crafts; they also provide excellent forage, and livestock particularly appreciate their green shoots in the dry season: even where tufts of *Andropogon* grow in a cropped field, they are not hoed (Roose and Rodriguez 1990).

NATURAL OR ARTIFICIAL MULCHING

The aggressive rainfall plus the permeability and natural resistance of ferralitic soils to water erosion make the main problem in these high-rainfall tropical zones finding a way to cover the ground during the critical period of hard rains, thus preventing destruction of the structure of the surface horizon, the formation of slaking crusts and the start of runoff. Natural conditions are such that most food crops (particularly, cassava, yam, maize and groundnut) and certain industrial crops (banana, pineapple, etc.) are incapable of covering the soil sufficiently before the critical period. **A light mulch, as a temporary supplement to plant cover,** may be composed of crop residues or other inputs, or a soil conditioner such as Curasol may be used to create a flexible crust to protect the surface. A dead cover (straw mulch or a layer of pebbles) can be a satisfactory substitute for living cover in conserving water and protecting soil; for example, a plot covered with a few centimetres of straw (4 to 6 t/ha) protects the soil as well as a covered, 30-metre secondary forest, even in years with very heavy rainfall (Table 13). A method widespread among market gardeners, mulching is very effective in helping infiltration of rainwater, reducing runoff and evaporation, and protecting the soil against erosion. It deserves extension in traditionally farmed areas where fields are always surrounded by quantities of available brushwood.

The situation can be different under semi-arid conditions, particularly Sudano-Sahelian zones that are overgrazed during the dry season so that soils are practically bare at the start of the rainy season. In these regions, the problem is finding mulch. Although the mulching method is widely known, it tends to be confined to fertilizing the fields of the poorest farmers who have neither livestock nor manure.

In this case, the farmers go into the bushland, collecting the branches of shrubs (*Bauhinia* and *Piliostigma*) and pulses that the livestock tend not to eat, and spread them over their small fields, partly to reduce runoff and partly to encourage the activity of termites, which will open up infiltration passages into the soil and redistribute the fertile elements in the mulch. Collinet and Valentin (1984), using simulated rain, have also shown that mulching can slow down the reduction in infiltration capacity following cropping. However, when soils are fairly impervious, sandy or poor in organic matter, **they can rapidly become degraded under mulching, simply through the wetting and drying out of the soil surface**. Effectiveness is therefore dependent on soil texture and capacity to resist degradation through simple wetting or through clay dispersion when the cation exchange capacity is rich in sodium. In tropical mountains, notably in Rwanda and Burundi, coffee fields that have been mulched for 40 years have suffered no erosion. This shows how effective mulching can be, both in maintaining soil fertility and infiltration capacity, and also in protecting from erosion. The problem is that of collecting enough biomass throughout the year to keep several centimetres of mulch on the surface of the soil. In the beginning, mulching under coffee trees had two purposes: the soil was kept moist and fresh under the trees at the end of the rainy season by providing a covering of 10 to 15 cm of straw, and the soil surface was protected against erosion during the rainy season by a thin (2 to 5 cm) layer of straw. On small farms of about one hectare on steep slopes, it proved difficult in these mountainous areas to produce enough biomass to cover the whole surface, especially when this biomass is needed mainly to feed livestock in order to produce milk, meat and manure. It seems that if the existing banks are transformed into productive sloping banks, covered partly with leafy plants and partly with a double hedge of shrubby pulses (*Leucaena leucocephala*, *Calliandra calothyrsus*, etc.), and if trees are planted every 5 metres along the lower side of the bank, this will allow production of sufficient biomass to cover the soil surface, at least after preparation of the seed bed and after sowing, by cutting the hedges and spreading the prunings on the ground. The twigs can then be collected again some months later and used as fuel for cooking. This method is now being tested in Rwanda (Ndayizigiyé 1992) and Burundi. Crop residues can be another source of mulch (ISAR).

In the case of industrial crops, it may be hard to obtain enough green matter to make mulching economical. However, as many crop residues as possible can be left on the surface of the soil in order to protect it between two crops and even during the following cropping cycle. There are various versions of this stubble mulching technique, and although it is very popular in the United States, it does require special equipment to aërate the soil without turning it or disturbing the mulch.

Lal (1975) simply suggests pushing crop residues into the space between planting lines and restricting preparatory harrowing to the sowing line. On plots prepared in this way at the IITA Centre at Ibadan in Nigeria, he showed that infiltration speed remains maximal under crop residues laid on the surface – thanks to the activity of earthworms – and that runoff and erosion remain slight whatever the slope, whereas soil losses increase exponentially with the slope on neighbouring tilled plots. An ORSTOM and IRFA experiment at Adiopodoumé clearly shows the role of crop residues in pineapple plantations, and that of tillage in water management as a function of slope. During the first planting cycle, with about 2 000 mm of rainfall, the average erosion on three slopes (4, 7 and 20%) was 197 t/ha on bare soil. Under pineapple, flat-planted in lines perpendicular to the slope, with the previous crop residues burned and turned in, erosion was under 25 t/ha. With similar treatment but with the residues simply dug in without burning, erosion was lower by half (12 t/ha). Lastly, when the residues were left on the surface, plant cover was total, and erosion negligible (0.4 t/ha, or 1% of that on bare soil, and less than 2% of that under pineapple when residues were burned and dug in). Similarly, runoff averaged 36% on bare soil, 6% under pineapple cover, 2% when residues were dug in, and 0.6% when residues were left on the surface. Moreover, no significant increase in runoff was observed under mulching when the slope increased from 4 to 22%. The main conclusion is that when crop residues are spread on the soil surface, the risk of erosion on the steeper slopes is reduced to the point where strict contour cropping could be abandoned, which would make it much easier to mechanize farming (Valentin and Roose 1982).

Lastly, ploughing organic matter into the soil can improve structural stability and resistance to rainfall impact. According to Wischmeier's nomograph, a 1% increase in organic matter in the surface horizon means that soil losses can be reduced by 5% for loamy soils due to improved structure and by 3% for clayey or sandy soils. However, this means digging considerable amounts of organic matter into the soil, for in humid tropical regions, most organic matter vanishes quickly, with less than 5% remaining in the soil as stabilized humus. On the other hand, if the same amount of matter is spread over the surface, it will act as a mulch and reduce soil loss by 60 to 99%. It therefore seems that managing the biomass on the soil surface not only considerably reduces losses through runoff and erosion, but also recycles nutrients through the gradual uptake by plants throughout the rainy season. Field observations under both humid tropical conditions (Adiopodoumé) and semi-arid conditions (Saria in Burkina Faso) show that crop residues can cover the soil surface for three to five months – the time needed for the crop to provide more than 80% cover – which is generally enough to reduce erosion to a tolerable level.

ARTIFICIAL MULCHING: SPRAYED "CURASOL"

Mulching methods and their variants generally have technical or economic drawbacks (risks of plant disease, insect-damage and weed infestation in the first case, and 250 to 300 days' work to collect the mulch in the second) which tend to be unacceptable in large-scale industrial farming. Hence the idea of testing an artificial mulch easy to apply with spraying equipment already found on a good many mechanized farms. An acetate of polyvinyl (sold under the name Curasol by the Hoechst company) was tested. At Adiopodoumé this product was sprayed on immediately after tillage, levelling and planting, in a single dose of 60 grams of Curasol diluted in 1 litre of water per square metre of soil. After some hours of exposure to the sun, this sticky, milky product forms a flexible 1-mm-thick film which protects the soil against the kinetic energy of falling raindrops (Roose 1975; 1977a). The treatment was tested for four years on three pairs of plots:

- a 7% slope planted to *Panicum maximum* at 40 x 40 cm intervals;
- a 7% bare slope;
- a 20% bare slope.

Table 32 shows that Curasol considerably reduced soil loss (a reduction of 40 to 75%), and to a lesser extent runoff (a reduction of 20 to 55%). Although its protective effect decreased after three months of violent rain (1 200 mm), it was still functional after one year. It had no significant effect on forage yields (*Panicum*) but was extremely effective against erosion under this plant cover.

It was not a foregone conclusion that use of this plastic glue might reduce runoff, for it could in fact have blocked the soil pores. On-site observation shows that when it is sprayed on to a well-aërated (recently tilled) soil it forms a flexible film which slightly increases runoff in comparison with the control plot for a number of rainstorms, but that after this the porosity of the untreated plot decreases faster than that of the protected plot, tipping the balance in favour of Curasol. The product does not form a unbroken, impermeable film, but coats soil surface aggregates, boosting their resistance to the onslaught of falling rain.

Curasol always allows a certain amount of erosion. Since protection is not uniform and unbroken, water discovers weak spots in the film, and raindrop energy digs holes into which runoff rushes, undermining the base of the microcliffs thus formed and broadening the areas attacked by headward erosion. This means that if there is a plant cover protecting the flexible plastic film against rainfall energy, the Curasol film lasts longer. It should also be noted that the plastic film will not stand up either to the abrasion of grains of sand carried in an active rill or to the passage of heavy machinery (tractors, etc.) and workers, for erosion sets in very fast at broken points.

TABLE 32

Erosion (t/ha) and runoff control (KR %) of plastic mulch on bare soil under *Panicum* (cf. Roose 1975; 1977a)

ADIOPODOUME 1970-1974			EROSION (t/ha and % of control)						RUNOFF (mm, % and % of control)					
	Rainfall		*Panicum*, P = 7%		Bare soil, P = 7%		Bare soil, P = 20%		*Panicum*, P = 7%		Bare soil, P = 7%		Bare soil, P = 20%	
	(mm)	R_{USA}	Control t/ha	Curasol % of control	Control t/ha	Curasol % of control	Control t/ha	Curasol % of control	Control mm and % of rain	Curasol % of control	Control mm and % of rain	Curasol % of control	Control mm and % of rain	Curasol % of control
5.70 to 3.71	1389	1057	89.2	25	150	50	532	27	368 mm 26.5 %	37	575 mm 41.4 %	56	423 mm 30.4 %	40
4.71 to 3.72	1816	1023	4.1	30	139	55	618	59	190 mm 10.5 %	77	562 mm 31 %	105	286 mm 15.8 %	49
4.72 to 3.73	1562	819	1.2	10	114	50	273	57	106 mm 6.8%	16	593 mm 36.3 %	66	363 mm 23.2 %	55
4.73 to 4.74	1887	1165	15.0	34	191	71	626	40	146 mm 7.7%	34	942 mm 49.9 %	70	425 mm 22.5 %	91
Average	1664	1016	27.4	26	149.4	58	512.3	45	203 mm	43	668 mm	73	374 mm	79

P = erosion control practices efficiency rate.

Runoff recorded on the control plots is given in two forms:

- depth of runoff sheet in mm
- runoff coefficient as % of depth of rainfall

Although very effective on these sandy soils, treatment with Curasol was unable to bring erosion on bare soil down to under 10 tonnes, the tolerance level on this type of soil. Its cost price (4 000 FF/ha in 1973 for an average dose of 60 g/l/m^2) and the large amount of water taken to apply it (10 m^3/ha) are major drawbacks to its widespread use even in intensive farming. However, Curasol can play a very effective role in fixing road embankments, irrigation channels and scoured surfaces in urban or industrial areas if applied in combination with certain grass seeds and the fertilizer needed for the latter to grow.

By way of comparison, in Côte d'Ivoire it takes 250 days' work to collect 40 to 80 t/ha of brushwood in the bush and spread it on the fields, equal to 4 000 FF in 1990. If a field of Guatemala grass (*Tripsacum laxum*) is available, it takes only 150 days to obtain a thick mulch. Tests have shown that 4 to 6 tonnes of dry straw are enough to obtain satisfactory protection against erosion (Lal 1975), so that the cost price of this technique could be cut still further. The protective value of the various forms of mulching has been shown time and time again and never disproven. If its use is still limited, this is because its applicability in tropical conditions on different soils and in various social contexts has yet to be proven (problems with herbicides and phytosanitary products). Implements capable of aerating the soil without disturbing the mulch also must still be developed, as must no-till cropping systems of proven long-term economic viability.

COVER PLANTS

Since the main difficulty connected with mulching is that of producing and transporting biomass to the field once the soil has been prepared and planted, the obvious answer was to try to produce this biomass on the spot. Experiments with a crop of deep-rooting pulses sown as catch crops under maize or some other cereal have therefore been carried out, first in Brazil twenty years ago (Séguy *et al.* 1989), then in Nigeria (IITA Station, Ibadan). While the main crop grows and makes use of the top layers of soil, it slows down the growth of the pulse, which, while awaiting better light, sends tap-roots deep under the area, and gradually forms a carpet of leaves and stalks in varying states of decomposition. After the main crop has been harvested, space and light allow the pulse to grow fast during the few weeks when there is still enough water in the soil under the area used by the main crop. During the dry season, the soil is therefore covered by a carpet, fostering mesofauna activity – earthworms in humid tropical areas, and termites in semi-arid areas or on too-sandy soil. At the start of the following cropping season, either the dry season has killed off all the pulses, leaving dead cover, or there has been enough water to keep them alive or to give rise to a new living cover from the seeds dropped by the pulses. In the latter case, either the pulses are killed off with a herbicide (3 l/ha of Gramoxone), taking advantage of this to kill off any other weeds that may have developed, or else they are left to grow, but then cut back before the following crop cycle begins. Instead of being ploughed in to prepare the ground for the following crop, this litter is separated by a toothed disc and the soil is broken up with a pronged implement, with the basic fertilizer and seeds being injected behind it. The soil is swept back over the sowing line, and a small roller presses it down to assure good contact between soil moisture and seeds. In this system, less than 10% of the soil moisture is bare, loosened and vulnerable to erosion. Experience shows that the soil surface is not degraded, the sand remains bound to the organic matter, and there is very little risk of erosion and runoff. The method also offers a certain number of other advantages: first and foremost, as in the original forest environment, it makes it possible to restore the organic matter and return a certain number of nutrients to the surface so that they can then be redistributed in the soil during the course of the rainy season. It is a neat technique, reducing

TABLE 33

The "erosion control practices factor" P in Wischmeier and Smith's equation for forecasting sheet erosion

United States (cf. Wischmeier and Smith 1978)		Maximum length	P
- Contour tillage	1 to 8%	122 to 61 metres	0.5
	9 to 12%	36 m	0.6
	13 to 16%	24 m	0.7
	17 to 20%	18 m	0.8
	21 to 25%	15 m	0.9
- Contour ridging = contour tillage x 0.5			idem x 0.5
- Contour tillage between grass strips			
	1 to 8%	40 to 30 m	0.25 → 0.50
	9 to 16%	24 m	0.30 → 0.60
	17 to 25%	15 m	0.40 → 0.90

West Africa (cf. Roose 1977b)	
- tied contour ridging	0.2 to 0.1
- erosion control strips 2 to 4 m wide	0.3 to 0.1
- straw mulch, over 6 t/ha	0.01
- Curasol mulch, 60 g/l/m^2 (depending on slope and crop)	0.5 to 0.2
- temporary pasture or cover plant (depending on cover)	0.5 to 0.01
- low earth bunds protected by stones or rows of perennial grass or low dry stone walls every 80 cm + contour tillage + hoeing + fertilization	0.1 to 0.05

Sierra Leone	time needed for 100 m	for rice E t/ha/yr	for rice P	for beans E t/ha/yr	for beans P
- horizontal bench	808 hours	7.5	0.14	-	-
- stone bund	31	29.5	0.5	4.4	0.1
- row of stakes	30	27.3	0.5	27.3	0.5
- contour bund	19	17.9	0.3	16.8	0.3
- no method	-	41 to 55	1	11 to 55	1

inputs, fertilizers and cropping operations while protecting the soil against the onslaught of rain and erosion. Eliminating runoff can perhaps allow water to be supplied to both crops, and hence reduce the competition between them. The system can be compared to the old method of green manuring, which consisted of introducing a crop when the fallow time came, and ploughing it in before the end of the rainy season. Part of this crop could be used by leaving the cover plant on the soil surface in the form of litter. The use of cover plants, particularly pulses, is well known and very widespread under industrial tree crops such as palm, coconut, rubber, coffee and cacao. It seems that a form of this system could be developed for use under temporary root and tuber crops. Lastly, a more stable system could be found than the intensive systems which call for so many inputs in the form of mineral fertilizers and tillage.

THE P FACTOR IN WISCHMEIER'S EQUATION

The "erosion control practices factor" (P) is the relation between soil loss on a treated field and that on a neighbouring, untreated plot of similar size, or a control plot. Small erosion plots (100 to 200 m^2) are generally ill-suited to the study of erosion control practices, and comparisons should be made on small catchments of about one hectare. Therefore here only a comparison is given of results in North and West Africa with the coefficients advocated in the United States after many trials carried out on small catchments (Wischmeier, Smith and Uhland 1958, Roose and Bertrand 1971, Roose 1973, Delwaulle 1973).

Erosion control techniques to divert or totally absorb water are not found in Table 33, since these are encompassed in the topographical factor, in which the length of slope is reduced to the breadth of cropped strips between two banks. In any case, very few studies have scientifically demonstrated a reduction in soil loss from catchment areas after treatment with terracing, for most of them do not differentiate between the effects of terracing and those of the consequent improvement in plant cover on the same catchment (Roose 1974, Goujon and Bailly 1974).

Table 33 clearly shows that biological techniques (maximum soil cover, use of fertilizer, correct tillage, mulching, cover plants, rotations, etc.) are much more effective than mechanical techniques (terracing, ridging, etc.), which are expensive to install and difficult to maintain. Despite this, mechanical techniques receive much fuller treatment in soil conservation manuals, and are advocated more often than not without prior adaptation studies (Roose 1971; 1973; 1974; 1977b). Nevertheless, it should be noted that the drier the area and the more difficult it is to implement biological methods, the more one should use mechanical methods to help the plants to become established and cover the ground as quickly as possible.

EROSION CONTROL STRUCTURES AS RELATED TO WATER MANAGEMENT METHODS

[Plates 26 and 27]

There are bound to be rainstorms whose water the soil cannot fully absorb – a point of major importance in arid and semi-arid areas, for this water can be collected and used to improve productivity locally. The following **four water management methods** and erosion control structures apply:

- runoff harvesting (catching runoff for supplementary irrigation);
- total absorption or infiltration;
- runoff diversion (redirecting excess water);
- runoff spreading (distribution of runoff energy).

STRUCTURES FOR RUNOFF HARVESTING

In semi-arid countries where rainfall is too sparse to allow crops to be grown on the whole slope, part is used to favour runoff, which is then retrieved lower down to irrigate smaller areas, make up for any lack in rainfall, and enhance crop security (Hudson 1990).

In their work on runoff harvesting to improve crop production, Reij, Mulder and Begeman (1988) classify the available techniques as follows:

FIGURE 33
***Tabias* and spillways**

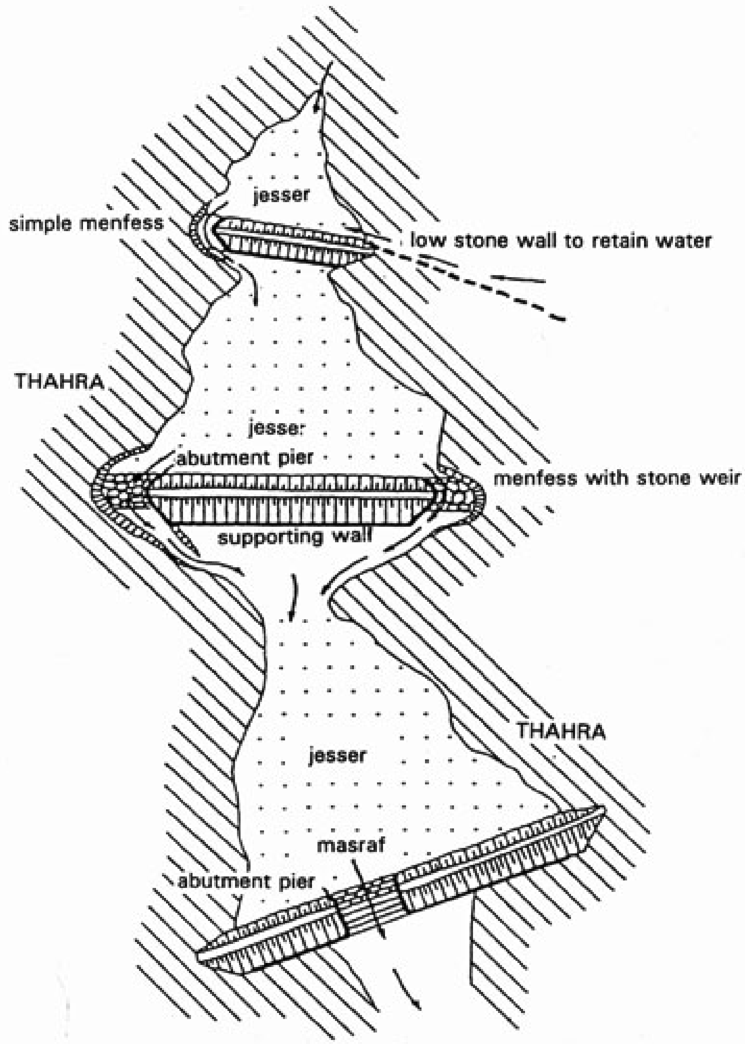


FIGURE 34
Cross-section of a *tabia* and its *jesser* (cf. Bonvallot 1986)

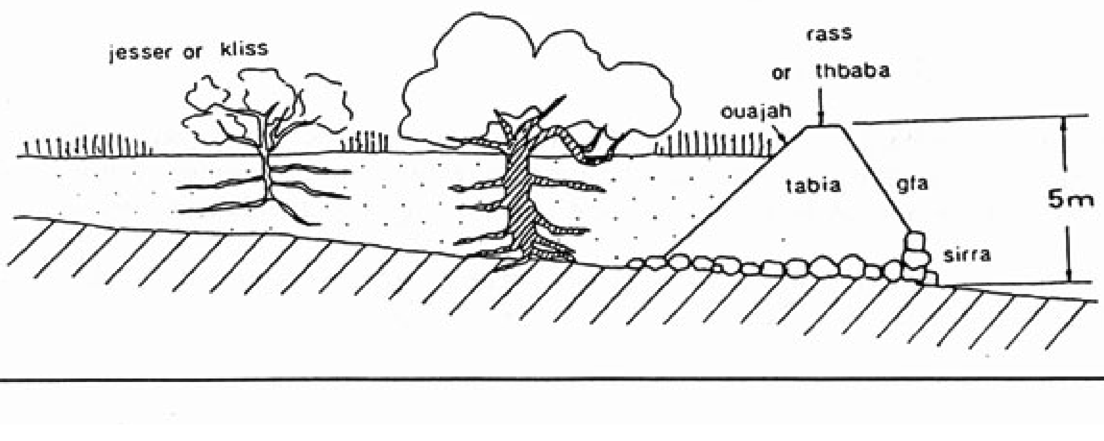
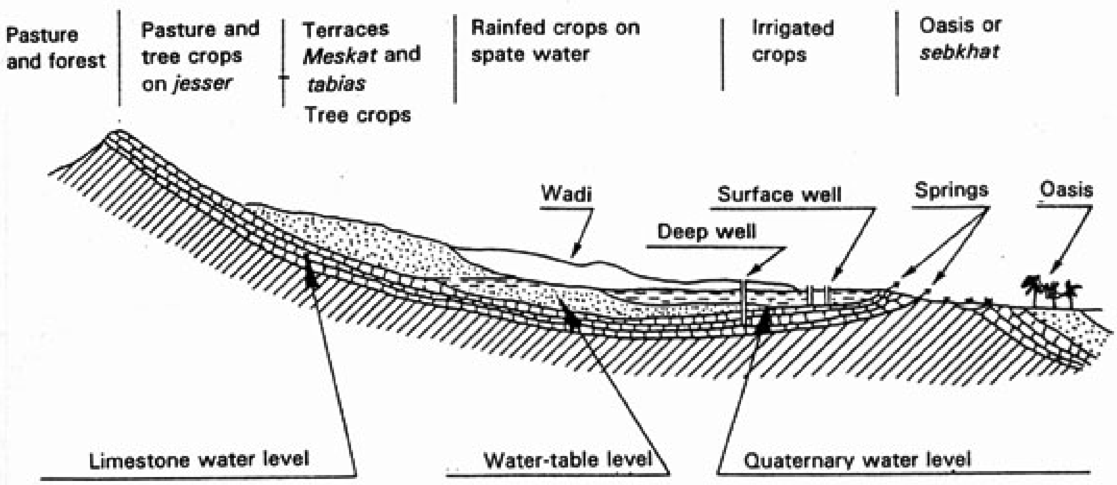


FIGURE 35

Rural land-use planning in the Maghreb as a function of hydrogeological factors (cf. Gosselin 1939)



- short-distance water harvesting: microcatchments, half-moons;
- harvesting water at the bottom of a long slope: earth bunds, *boulis*, trapezoidal bunds, in Turkana in Kenya;
- harvesting river-water from its bed;
- diversion of wadi flows;
- dam with reservoir cropping after absorption.

In Tunisia, Gosselin (1939) studied rural land use planning from the hydrogeological perspective (El Amani 1983). In the upper watershed, he distinguishes *tabias*, trapezoidal earth bunds, reinforced below with a stone wall and on the sides with a stone-lined spillway. Some 2 to 5 metres high, they bar a valley several dozen metres wide. A *tabia* acts as a path, behind which runoff water and loamy-sandy silt collects, bounding a *jessour* – a kind of well-watered field where annual crops (barley, peas, lentils, beans, water melons) are grown in the shade of trees suited to the successive silt deposits (fig, olive, pomegranate, almond) (Figures 33 and 34).

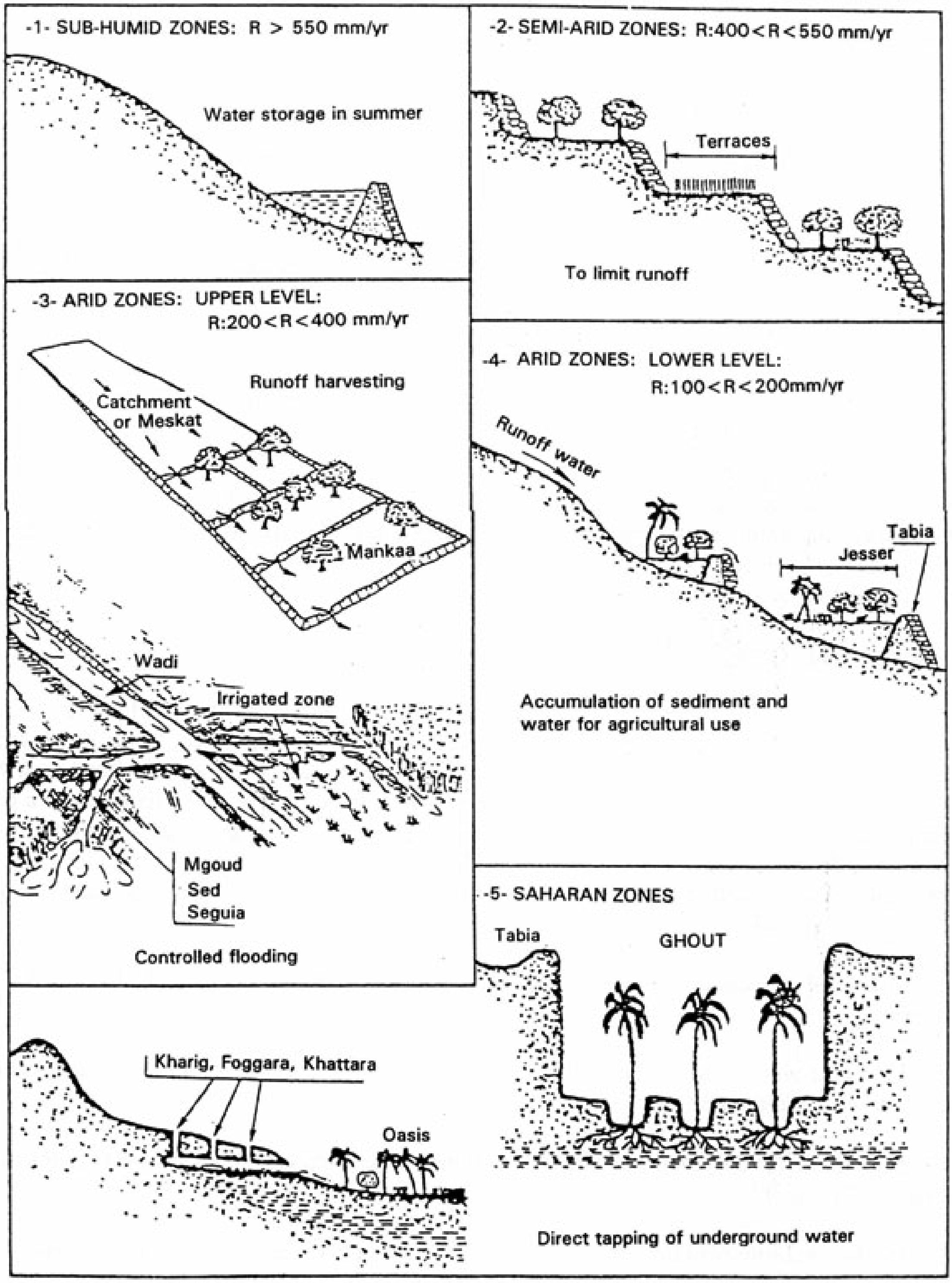
Terraces or *meskats* are engineered on the slopes, irrigated by channels that catch slope runoff.

Lastly, a whole series of structures in the valley allows flood spate or groundwater to be harnessed (Figures 35 and 36).

El Amani (1983) then classified traditional water management systems in terms of climate (Figure 36).

In the Sudano-Sahelian region of West Africa, most soils have a surface crust. This gives rise to particularly harmful surface runoff in these semi-arid climates, selectively carrying away organic matter and nutrients from the surface horizons.

FIGURE 36
Classification of traditional water management systems by climate (cf. El Amani 1983)



A whole series of traditional soil fertility and water conservation techniques can be seen in these areas in which both the water balance and the ethnic make-up vary greatly.

Many such methods are seen in operation on the broad pediments below rocky or lateritic hills used as extensive rangeland for livestock, so that these rangelands act to harvest the abundant runoff.

The Zaï method

This is a complex traditional method allowing recovery of degraded soils on broad, loamy-sandy pediments. It combines harvesting runoff with concentrating manure and available water in pans, making use of termite activity. There are many variants, including forest zaï which is particularly suitable for introducing agroforestry into a Sudano-Sahelian area (Figure 5).

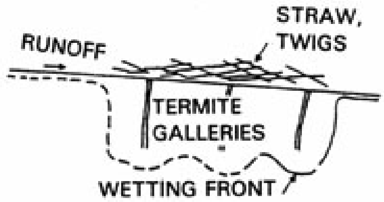
Half-moons (Figure 37)

On broad, loamy pediments which degrade very fast once the natural plant cover disappears, runoff from 10 to 20 m^2 can be harvested by arranging half-moon shaped bunds, 2 to 6 metres in diameter, on which cereals or trees are grown. At Ouramiza in Niger, the 20-cm-deep half-moon has a cropped area of 6 m^2 for a reception area of 16 m^2 (2-m-wide semi-circles are set 4 metres apart along a contour line and 4 metres from the next contour line and there are 313 half-moons per hectare, for an estimated cost of 900 FF = 80 work-days/ha). Pans 3 x 0.6 x 0.6 m (1 m^3) can also be dug to drain 10 m^2: one or two trees are planted at the low point (FAO Keita Valley project). There is a serious risk of clogging in these microcatchments in the case of millet and certain trees because of the suspended load in the runoff, which quickly forms fairly impermeable crusts. The use of straw or branches would allow wind-blown sand to be trapped in order to maintain a good infiltration capacity -and the localized use of manure could also help.

Cisterns or boulis (Figures 37, 38 and 41)

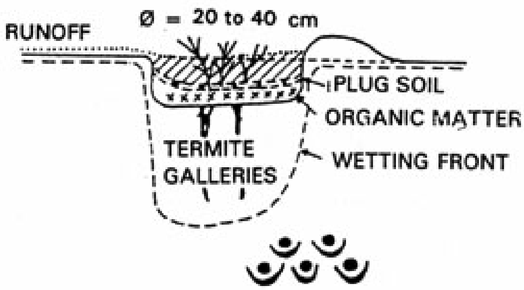
Cisterns or *boulis* are dug out of the broad pediment where rangeland (gravel pediment) meets cropped land (loamy pediment). Some Mossi farmers have progressively dug out water holes, cisterns or *boulis* 1 to 2 metres deep, using the soil removed to build a crescent-shaped bund extending over a hundred metres or so. When the first rains come, they give farmers 100 to 500 m^3 of runoff water with a fairly heavy washload. The water can be used either to irrigate a small garden, which can produce two well-manured, furrow-irrigated crops of lean-season maize and late watermelons, or stock-watering so that the animals, not having to migrate to a watering point in the valley, will lose less weight at the end of the dry season. This system improves food security, especially in the lean season, but it does require a great deal of work, which can, however, be done gradually over several dry seasons with the help of a team of neighbours. The necessary labour could also be reduced by locating the *boulis* at the top of a gully where a great deal of runoff is concentrated before acquiring much solid matter in suspension. The latter approach would also solve the problem of treating gullies, which could become stabilized below the *boulis* through the simple reduction in peak flows. There are now hand pumps (e.g. ETSHER 2000 at Ouagadougou) capable of raising 10 m^3 of water/day 1 metre in height.

FIGURE 37
Harvesting and storing runoff from a semi-arid catchment (cf. Roose 1989)



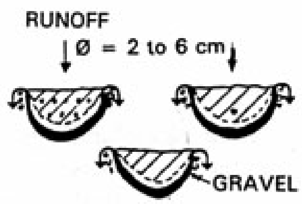
Mulch (grass + twigs)

- termites will eat the organic matter
  - dig galleries
  - encourage penetration of runoff
  - distribute nutrients
- improves infiltration and manure



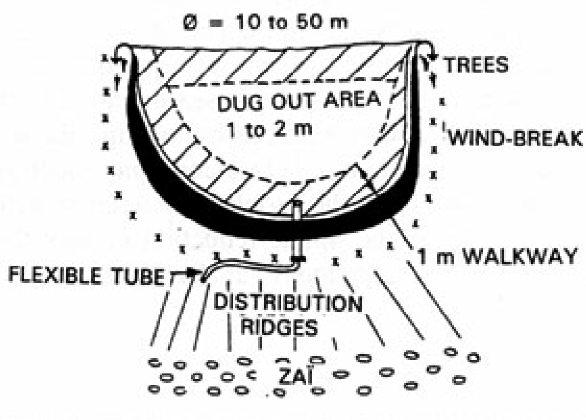
Zaï (pitting + manure + termites)

- pit 20-40 cm Ø, 10-15 cm deep, earth on downside in a crescent
  → runoff harvested on basin 3/1
- water concentration + OM + nutrients
  → yields > 800 kg/ha on exhausted soil
- action + + of termites on infiltration. The tunnels protect infiltrated water deom direct evapotranspiration



Half-moons (micro-catchment 1/5 to 1/10)

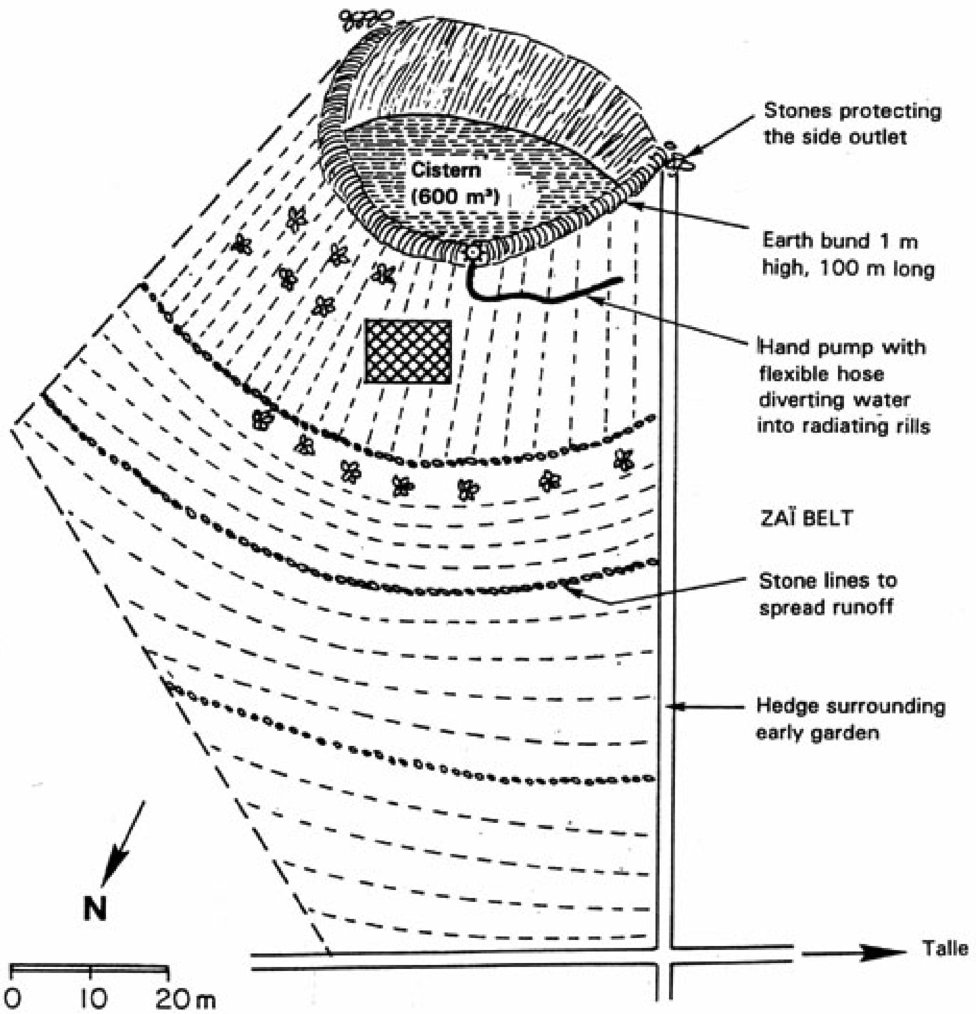
- runoff harvested on 10 to 20 m^2 on loamy pediments in order to irrigate:
  - cereals or
  - 1 or 2 trees
- the ends of the bunds are protected by three stones to prevent erosion during overflows



Boulis = a cistern dug at the foot of a pediment on the edge of rangeland

- bund built with earth gradually extracted from the centre of the crescent
- fine sediment carried down by runoff clogs the bottom of the cistern
- 3 objectives:
  - watering cattle (filtered)
  - supplementary irrigation of an early-season garden (1 000 m^2)
  - fine sediment can be recovered
  → bricks or organic soil

FIGURE 38
Cistern and plot used to test contingency irrigation of a garden (cf. Dugue 1986)



Scale 1 : 1 000

Area: 0.64 ha

Legend:

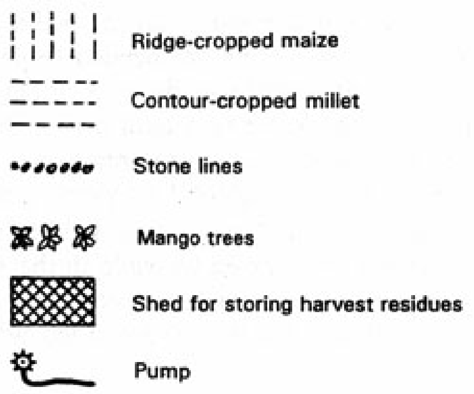
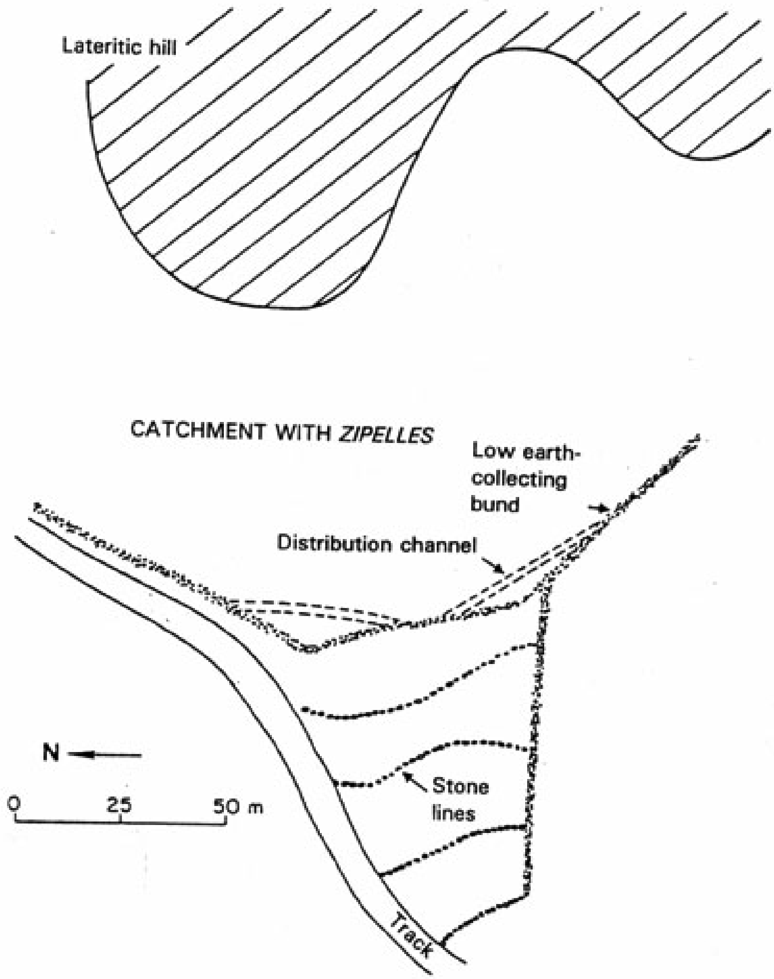


FIGURE 39
Water harvesting: experimental site at Bossomboré (Ziga, near Ouahigouya, Burkina Faso) (cf. Bedu 1986)

The catchment field ratio should be reduced to <3.



A number of risks must be taken into account. Erosion on the pediment above the *boulis* could progressively fill in the pool, and so measures are needed to keep the soil in place (lines of stones, grass strips) without reducing runoff too much. Another solution is to recover the fresh sediment for brick-making once the water falls (sun-drying them in the dry season). The bund can slide into the pool if not ringed by a paved area about 1 metre wide, and may also be damaged by livestock or rain. It can be helpful to install a paved area (or grassy vegetation) uphill of the bund, pressing the ground down well and protecting it from livestock with a thorn hedge. Livestock must not be allowed to wade in the pool itself for fear of infection from a sick animal. A drinking trough must be set up below the bund, fed by a flexible pipe that siphons the water to a filter (200-litre drum filled with alternating layers of sand and wood charcoal). The bund must be protected by blocks of laterite or tufts of perennial grass (e.g. *Andropogon*) to prevent erosion of the edges if it overflows.

Earth bunds for water harvesting

Runoff from the surrounding hills or rangeland can also be harvested behind an earth bund and used to irrigate a field. A series of stone lines should be laid out every 20 metres (Figure 39), bringing the ratio between catchment and field below one to three in an area with 400 to 600 mm of rainfall, and slowing sheet runoff to under 25 cm/sec, thus preventing gullying when a storm spreads additional water over a field that already has a tendency to runoff. However, this method of runoff management has its risks, for in dry years harvesting may not provide enough water for seeds, and in wet years the excessive water can reduce production by temporarily waterlogging the soil (Hudson 1990) and breaking down the bunds.

In the Turkana district of Kenya, Finkel (1985) worked out a simple equation to estimate the ratio between water harvesting area and cropped field:

$$\frac{\text{water harvesting area}}{\text{cropped area}} = \frac{\text{water needs of crop} - \text{mean annual rainfall}}{(\text{mean ann. rain x runoff coeff.}) \text{ x effic. of crop water}}$$

In this semi-arid region of Kenya, the ratio (R < 200 mm) ranges from 15 to 40 for sorghum and various pulses (cf. Reij, Mulder and Begeman 1988), but the bunds have recently suffered damage in a year with high rainfall. In the 600-mm rainfall area around Ouahigouya, this ratio would be 1 to 3.

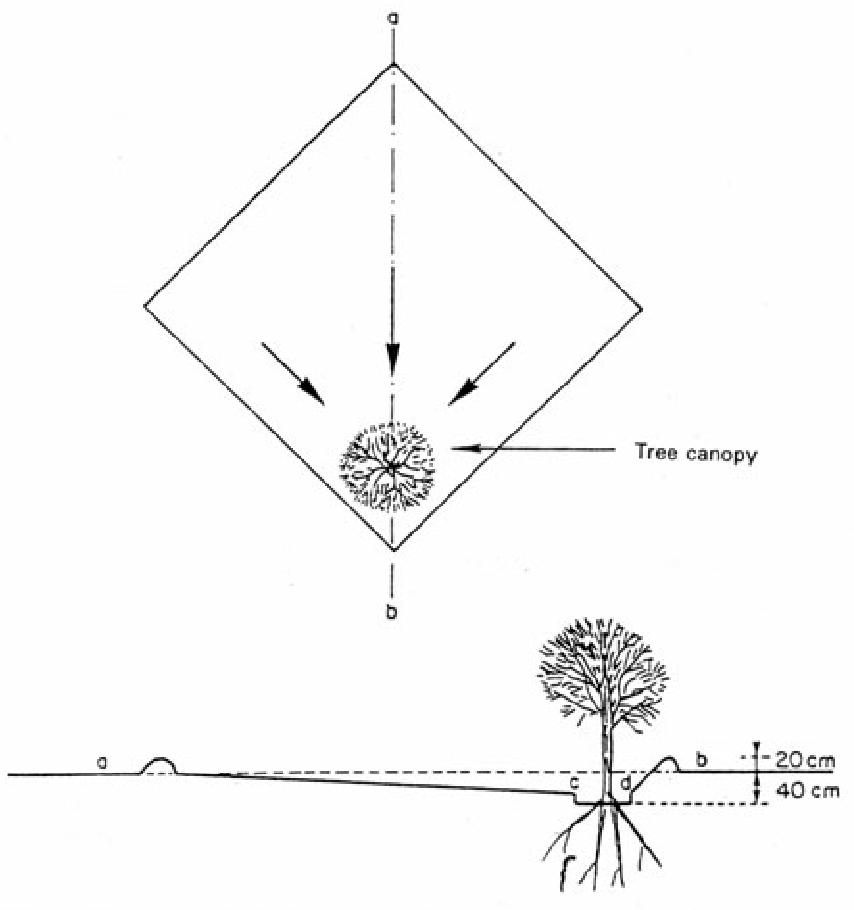
Negarim microcatchments

This is the best known system of water harvesting on short slopes in order to irrigate a tree crop (Figure 40). The basic element is a small hole, forming an absorption basin 40 cm deep, and a rim formed of a V- or half-moon-shaped earth berm 20 cm high. In a new orchard in Israel, the absorption area would be about 4 x 4 metres, while the catchment area would be three to six times larger.

Earthen beds draining excess water into a cistern (on a vertisol)

Vertisols are very clayey and chemically fairly fertile soils extremely difficult to work in the rainy season, when they are muddy. However, they can be tilled in the dry season one month after the end of the rains, dividing the fields into a succession of beds 1.5 metres wide separated by small, gently sloping (0.5%) furrows to carry drainage water to a spillway and into a cistern dug out of the ground (Figure 41). This system allows two crops: a rainy season crop where drainage allows sorghum to grow on the beds prepared and sown before the onset of the rains; then, after the rainy season, the ground is so swollen that it has a reserve of about 400 mm of water when the vertisol is 1 metre deep. The cistern holding the runoff water contains several hundred cubic metres, which can be used only as supplementary irrigation from the fields to make up for a sudden break in the rains or the end of the season. This system, developed by ICRISAT near Hyderabad in central India, allowed farmers to double their income, although requiring considerable work at a time of year when they would rather concentrate efforts on the rice fields in the valley bottoms. This whole approach is suitable only for vertisols rich in swelling clay, and not for red, ferruginous, tropical soils, which cannot hold enough water.

FIGURE 40
Diagram of a microcatchment (cf. Evenari, Shanan and Tadmor 1968)



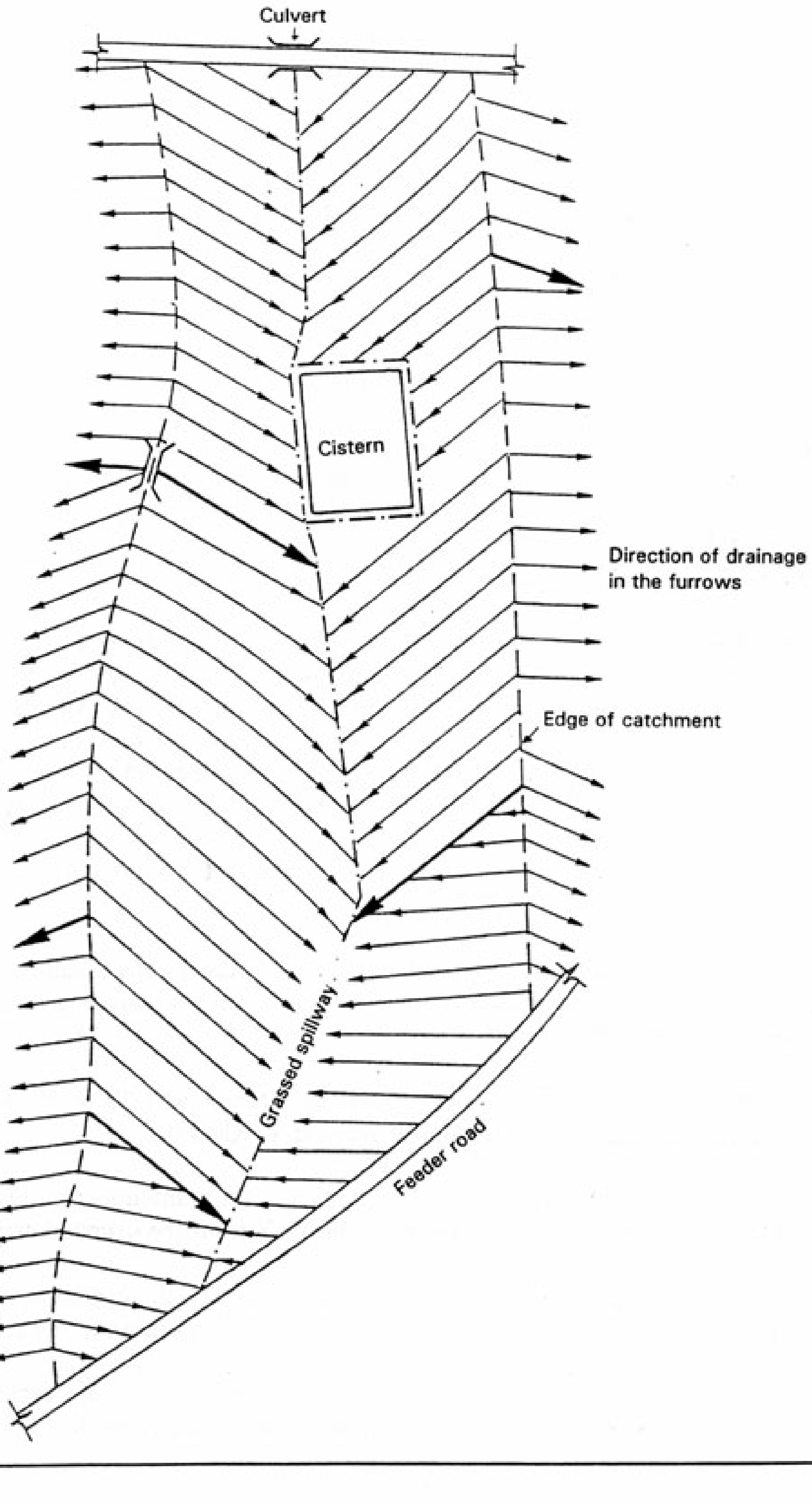
Conclusions

Study of traditional water management methods in a given region makes it possible to choose the methods best suited to local environmental conditions over a long period, and also closest to the habits of the people concerned.

Soil degradation from cropping probably forces the conclusion that runoff is inevitable. So before setting up erosion control structures it is vital to study the origin of runoff under the different cropping methods observed in the local area. Agricultural engineers tend to start from the assumption that the heaviest rain cannot be absorbed, and they therefore largely neglect cropping techniques that would allow increased infiltration. Now, if farmers’ expectations - increased efficiency, better returns for their labour and higher yields - are to be met, the supply of water and minerals to crops must be enhanced, implying a major effort to foster total absorption of rainfall (except in special circumstances in mountainous areas where this would entail the specific risk of landslides). Cropping techniques such as tied ridging, mulching or permanent cover lead to almost total rain absorption and curb the energy of sheet runoff, in which cases there is little point in investing in costly and fairly ineffective erosion control structures.

FIGURE 41

Beds drained by furrows channelling water to a grass spillway and cistern on a vertisol at the ICRISAT Hyderabad Center (cf. Kampen, Krishna and Pathak 1981)



TOTAL ABSORPTION STRUCTURES

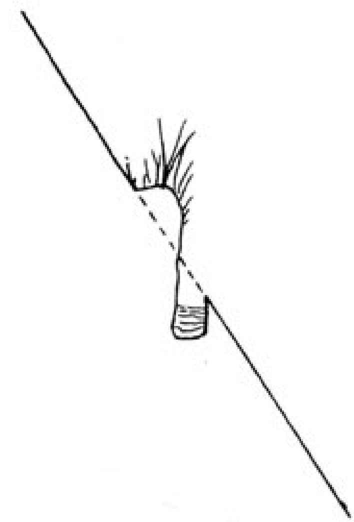
Total absorption structures are used in two cases: when rainfall barely ensures crop evapotranspira-tion, and in very permeable places.

Rwandan blind ditches with grassed risers (or Kenyan* Fanya Juu*) (Figure 42)

As early as the mid-1930s in Rwanda and Burundi, the Belgians suggested digging contour ditches on slopes of less than 20% where the ferralitic soil cover is deep and very permeable and where there is little risk of landslides.

Runoff water trapped in the ditches is prevented from collecting at a low point (due to construction errors or localized fragility), and carving deep gullies, by 50-cm-thick ties marking off sections of ditch 3 m long and 60 cm deep and broad. The soil must be thrown uphill and fixed with tall grasses (*Pennisetum purpureum*, *Setaria splendida* or *sphacelata*, *Tripsacum laxum* or Vetiver) to create a gradual concave terrace.

FIGURE 42
Infiltration (blind) ditch with a grassed riser above it



Advantages. Infiltration (blind) ditches provide good dividers for overly-long slopes, with storage of runoff and silt that can be particularly useful in dry regions; the formation of gradual terraces can also be encouraged by throwing the earth and silt uphill and protecting the risers with plants that fix the soil in place. These ditches restock the groundwater and moisten the surroundings, so that bananas and other water-demanding trees can be planted near the ditch.

Disadvantages. This technique is restricted to deep permeable soils and slopes of less than 20% (Tondeur 1950).

- Such ditches have been widely used under the wrong conditions (shallow soils on schist or granite), and where they have failed to receive proper maintenance, gullying and landslides have been the result.

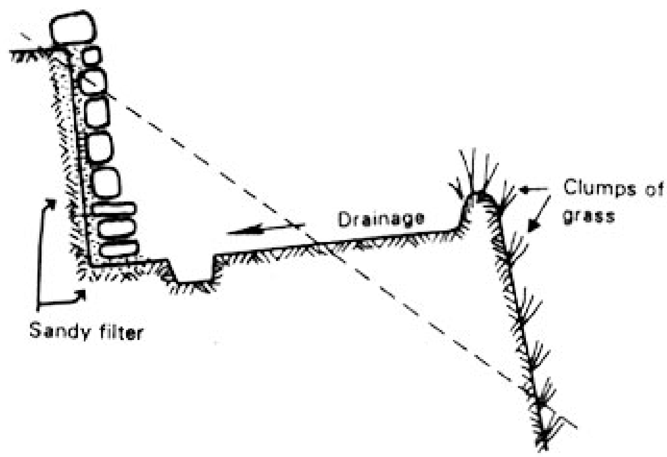
- It takes 300 days' work per hectare to dig the ditches, and 20 to 50 days of upkeep before the farmers see any clear improvement in production.

- The area occupied by the ditches (1 m every 10 to 20 m) amounts to a loss of 5 to 10% of arable land without much increase in production from the cropped strips.

- If the soil cover is shallow (on mica schist or volcanic ash on granite), these ditches increase the risk of landslides by accelerating the water's access to the slide bed-plane.

- If the soil is not very permeable or the ditches are too small, badly kept and silted up, then runoff overflows, creating the very gullies one meant to avoid.

FIGURE 43
Mediterranean, bench, or radical terrace



• The vertical risers often tend to be unstable because of failure to maintain the grass strips, and especially where they are undermined by workers preparing the fields below.

Suggestion. In order to increase stability, the risers must be re-cut, and the humus-rich top part slid down together with its plant cover onto the sterile, uncovered area. In Burundi, it has been seen that water, soil and nutrients tend to collect on these sloping banks, and that these deposits can be protected and improved by intensive forage production on the risers, and by planting trees to drain the foot and reduce the risk of sliding, and lastly by hedges or fruit bushes, cut back each year to keep the height of the riser the same.

Instead, if large trees were planted above the riser, they could easily loosen it in high winds. There is a trend away from such ditches today, with access paths being set up in their place, or those still existing being transformed into compost pits for planting bananas (Roose 1990).

Mediterranean or Bench Terraces (Figure 43)

Bench terraces are most often seen in mountains around the Mediterranean basin, but also in the Peruvian Andes, Bali (Indonesia) and China – in places where there is little level land, or where the population is dense or threatened by an invader (as in the case of the Dogons in Mali), or where work is obligatory or labour very cheap, and where products with high added value (e.g. carnations in Nice, strawberries in Spain and Lozère, kif in the central Rif and kat in the Hararghe region of Ethiopia) can be grown by irrigation and exported.

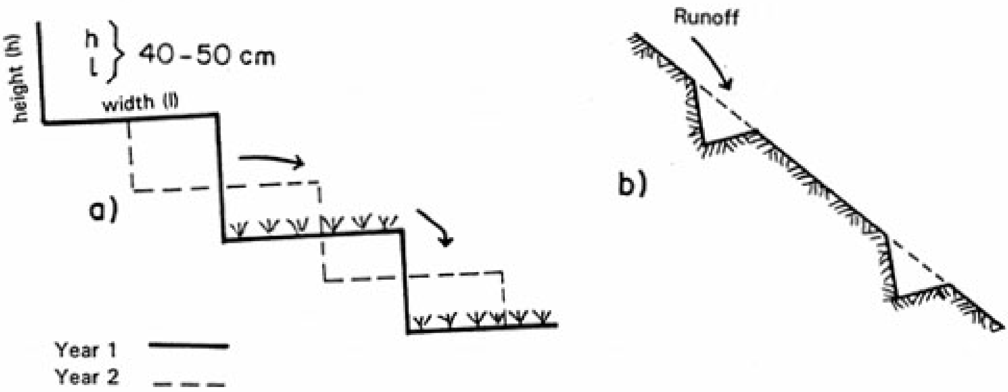
The benches are made of a subvertical riser reinforced with stones or plants, and a terrace with a slight reverse slope, with a possibility of irrigation and drainage down the slope.

Advantages:

• The benches create flat areas and suppress sheet erosion.

FIGURE 44
(a) Step microterracing
(b) Discontinuous forest step terracing

No sign of runoff, but slow creeping of the soil cover



- They allow investment in steeply sloping land leading to greater productivity.
- They increase the available crop water.
- They make irrigation possible by harnessing mountain water and runoff on the risers.

Disadvantages:

- They are very expensive to build, requiring 500 to 1 200 days' work per hectare, and then requiring upkeep of the risers.
- They increase the risks of landslides, for they foster absorption closer to the rock; ruling them out on schist, gneiss or very shallow soil, or in areas subject to frequent earthquakes.
- Once they are built, **soil fertility must be restored** through massive doses of manure, lime and phosphorus if yields are to double or triple after some years; since the risers are not vertical, 20 to 50% of the land area cannot be cropped, although it can still produce forage.
- The risks of leaching of soluble nutrients are increased by reducing surface runoff.
- A lot of the topsoil is concentrated in the clods that make up the banks, which means that soil fertility must be restored before any advantage can be seen.

Proposal. This method is too expensive to be recommended for generalized use, and too hazardous on shallow soils and in areas prone to frequent earthquakes. It is at present viable only in the perspective of mechanized cropping on a site with an average slope of 15 to 30%. It is important to place tracks at the foot of the risers.

The traditional method of **step microterracing** (Figure 44) is directly derived from the bench terracing method, and consists of digging steps 50 cm wide, which are then moved 25 cm each year in order to keep a rough surface, and turning in the plants that grow during the fallow period. This method exerts a brake on runoff energy on slopes of up to 80%, but does not prevent the soil cover from slowly creeping downhill due to dry mechanical erosion (Rwehumbiza and Roose 1992, Hudson 1973, Fournier 1967).

There is an arid zone variant in which only part of the slope is terraced to collect runoff on the banks and encourage full absorption of rainwater and the recovery of runoff. This means that the water from most light and average rainstorms is absorbed totally by the strip of cropped soil. However, the method does envisage a drainage system allowing excess water to be evacuated during the exceptionally heavy rainstorms that are so dangerous around the Mediterranean.

Conclusion

Total absorption structures offer radical solutions in semi-arid regions where plant production is closely dependent on the availability of water, and also on steep slopes where it is difficult to control runoff without creating gullies.

However, installation and upkeep of such structures require a heavy investment. Furthermore, they cannot be installed indiscriminately without increasing the risks of landslides and the leaching of nutrients.

RUNOFF DIVERSION

When rainfall is too abundant or too intense to be stored or totally absorbed by the soil, it has to be drained via diversion ditches, bunds or terraces (Figure 45) in order to trap the sheet runoff before it gathers enough energy to gully the slope. Runoff is then evacuated from the cultivated area toward natural or manmade spillways to allow it to reach the low water point without causing too much damage.

Bennett developed this method of runoff management to counter the degradation of soils subject to mechanization in the Great Plains of the United States, but its application in developing countries is unfortunately fraught with problems.

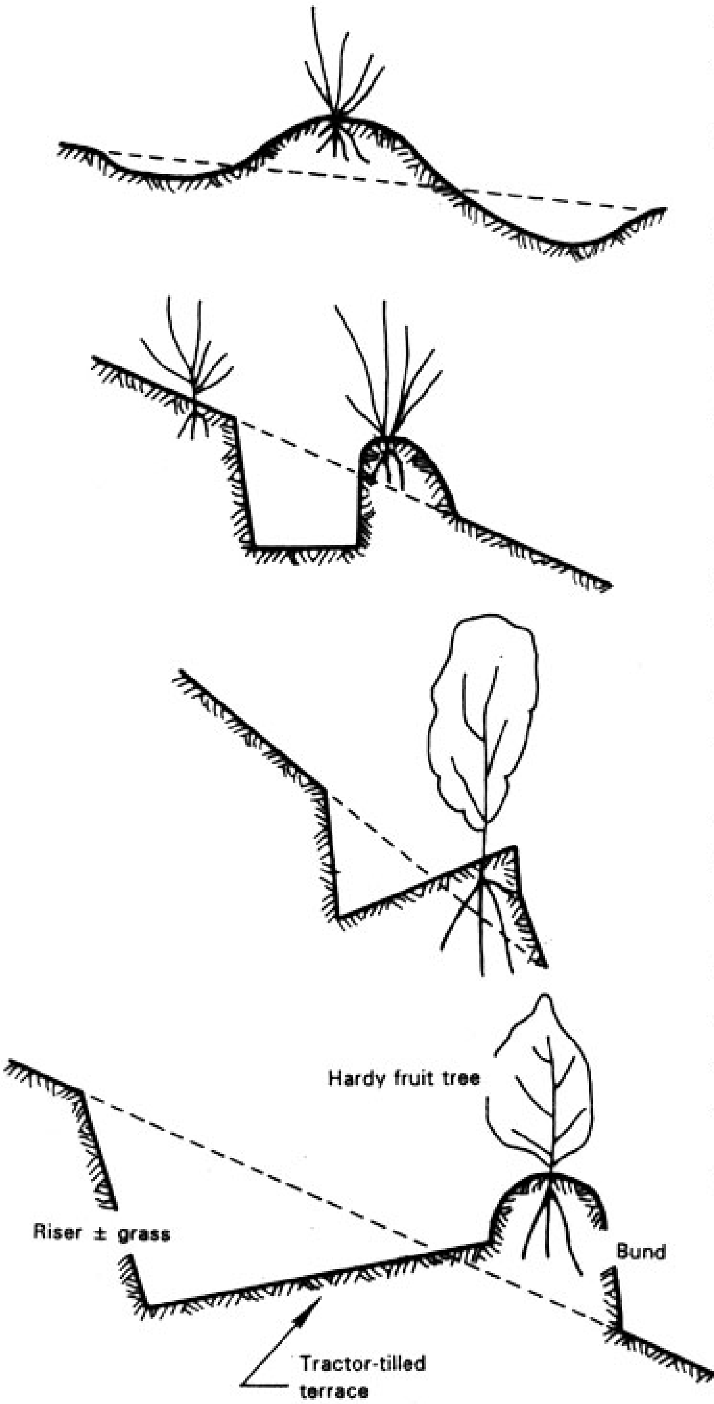
Advantages. These ditches do drain excess water from cultivated areas.

Disadvantages. The ditches represent a loss of 5 to 15% in arable land.

Sheet erosion between the structures can persist, in which case soil will silt up the ditches (gentler slope), causing overflowing and gullying, and ruining the whole installation. The structures require very precise surveying in order to allow the slope of the channels to increase gradually from 0.2 to 0.4%. They are expensive to build and maintain, requiring resources for rapid channel clearance and maintenance.

There are two kinds of gullying risk: on slopes when ditches overflow, and at spillways where water from a whole hillside is concentrated. This means that the problem has simply been shifted: there has been no reduction in soil degradation, nor in sheet erosion between the erosion control structures. In Africa, this system is rarely maintained as it should be, so that it generally ends in failure after four to ten years – and sometimes less – as ditches intended to evacuate runoff fill with eroded soil and subsequently overflow during the heaviest rainstorms.

FIGURE 45
Various runoff diversion structures



Earth diversion bund

- effective on slight slopes (1 to 8%);
- requires maintenance and stabilization with grass and shrubs;
- requires control of rodents and burrowing animals which find the soft earth good for tunnelling;
- not suitable for vertisols and other soils that crack in the dry season.

Diversion ditch

- effective for draining steep slopes;
- sometimes permits irrigation of pasture through overspill and tying;
- increases the risk of landslides if it increases infiltration.

Forest terrace

- suitable for reforestation in degraded mountain zones;
- allows plants to get a good start;
- requires simultaneous planting of an under-storey of booster plants (legumes, clover, *Sylla*).

Algerian terrace

- introduces fruit trees which diversity production on farmland;
- loses 5 to 15% of land area;
- no yield increases;
- 80% failure on slopes > 40%;
- very often rejected by farmers because it hampers mechanized farming;
- land is sometimes abandoned because such structures are installed by State SPR departments (fear of expropriation by the State).

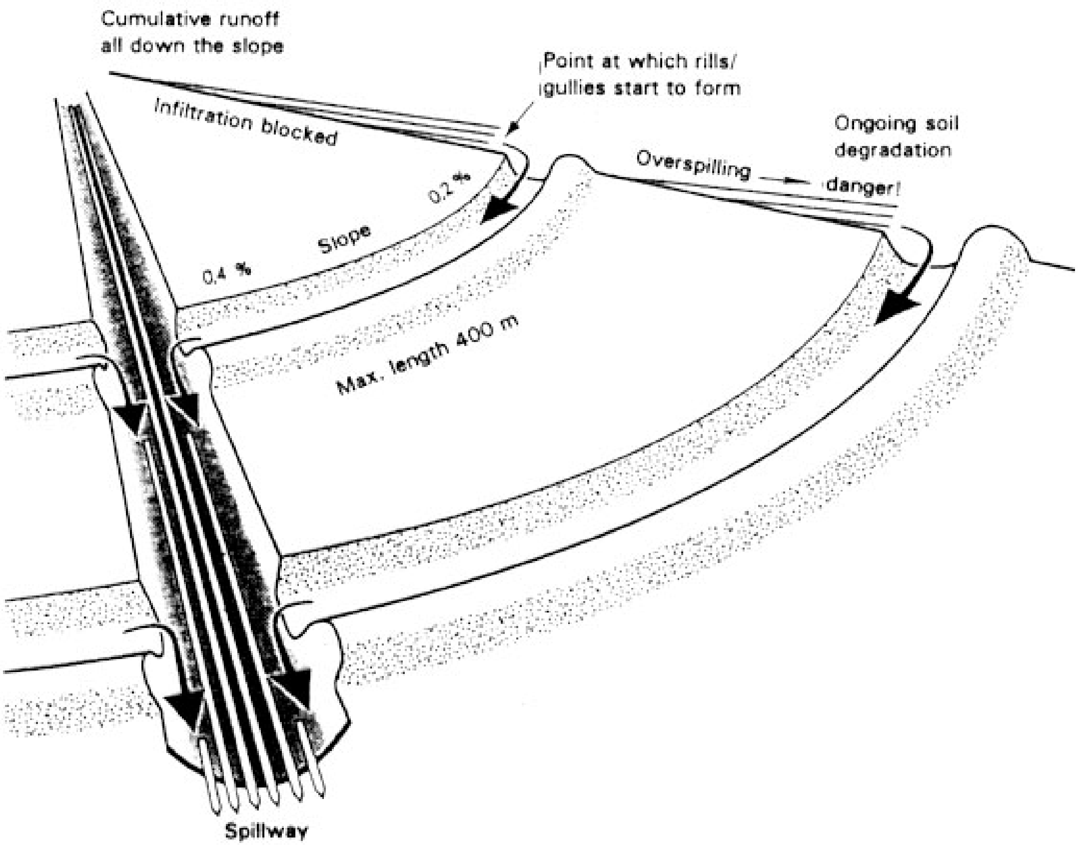
FIGURE 46
Runoff diversion: principles, practice and drawbacks

Erosion depends on:

- rainfall energy (constant all down the slope)
- runoff energy (which increases with slope

Terraces:

- can evacuate accumulated runoff energy
- cannot reduce rainfall energy or soil degradation



DRAWBACKS

1. Need for expert surveying teams (high cost).
2. Considerable labour for installation and maintenance, hence generally:
   - unprotected bunds
   - channels clogged with sediment
   - spillways neither grassed nor protected (dug too deep or silted up).
3. Loss of 5 to 15% of cultivated area with no increase in yields.
4. Loss of water and nutrients for fields downstream.
5. The structure will break down in a once-in-a-decade storm.
6. Varied widths of fields (making mechanization difficult).
7. Prevents neither sheet erosion nor degradation.
8. Serious risks of gullying if the bunds are breached (once in 4 to 10 years).
9. Water concentrates more quickly, causing:
   - high flood flows
   - erosion of oxbows
   - headward gullying

TABLE 34

Diversion bunds and an intensive motorized system of preparing a shallow ferruginous soil on gravel sheet have little effect on runoff, erosion and yields of various crops: Gampela, 25 km from Ouagoudougou (Burkina Faso) (cf. Roose and Piot 1984)

Plot area (about 0.5 ha)	Runoff: KR %		Erosion t/ha/yr	Yields as % of control
	Max 24 h	Kaar		
Diversion bunds dh (difference in level) = 40 cm + tillage + weeding-hoeing perpendicular to slope, tied	31	4	1.4	
not tied	37	20	3.4	106
Idem but ridges parallel to slope, not tied	45	24	5.9	98
Traditional Mossi = non-tillage Sod seeding in seed holes, then hoed twice	43	23	4.1	100
Bare soil (standard USLE) (100 m^2)	70	40	16.0	-

Table 34 shows how little effect diversion bunds have on runoff, erosion and yields for cultivation with intensive mechanized tillage on a shallow, tropical, ferruginous soil on gravel sheet (Roose and Piot 1984). On a broad pediment with a 0.7% slope, the CTFT compared runoff, erosion and yields on four plots between 1967 and 1972: a standard control plot, a traditional untilled Mossi field with sod-seeding in planting holes, and two plots with diversion bunds, using intensive methods of tillage, hoeing and ridging, parallel to the slope and untied on one, and perpendicular to the slope and tied in certain years on the other. The maximum runoff observed during the heaviest rainstorms on bare soil was 70%, while it varied from 37 to 45% on cropped soil, whatever cropping method was used, even falling to 31% when the ridges were tied.

Average annual runoff reaches 40% on bare plots. Plant cover reduces it to 20-24% whatever the cropping system, but only tied ridging brings a real reduction (4%). Erosion on these gentle slopes can be as much as 16 t/ha/yr on bare soil (but is cut to a quarter on cultivated soils), and a little higher on soils with ridging in the same direction as the slope (but significantly lower if the ridging is perpendicular to the slope and tied). However, there is no significant difference in yields under a traditional non-till system or under an elaborate system, with the use of numerous cropping techniques as well as diversion structures. On these shallow and fairly unproductive soils, there therefore seems no point in investing in either tillage or diversion ditches. Runoff reductions are slight, and even if they *were* sizeable, the soils are incapable of storing the water, so that the nutrients saved from runoff would quite probably be carried off in the drainage water.

Conclusions on diversion structures

Following Bennett's manual and other work by American researchers, runoff diversion structures have been built all over the world in the past 50 years, with no prior tests of their effectiveness or suitability under local social and economic conditions.

Today it has become clear how ineffective they are in Mediterranean areas, Sudano-Sahelian areas (Burkina Faso, Niger) and the mountains of Central Africa, and on the long pediments of South Africa. These methods are expensive (especially the surveying work), reduce arable land, and fail to prevent either loss of soil fertility or sheet erosion. They are valid options only under mechanized cropping systems, but are difficult to maintain and should therefore be avoided in developing countries.

STRUCTURES TO DISSIPATE RUNOFF ENERGY

When rainfall exceeds the soil's absorption capacity, the sheet runoff can be controlled by spreading it across the whole slope rather than concentrating it in channels and outlets, where it can cause problems.

Its energy can be dispersed by keeping the speed below 25 cm/sec – the speed corresponding to the energy needed for runoff to detach particles (Hjulström 1935) (Figure 20).

Such dispersion across the slope is achieved partly by cropping techniques that keep the soil surface rough (clods, many grass stalks, effect of weeds and mulching, etc.) and partly by structures such as **permeable microdams**, which temporarily slow the flow, allow some sedimentation, spread the flood, reduce peak flows and improve absorption.

Grass Strips (Table 35) reduced runoff to 30 or 60% of that on the control plot, and erosion to 30 and even 10%.

Hedges made up of two or three staggered lines of grasses or shrubs also operate as very effective permeable microdams.

On the Ruhande Experimental Station near Butare in Rwanda, König (1992) showed that on a 27% slope where erosion on bare soil can be as much as 550 t/ha/yr, isolated trees have very little effect, whereas hedges of *Calliandra* or *Leucaena* planted every 10 metres cut erosion to less than 7 t/ha/yr. Hedges of *Setaria* are twice as effective in reducing erosion (0.3 t/ha/yr), but are exhausted after being used for forage for three to five years (Table 36).

On the ISAR Rubona Station, 20 km from Butare in Rwanda, Ndayizigiyé (1992) compared the erosion control effectiveness of shrub hedges of *Calliandra*, *Calliandra* plus *Setaria*, and *Leucaena* (two lines, 50 cm apart), placed 7 metres apart on a 24% slope on a very desaturated, sandy-clayey, ferralitic soil.

For rainfall of 1 000-1 250 mm (established over ten months), the average annual runoff coefficient (bare soil or traditional cropping) remains moderate (6 to 12%), but tends to increase as the soil surface degrades, and can exceed 45 to 50% with the heaviest rainstorms in the second rainy season on waterlogged soil. On the other hand,

TABLE 35

Effect of buffer strips and contour cropping in humid and dry tropical zones (trials on erosion plots) (cf. Roose and Bertrand 1971)

Buffer strips	Width	0 m	2 m	4 m	Effectiveness
Adiopodoumé (1965) Rainfall: 2 300 mm Cassava Slope 7%	KR % E t/ha/yr	16.5 18.9	10.3 5.7	6.0 1.8	1-0.6-0.3 1-0.3-0.1
Bouaké (1965-66) Rainfall 1 180 mm Groundnut/maize Slope 4%	KR % E t/ha/yr	12.6 7.6	5.1 0.9	3.8 0.6	1-0.4-0.3 1-0.1-0.08

Treatments Allokoto (1966-71) Rainfall: 437 mm Groundnut, millet, sorghum, cotton Slope 4%	Traditional Haoussa control strip	50 cm buffer strips dh = 40 cm °tillage + ridging °frequent hoeing	low stone walls dh = 80 cm °tilling + ridging °frequent hoeing	protected ridges dh = 80 cm °tilling + ridging °frequent hoeing	Effectiveness
R % E t/ha/yr	17.6 9.5	5.2 1.1	3.8 0.5	0.9 0.3	1-0.3-0.2-0.5 1-0.1-0.05-0.03

dH = difference in level

TABLE 36

Effect of barriers of grasses (*Setaria*) or shrubs (*Leucaena* or *Calliandra*) on erosion: Ruhande hill near Butaré in Rwanda (cf. König 1991)

Treatment		E t/ha/yr
International control	- bare tilled fallow	557
Regional control	- traditional cassava crop	303
	- idem + *Grevillea robusta* trees + combination crops	110
	- alley cropping (*Calliandra* every 5 m) + cassava	16.1
	- idem + companion crops	2.8
	- *Calliandra* planted every 10 m	12.3
	- *Calliandra* every 10 m	7.6
	- *Leucaena* planted every 10 m	7.4
	- idem + ridges every 5 m	3.9
	- *Setaria* hedge grown from cuttings	3.2

° hedges = three staggered lines on a horizontal terrace 1 m wide, every 10 m

° alley cropping = two lines of shrubs every 5 m

° if the hedges are to be effective, a filtering layer - a mulch of brushwood, weeds or prunings from the hedges - must be placed on the ground

° **Note:**
- the ineffectiveness of free-standing trees
- the reasonable effect of alley cropping
- herbaceous hedges are more effective than shrub hedges, which may be supplemented by adding covered ridges every 5 m

on plots protected by hedges, runoff tends to fall to under 2% whatever the type of plants, especially if prunings are spread on the soil surface between crops, and the weeds collected during hoeing are arranged at the foot of the hedges.

Erosion reaches 300 to 500 t/ha/yr on the bare control plot, and 200 to 250 t/ha/yr under traditional cropping, but falls toward 1 t/ha/yr on plots protected by grass or shrubs, clearly indicating that treated plots are stable after two to three years. So SWC has been successful, but what of crop yields?

Tests show that the biomass produced by shrubs increases gradually from 1.5 to 3.2 kg per linear metre of hedge, that the presence of grass (*Setaria*) at the foot of the shrubs gives good results in the first year but that after this *Calliandra* alone produces more than *Leucaena*, and lastly that annual nutrient intake by the deep-rooted shrubs can be as high as 78 kg of nitrogen, 10 kg of phosphorus, and 17 kg of potassium, which are then redistributed in the form of mulch during the crop growth cycle.

It had been hoped that a combination of prunings from hedges and 10 t/ha/yr of manure (dried paddock dung) would gradually improve crop yields. In fact, however, levels remained only fair (500 to 250 kg/ha of maize, plus 500 to 800 kg/ha of beans in the first season, and 450 to 650 kg/ha of sorghum in the second season). In the fourth year it eventually became clear that soil fertility had to be restored (a supplement of 2.5 t/ha of lime, 10 t/ha of paddock dung, and 300 kg/ha of NPK – 17.17.17) if crop yields were to increase significantly (more than 2 t/ha of beans and 1.4 t/ha of sorghum).

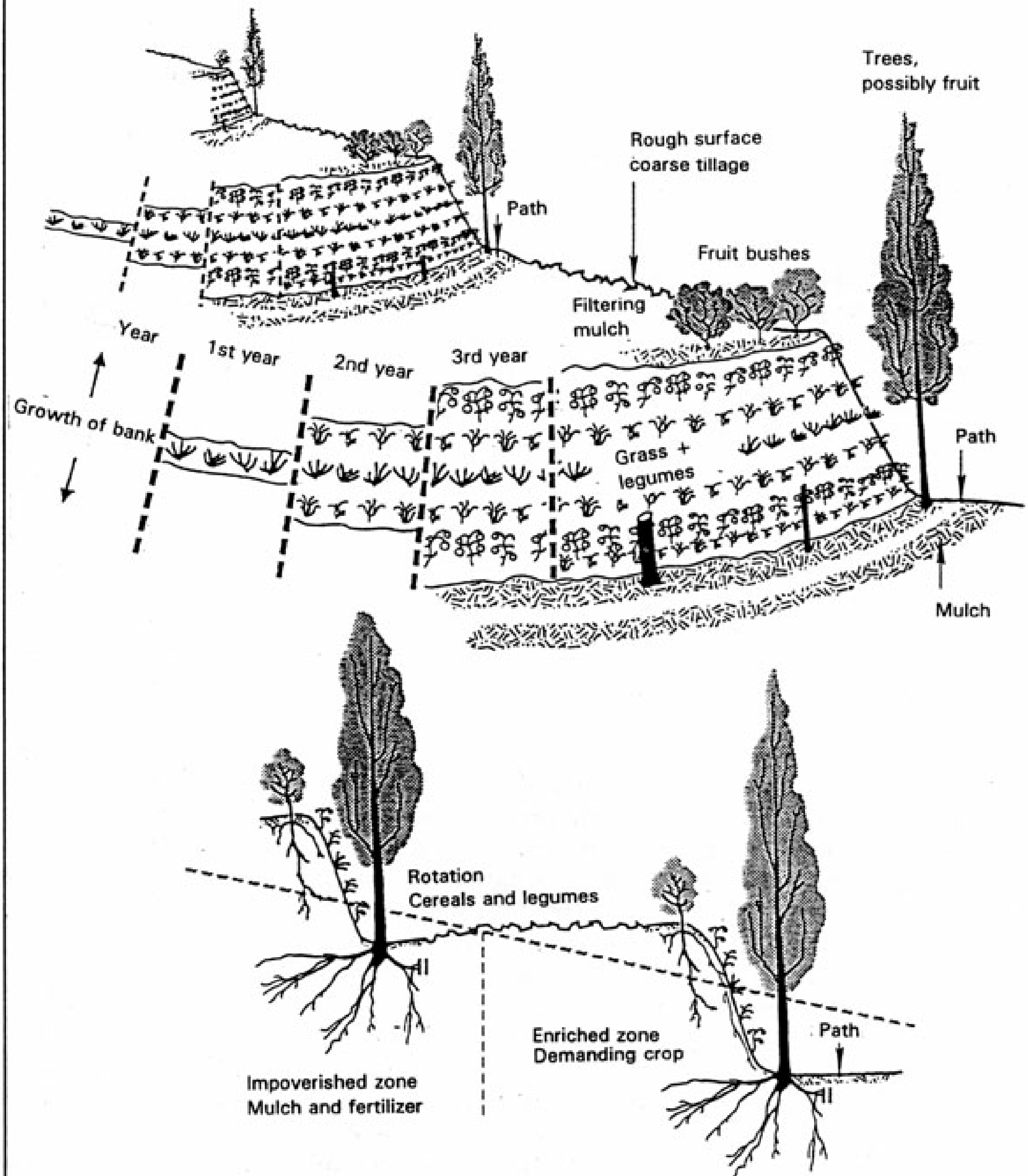
Complex grassed risers. After some years the microdams (grass strips, hedges, etc.) have produced gradual terraces divided up by steep-sided banks protected by a grass sward.

Figure 47 shows the development of a grassed riser on a 20 to 60% slope over a five- to ten-year period, during which it reaches a maximum height of 1 to 1.5 metres, after which there is an increased risk of destruction from animal burrows, gullying, and landslides, and farming problems as well (Roose 1990).

Since any break in the line of the riser across the hill compromises these measures, it is recommended that the whole length be pegged out with the rural community, and the first line of grass indicating the basic contour line planted across the whole slope or hill, leaving the individual farmers to complete the work during the five successive years, at their own pace on their own land. Imposing treatment of the whole hillside on the rural community can undermine the farmers' sense of responsibility, leading to neglect of the necessary upkeep (Ngarambé 1991). If the grassed strip is not continuous, runoff water will rush into the breach, carving out a gully and undermining the whole system.

Lines of Stones, Stakes, Grass or Straw (Figure 48a and b). This heading covers single barrier lines established along contour lines and permeable to sheet runoff. Many examples can be seen in Sudano-Sahelian semi-arid areas of Mali, Burkina Faso and Niger. Stone lines slow down the runoff so that it spreads out in sheets several centimetres deep, thus causing sedimentation first of sand particles, and then of finer particles which tend to clog the surface. The lines filter the water, trapping straw, animal faeces dropped during the dry season on rangelands, and various types of floating organic residue. This creates a localized deposit of fertilizer in the sedimentation area and in the watered area. And if these lines are laid out in the right direction, in the dry season they also trap sand carried

FIGURE 47
Development of a semi-pervious erosion control structure to dissipate runoff energy (cf. Roose 1991)



NOTES ON FIGURE 47

Objectives

1. Dissipating runoff energy by spreading the sheet over the soil surface, which is protected by a thick sward of grass.

2. Transforming the soil cover into a series of gently sloped, cropped areas and protected banks (0.5 to 2 m high depending on soil depth and resistance).

Methods

1st year — Mark out the contour line (every 5 to 20 m depending on slope and soil depth) by planting perennial grasses. Tillage will add 10 cm of soil above, and remove 10 cm of soil below.

2nd year — Plant 2 additional rows of grass x pulses.

3rd year — Plant another 2 additional rows, then plant quick-growing trees at the foot of the bank to reduce risks of landslides.

Since the soil cover will now vary in depth, more demanding plants can be grown in the zone above the bank where soil, water and fertile elements accumulate, and hardier plants below it in the scoured area to be restored.

Advantages

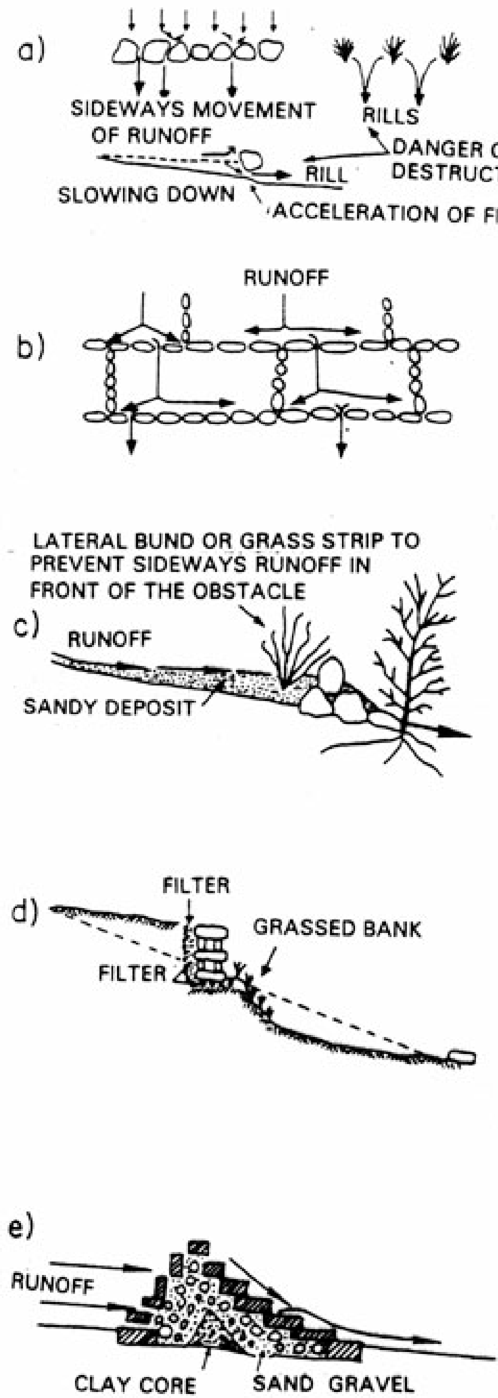
Terraces are formed progressively through erosion, but primarily through tillage (+ 20 cm in height per year). The farmers can do all the work themselves.

Such a system requires neither major investment nor major upkeep, and pegging out the contour line does not require such precise surveying as do drains.

There is no loss (as against 6 to 10% for ditches) in crop area: (wood, fruit and forage crops will grow particularly well on the banks).

Effectiveness is maintained even in the case of very heavy rainstorms, and increases with time.

FIGURE 48
Examples of semi-pervious microdams in a semi-arid area (cf. Roose 1989)



Stone line or line of grass, straw, stakes

- a single row of semi-pervious obstacles
- slows down and spreads runoff
- traps wind-blown sand and fine particles in runoff
- delicate: knocked over by livestock and rills, buried by runoff

Honeycomb network

- tying → reduction in lateral flow
- used to restore soil at the foot of hills for water harvesting

Low stone bund

- at least 2 to 3 layers of well-fitted stones
- held together by:
  - grass > < sideways movements
  - hedge + trees > < livestock (downstream)
- traps 5 to 15 cm of sand + OM + silt
- filters floating organic matter
- slows and spreads flow over more time and a larger area

Stone walls

- carefully stacked flat stones
- wall + upstream sand draining filter beneath the wall
- develops into gradual terraces

Semi-filtering dam

- large stone dam across the head of the valley
- reinforced horizontal crest
- slows flow
- core of finer packed material if a sheet of water is to be held back

off by wind erosion. They enhance production potential by concentrating both water and nutrients over an area 2 to 6 metres broad above the barrier, and redistributing it below it when there is excess water.

Hazards. When sheet runoff builds up before the barriers, it eventually finds a way out, and at this point it speeds up (the Venturi effect), carving out a channel below the line, then under the stones, thus burying them.

As it spreads out in front of the barrier, the sheet creates a lateral movement which can lead to a local concentration of runoff and the formation of a more aggressive **drainage line** capable of carving out channels and shifting gravel and pebbles.

These lines are fragile: a single kick from the hoof of a passing animal can shift a stone, causing a breach through which the water will pour. The resulting rills then develop into gullies.

The lines have a limited life-span. The stakes and straw rot and are attacked by termites. The clumps of grass are choked in the centre, so that they thin out and leave pernicious breaches. The stones are overturned by livestock or buried under sand.

However, the organic matter accumulated in front of the barriers will have drawn termites, which often improve macroporosity and absorption capacity at this point, so that abundant grass and shrubs, and sometimes even trees, will grow there. In order to counter the lateral movement of water that leads to soil erosion, lateral ties can be introduced either by making small ridges perpendicular to the barrier, or by tying the field laterally in a bee-hive pattern – as is often done by the Mossi in north-western Burkina Faso to restore soil at the foot of hills. Another option is to wait a year until the drainage lines become clear and then use large stones to reinforce the weaker points where water collects. The soil must also be kept rough through regular tillage in order to break up the slaking or sedimentation crust which seals the soil surface. Hoeing the earth up into tied ridges lowers the risk of water concentration. Lastly, a filter of straw or a hedge above the stone or grass lines will make them much more effective.

Low stone bunds (Figure 48c).

Two or three layers of stones are so arranged along the contour line as to reinforce one another, a technique widely used in Yatenga Province of Burkina Faso. Lining one hectare with these stone bunds (400 m) takes about 30 to 60 days' work, plus transport between quarry and field (1 day's use of a truck). The bunds slow down runoff, spreading it in sheets so that it is absorbed in less than one hour, thus causing successive sedimentation of sand, aggregates, and fine, humus-bearing particles, which will then form a sedimentation crust. Only the excess water flows over the first layer of stones. More water is stored than in the case of stone lines, and the sheet of water often covers 5 to 8 metres in front of the permeable barrier. The bund filters straw, animal faeces and various kinds of floating, organic matter, so that farmers see one of its most useful functions as that of maintaining soil fertility.

Theoretically, these stone bunds are laid perpendicular to the direction of the water flow, but not necessarily to winds. They thus do not always trap sand blown across the ground during the dry season.

The bottom of the first layer of stones is planted several centimetres deep in the ground, with soil between them, so that 5 to 15 cm of filtering, organic, sandy soil collects above the bund, improving soil storage capacity and forming new topsoil.

The second and third layers downhill (made of smaller stones or grass) divide the excess flow, absorbing the runoff energy and preventing channels from being dug out downstream of the barrier during major rainstorms. Tillage of the cropped strip and erosion will soon cause an embankment to form. It must be stabilized with grass, for example *Andropogon* and *Pennisetum*.

Hazards. If the top of the bund is not strictly horizontal (as in the case of smoothed contour lines), the sheet runoff flows toward the lower points and forms drainage lines, speeding up and carving out channels, which then develop into gullies and drain water from the whole slope. However, a strictly followed contour line will produce fields of widely varying sizes and shapes (a deviation of 10 metres for the slightest termite hill on 2% slopes), which causes problems for mechanized cropping. Even then, small drainage lines will form, but these can be treated in various ways:

- using large stones to reinforce the points where the water collects, and gradually levelling these areas;
- increasing the roughness of the soil through coarse tillage with toothed implements, repeated hoeing, and tied ridging;
- sowing grass (*Andropogon*) above and around the bund to brake sheet runoff;
- tying the field for 5 metres above the bund with earth ridges or stone bunds – although the latter can cause problems for mechanized cropping (Lamachère and Serpantié 1991).

Damage to the bund by passing livestock can be reduced by planting grass (to cover the stones), and a hedge below the bund, as well as trees which will eventually “tie” the landscape, creating an area dominated by hedges. In areas where stones are scarce, the same effect can be achieved by sowing a 50-cm strip of grass (*Andropogon*) or a hedge (at least three lines staggered on alternate rows) between two contour ridges (20 cm high) (Roose and Rodriguez 1990). In mountainous areas farmers often collect stones that come to the surface and heap them up on the edges of their fields (particularly on banks around the fields). If these heaps of stones are arranged along contour lines, they act as stone bunds.

A team of ORSTOM scientists (Serpantié, Lamachère, Martinelli and others 1986-1992) have studied the combined effects of stone bunds and tillage, comparing this with a control plot in a water-harvesting area in the Bidi region near Ouahigouya in Yatenga, in north-western Burkina Faso (Table 37, Figure 49) (Serpantié and Martinelli 1987; Lamachère and Serpantié 1991).

Stone walls (Figure 48d).

These walls are carefully built by piling up flat stones, wedged with small rock chips. They are often found in sandstone hills, for example near Bamako in Mali. The first step is to dig a trench along the contour line, digging down to a coherent horizon, and build a drainage filter made of a layer of sand and gravel on the sides and bed of the trench.

On a medium to steep slope, gradual terraces are quickly formed by throwing the earth from the trench uphill and by water erosion, but above all by dry mechanical erosion during tillage.

Hazards. The direct pressure exercised on the wall by the soil cover and ground water can push it out of true so that it will bulge and, eventually collapsing unless there is good drainage above the wall and a bed of gravel below.

As time passes, the foot of the wall will be eaten away by water erosion or tillage in the field below it. This process can be slowed by planting grass or fruit trees on the bank that develops at the foot of the wall, which will prevent soil from creeping downhill.

Pervious and semi-pervious check dams (Figures 48e and 52).

This approach entails heaping up a line of large stones with the crest following the contour line, in order to dam the head of a valley, thus slowing flow and facilitating groundwater recharge. It can take 300 to 600 days' work to build these enormous stone bunds which are 200 to 300 metres long and 1 to 2 metres high. The length of the dam depends on its height and the depth of the gullying at each point. **The crest of the dam must follow the contour line strictly** and the dam itself must be set in a foundation trench 20 to 40 cm deep, which must also be covered by a pervious bed. This barrier slows down runoff to the valley bottom, although it passes quickly through the large stones – unless the dam has been built with a pervious core of finer gravel, which can hold back water for several days.

If a sheet of water is to be kept upstream of the dam (in other words, if it is to be a semi-pervious rather than a pervious dam), for example to grow rice, a clayey core behind the gravel filter will be necessary.

Sedimentation upstream of the stone dam is fine and slow (1 mm per year) in a fairly undegraded, undulating landscape, but can be fast (10 to 50 cm per year) in a gullied, hilly landscape (e.g. the area north of Ouagadougou – Dezilleau and Minoza 1988).

Hazards. If water filters too fast through the dam, erosion can burrow through it and below it. If there is too much pressure beneath, the water carves out a gully which will eventually breach the dam through headward erosion. A gravel and sand filter must therefore be built to slow down runoff: this material is poured into the foundation trench under the structure, as well as between the large stones that make up its core (Figure 52).

If the sheet of water flowing over the dam is over 20 cm, the structure may well be swept away by the speed of the current. This can be prevented by placing large stones, or better a small gabion, on the brow of the dam, and also on the slope of its upstream side (2/1 slope).

The water normally drains away fast after the rains stop, although the land immediately above is left water-logged, so that the sorghum traditionally grown in flat valley bottoms rots and suffers from waterlogging, while water is not available long enough to grow rice – which is prized for feast-days. Only off-season gardens and fruit trees

TABLE 37

Tests on the effect of stone bunds and tillage on runoff, erosion and millet yields at the Bidi Station, Samniweogo, northern Yatenga, Burkina Faso (cf Lamachère and Serpantié 1991)

Tropical, sandy-clayey, well-drained, ferruginous soil, 25 to 220 cm deep over ironstone. Slope 2.5%. Plots of 3 100 m^3, receiving runoff from a 1 250 m catchment area until the end of 1987.

Year	Rainfall mm + 2	Treatments	Runoff				Erosion t/ha/yr	Yields kg/ha	
			Kaar %	Smooth moist soil	Max KR %				
					smooth dry	rough		biomass	grain
1985 + harvesting runoff	239	1. Traditional 2. T + stone bund	29 24	35 40	34 32	75 57	- -	1080 1470	137 136
1986 + harvesting runoff	530	1. T 2. T + SB 3. T + SB + Tillage	24 23	34 48	67 49	42 30	(2,80) (1,96)	2520 3010 (+19%) 4640 (+54%)	233 406 (+4%) 837 (+106%)
1987 + harvesting runoff	400	1. T 2. T + SB 3. T + SB + Ti	11 9 3	62 60 16	32 16 0	29 11 10	1,01 0,32 0,40	1770 2330 (+32%) 3140 (+35%)	346 443 (+28%) 679 (+53%)
1988 + ties - catchment runoff	520	1. T 2. T + SB 3. T + SB + Ti	18 10 13	50 24 35	23 14 20	34 16 19	1,60 0,57 1,30	1890 2090 (+ 11%) 2290 (+10%)	385 362 (-6%) 438 (+21%)
Average effect over 2, 3, 4 yrs			Infiltration				Erosion	Biomass	Grain
bund - control bund + tillage - bund			+ 4% + 4.3%				- 34% + 52%	+ 22% + 48%	+ 22 %/4 yrs + 61%/3 yrs

35 = Markedly different from control treatments

Notes on Table 37

Treatments are as follows:

a.
1. T = traditional millet crop + light manuring: 7N + 10P + 7K sod seeding of 45 000 plants then 2 hoeings, loosening around roots.
2. T + SB = *idem* 1 + stone bunds on contours at 40 kg/m^2, i.e. 2 lines of ironstone blocks every 20 m + lateral ties as from 1980.
3. T + SB + Ti = *idem* 2 + ox-drawn ploughing between 15 June and 15 July and sowing on the same day.

b. The stone bunds have little effect on overall runoff or on runoff during rainfall on rough soil (Kaar - see page 46), but much more on peak flows, the curbing and spreading of flow, and risks of erosion. The hydrodynamics depend on interaction between the bunds and the roughness of the soil. The impact on yields depends on the volume of rainfall and its distribution at flowering and earing.

c. Tillage, here combined with erosion control, can significantly improve infiltration of the first 100 mm of rain. After this, slaking and sedimentation crusts are so marked that gains in infiltration due to stone bunds become negligible.

d. The contribution of runoff harvesting is noticeable primarily on the **uphill plots** as long as the soil is absorbent enough; it increases the risks of drainage on the uphill side of the bunds.

e. Improving the water supply to plants raises the problem of replenishing available soil nutrients: increasing production of unrestored biomass hastens soil impoverishment.

f. The positive effect of tillage on improved infiltration and yields decreases from one year to the next, while losses through erosion increase. It seems that tillage weakens the soil, making it more erosion-prone, while hastening the mineralization of humus in the soil.

These results prompt certain observations:

1. The gain in infiltration when the flow of sheet runoff is slowed down by the stone bunds is relatively meagre if the ground is smooth, but much more substantial when the ground is kept rough by tilling, hoeing and ridging. There is thus a very positive interaction between tillage, soil roughness, and the effectiveness of stone bunds (Figures 50 and 51).

2. Since the main effect of stone bunds is that of curbing the flow of water by spreading it before these obstacles, peak runoff flows near the foot of the slope are reduced, flow persists longer after rainfall, and the speed of sheet runoff is reduced - which means that the sediment load is reduced by 50%.

3. Normally more biomass is produced with stone bunds except when waterlogging hinders the growth of millet. Millet grain production increases by 15 to 50% on fields with stone bunds, and by 50 to 80% when tillage is combined with stone bunds. However, during the driest years (e.g. 1985), yields are as low as on untreated plots. The use of such lines therefore does not reduce famine risk in years of serious drought. Millet yields can also suffer from waterlogging when monthly rainfall is over 200 mm.

4. The effect of a stone bund is felt primarily uphill, and secondarily downhill:

   - uphill, sedimentation of sand and organic matter over 2 to 6 m, due to the spreading of sheet runoff; the stone bund becomes blocked to a height of 5 to 15 cm, which improves the topsoil; this area then receives an extra amount of water, which can improve the crop water supply but may lead to waterlogging and to leaching of nutrients through drainage (sorghum is less prone to this than millet);

   - downhill, water trickles through between the top stones, and may either spread out in a sheet and irrigate the whole area once more, or concentrate into rills and dig paths for itself (gullying sheet erosion) which will drain, dig into and dry out the downhill area, and possibly destroy the system of stone bunds at some points through headward cutting; since the positive effects are confined to the neighbourhood of the bunds, it would be better to set up small lines every 20 m (25% of the area affected by treatment) rather than large ones every 50 m (only 10% of the area affected by treatment), particularly since large stones tend to funnel the flow into larger streams and hence increase the risks of heavy concentrations of water.

5. When sheet runoff is slowed down, pools accumulate along the line. This water will then move sideways to exit at a low point in the bund, and can thus cause lateral erosion and a dangerous concentration of water. Many solutions have been suggested to this problem of sideways movement: tied ridging or loosening around the roots to give a very rough soil surface, setting up ties perpendicular to the bund, or planting grass (*Andropogon*) to stabilize the immediate area of the bund.

FIGURE 49
Diagram of the experimental layout at Bidi in Burkina Faso

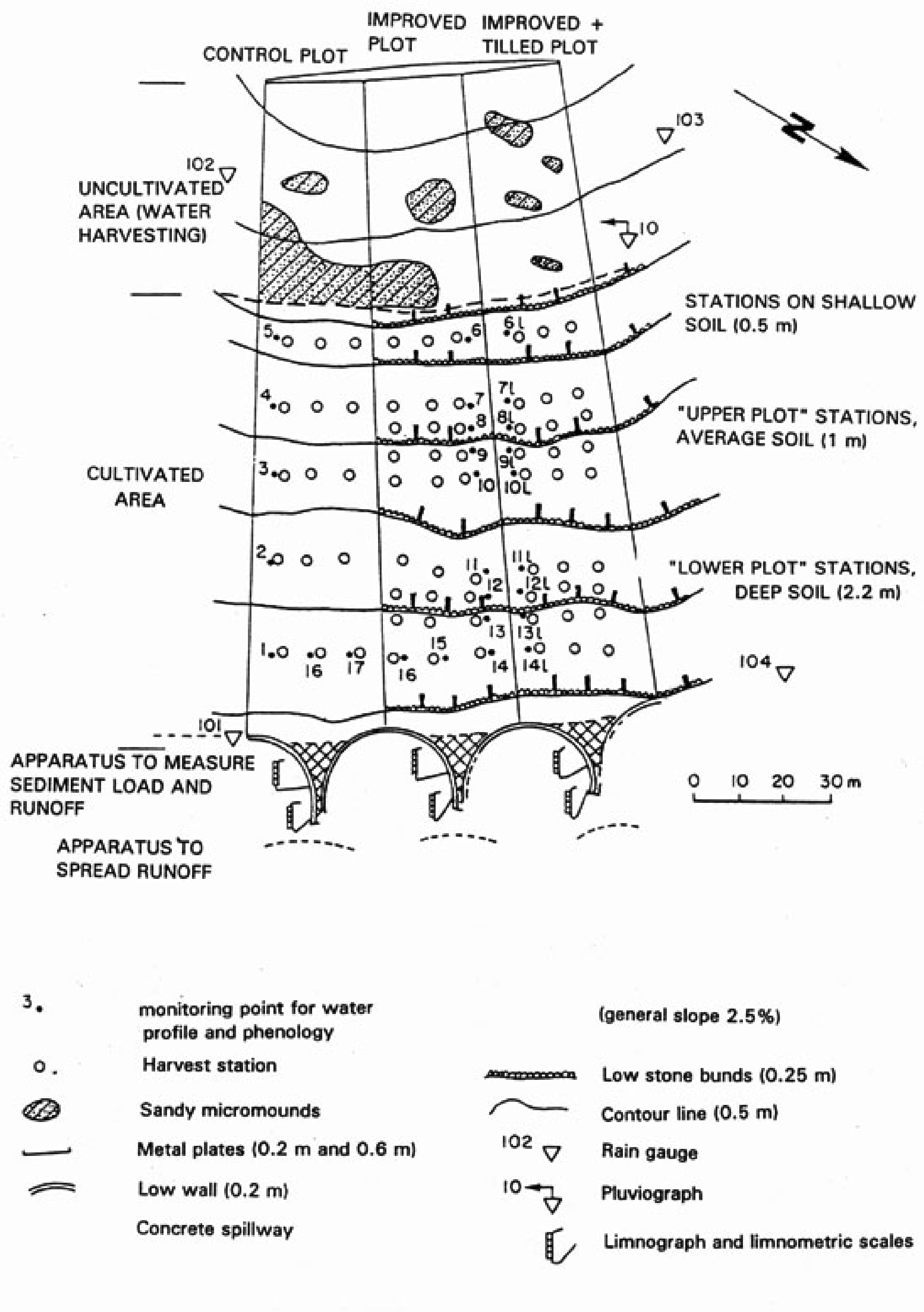


FIGURE 50
Comparison of runoff: control plot/treated plot. Average rainfall

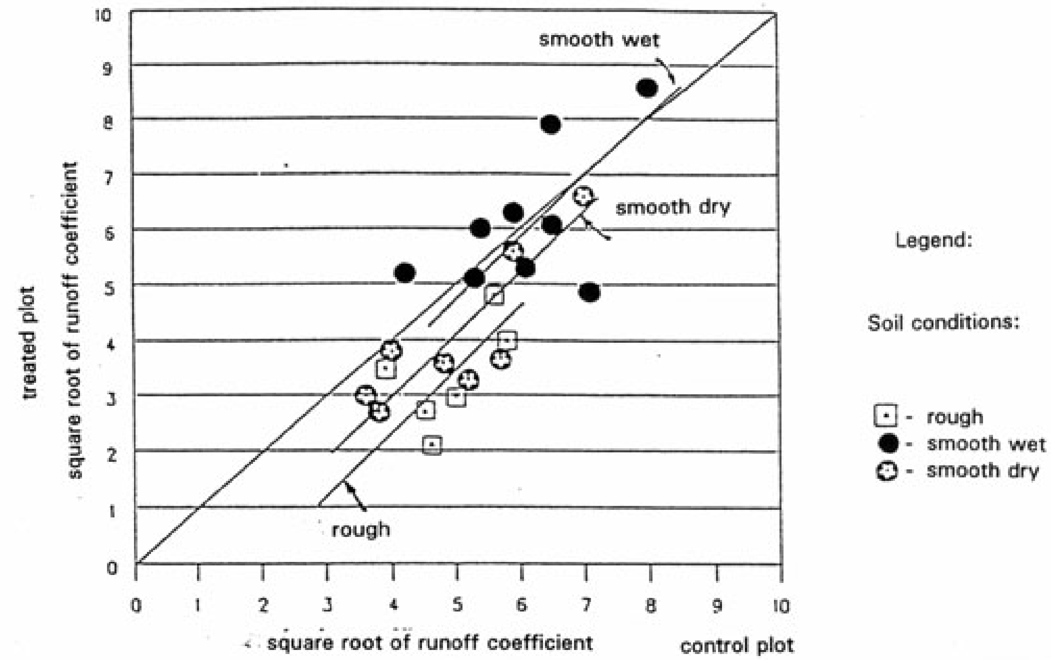


FIGURE 51
Comparison of runoff: control plots/treated plots as a function of rainfall aggressiveness

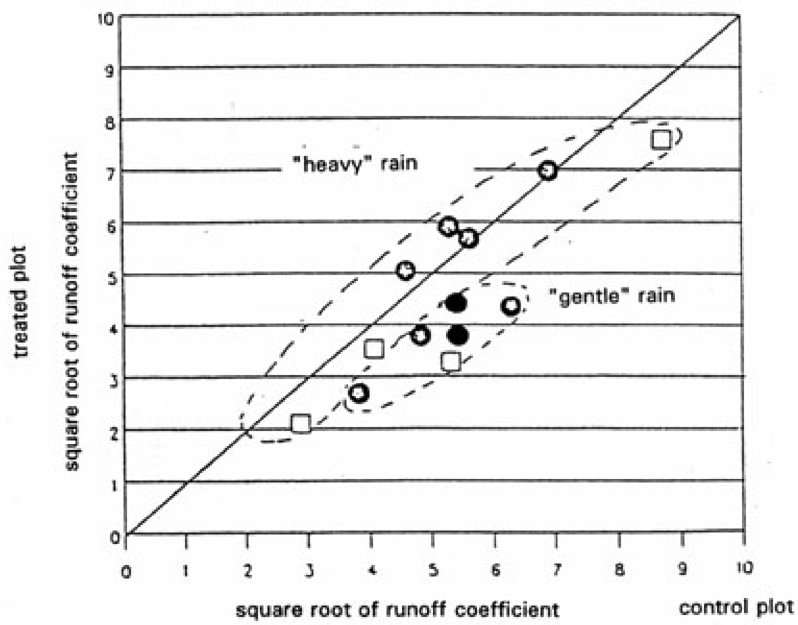
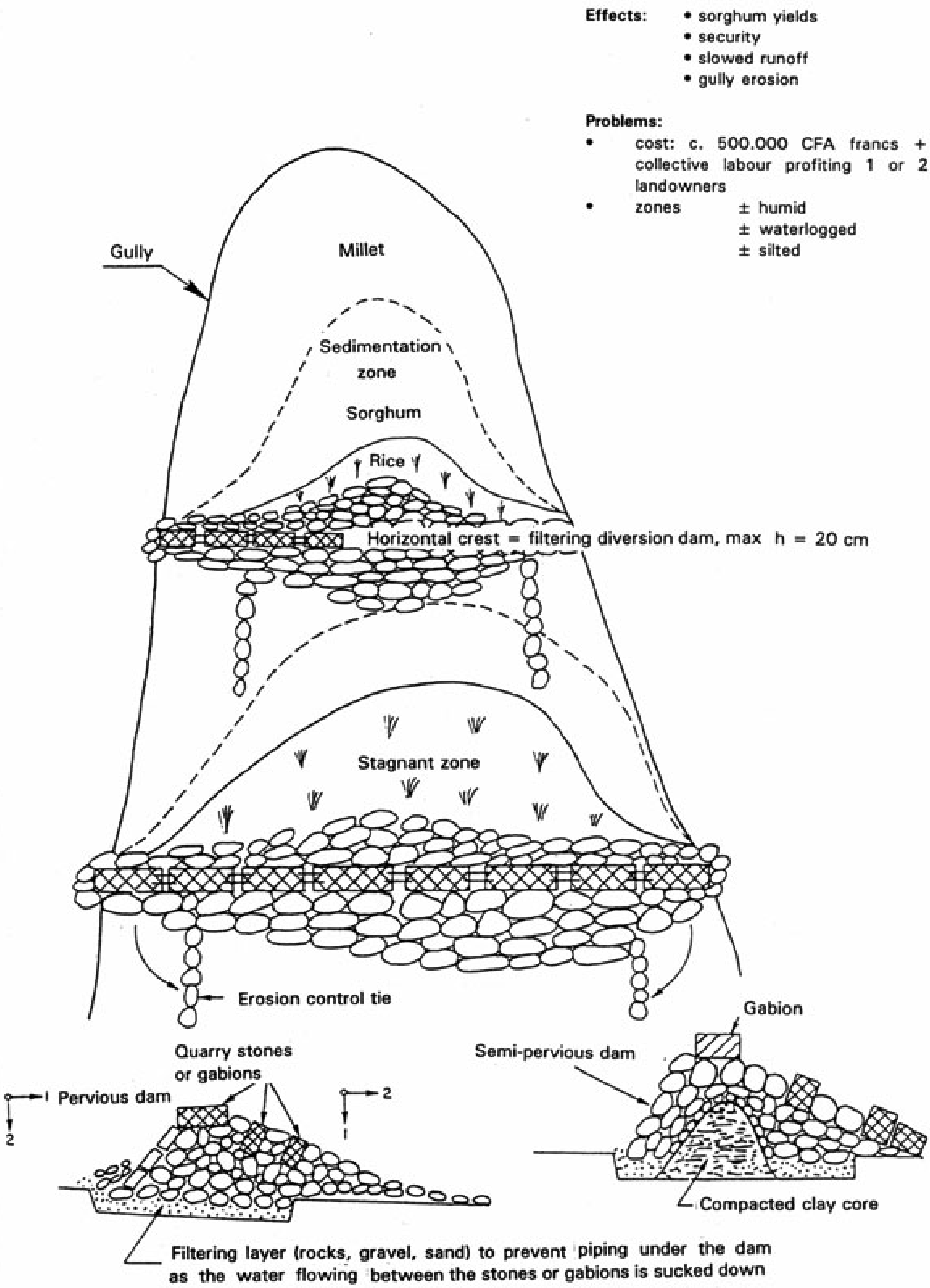


FIGURE 52
Pervious or semi-pervious check dam



located around the valley in fact profit from the increased groundwater recharge from a check dam. It is therefore important to have a clear idea of objectives. Check dams recharge groundwater but do not hold back much water – in any case not enough to produce rice four years out of five in the Ouahigouya region. If the aim is to create a rice field, it is best to choose an impervious soil-saving earth dam, which will hold back a large enough sheet of water for this crop.

Problems connected with land ownership should also be borne in mind, for building a check dam of this type requires considerable work on the part of the local community (15 people for 30 days) and the transport of a huge volume of stones (from 100 to 500 m^3, at an average cost of 4 to 40 000 FF). And although the structure takes all this effort on the part of the community, it in fact allows improvement of a mere 0.5 to 1 hectare, probably belonging to a single family. In order to avoid wrangling, advance plans should be made to redistribute the improved land to those taking part – not always a possible solution. Another solution is to negotiate a form of payment by the beneficiary to the neighbours who help in the work, by creating a bank which advances money and recovers it on improved harvests in the following years. Food for work, payment in kind, or an undertaking to work for the others for some days, are other possibilities.

The same amount of effort and the same volume of stones could go to improve 10 to 20 hectares of sloping land belonging to twenty families, who could easily build the necessary stone bunds on their own. It has not yet been ascertained whether this form of watershed management can offer the same production security as management of the valley bottoms, bearing in mind that although certain bottoms are completely flooded in the rainy season, in particularly dry years they are the only places where villagers can be sure of a certain level of productivity.

The importance of ensuring household food security makes it vital to improve both the land in the valley bottoms, which will produce even in dry years, and the land on the hillsides, which will produce best in wet years.

However, it must always be borne in mind that, like other methods, this is not the universal solution. It is valid for certain gullied valley bottoms, but much less so for flat bottoms, where there is very little sedimentation.

In conclusion, there is a wide variety of semi-pervious microdams. They have the advantages of being easy for villagers to build, and of changing topographical conditions (the gradient of the slope). However, they do lead to the loss of some runoff as well as the nutrients and colloids that represent the wealth of these soils. This water could be recovered further downstream by irrigation infrastructure.

VARIABILITY OF EROSION FACTORS

Before opting for a specific erosion control method, it is best to take another look at the causes of erosion and the factors that modify the form it takes under the environmental conditions where this work was done – i.e. the old and weathered hills of Africa.

By analysing the available findings of the erosion forecast equation – i.e. 560 plots per year – these various factors can be reviewed and quantified (Roose 1975):

- **The climatic aggressiveness factor** (R_{USA}) is very high, rising from 200 units in northern Burkina Faso to over 1 400 in southern Côte d'Ivoire (Figure 17). Moreover, it is very unevenly divided over the year: 75% of annual R is often concentrated in 2 or 3 months at the start of the cropping season when the soil has little covering.

R, the erosive force of rainfall, varies from 100 to 2 000

- **Soil resistance to erosion** of ferralitic soils (K = 0.01 to 0.18) and cropped tropical ferruginous soils (K = 0.2 to 0.3) is much better than that of many leached soils in temperate regions (where K varies from 0.2 to 0.7).

K, soil erodibility, varies from 0.01 to 0.3

However, it is difficult to reduce erodibility once a soil has become degraded and lost its organic matter, clay, structure and permeability: K rises from 0.1 to 0.2 or 0.35 with the degradation of cropped soils.

- **The topographical factor** combines the length (L) and slope (S) factors. The length factor is neither constant nor very great: for practical reasons, a team of American scientists has estimated that erosion increases in proportion to the square root of slope length (SL^2). Slope (gradient), on the other hand, does have a decisive effect. Sediment load increases exponentially (exponent = ± 1.4 to 2) with the percentage of slope (Zingg 1940, Hudson 1973, Roose 1975) – or in accordance with a very close second-degree equation (Wischmeier and Smith 1960). On the commonest slopes (0.1 to 15%) with a length of 60 metres, SL varies from 0.1 to 5.

SL, the topographical index, varies from 0.1 to 5
(and up to 20 in mountainous areas)

- **Soil cover** (the C factor) from plant cover (and stones) has a much greater effect than all the other erosion factors. Thus, however aggressive the climate, whatever the slope, whatever the soil type, erosion will be slight with a soil cover of over 90%. However, it should be noted that cropping techniques play a major rôle during the crop growth cycle.

C, the interaction between plant cover and cropping
techniques, ranges from 1 to 0.001

In conclusion, in the tropical regions of interest here, the most important factors for interventions to curtail erosion and runoff are plant cover and slope. There seem to be four feasible biological approaches.

1. Intensified cropping on the best and least sloping lands. Special attention should be given to sowing dates and rates, fertilizer, straw and crop residues on the soil surface, preparation of the seed-bed, and management of organic matter.

2. Protection of the areas most vulnerable to fire and overgrazing by the provision of permanent cover (forest, savannah, pasture or orchard).

3. Treatment of gullies and outlets to evacuate temporary excess water with minimum sediment transport. Provision of access to plots and drainage systems.

4. Definitive land management at the watershed level, with the use of erosion strips as risers and the rough alignment of all tillage operations perpendicular to the steepest slope.

Unlike mechanical interventions, which are not cheap, not cost-effective, and not easy to maintain, the biological methods suggested here are well-suited to tropical conditions where grass is abundant, slopes are medium, and technical and financial resources are scarce. Similarly, with a view to stabilizing water supplies and waterways and protecting roads and irrigation works, as well as increasing farm production, there is no doubt that it is more helpful to increase absorption over the whole farmed area by extending plant cover than by evacuating all excess runoff.

CONCLUSIONS ON THE APPLICABILITY OF THE USLE IN AFRICA

Now that erosion has been measured on quite a few -- more than 560 -- experimental plots in West, North and Central Africa, there is a basis for questioning the applicability of the “universal” soil losses equation (Wischmeier and Smith 1978) in Africa.

1. The equation applies only to **sheet and rill erosion** (hence to the nascent erosion that concerns us here) in hilly country, excluding mountainous areas where landslides and linear erosion (rills, gullies and torrents) are predominant. It addresses neither the type of runoff nor suspended load. If necessary, each subequation can be adjusted to take account of runoff energy on steep slopes.

2. This empirical model requires **a large number of results** replicated at different times and places, for it looks at behaviour in the medium and long term (20 years). The use of rainfall simulators (with one-time data for each situation) can offset the lack of data on plots under natural rainfall, but cannot replace them. It is always difficult to compare specific results obtained under simulated rainfall with average results over a number of years on actual plots. Experiments on agricultural stations are long and costly. In practice, in the absence of sufficient local results, **use can be made of the tables presented in this work**, which give the corresponding coefficients for Africa or the United States (cf. Wischmeier and Smith 1978).

3. The equation is based on results on **small plots** (100 m^2), fields or very small catchments (a few hectares). This leads to **problems of scale** when trying to forecast regional figures for erosion, and especially for predicting sediment load in large watersheds where water management systems may be threatened by siltation.

4. **It is difficult to set precise figures for tolerable erosion levels**, since the equation ignores the quality of eroded material. The wealth of many tropical soils is stored in the top 20 centimetres (especially under forest), and sheet erosion selectively carries away organic and mineral colloids, plus nutrients, which together assure the soil's water and chemical reserves (Roose 1967; 1973).

5. **The equation seems to apply fairly well to soils rich in kaolinite**, tempered, leached, brown soils, and tropical ferralitic and ferruginous soils, excluding soils rich in swelling clay (vertisols, tropical brown soils, saline soils), which very quickly present large-scale gullying due to their poor absorption capacity once they are wet.

6. Lastly, **the equation ignores interactions between the different factors –** interactions that proved very numerous as the results were analysed. For example, soil reaction to rainfall aggressiveness differs greatly depending on slope, whether the soil is clayey (rill erosion) or sandy (sheet erosion), and the condition of the soil surface (roughness due to cropping methods, prior soil moisture, management of crop residues).

Granted all this, it must be recognized not only **the practicality of this equation** in the field for rational land use planning, but also **its scientific value** in defining the relative influence of each of the factors involved. It is therefore very effective in fulfilling its purpose of defining the erosion control techniques to select in a given situation. On the old continent of Africa, use of Wischmeier's equation seems justified by a large number of results (560) concerning the soils, crops and slopes most widely farmed.

The aggressiveness factor takes full account of how cumulative rainfall and rainfall intensity and duration interact with soil losses. It might also be combined with a soil moisture factor that would show how wet the soil was before the rain. The laborious processing of thousands of pluviogrammes gave a first rough idea of the geographical distribution of mean annual rainfall aggressiveness in the southern part of West Africa, apart from the coastal strip and mountainous areas, indicating that rainfall is fairly homogenous in terms of how much, how hard, how long and how often. However, there is still the question of whether erosion control should be based on average figures for rainfall aggressiveness or on **the dangers represented by exceptional storms that occur at ten- or even hundred-year intervals**. Tests on the latter approach have not yet been carried out.

Soil cover in the form of plant cover and stones is much more important than all the other factors affecting erosion. Plant architecture and cropping techniques become secondary once the soil has a 90% cover. However, cropping techniques can have an effect during the growing phase, and the C factor allows selection of the techniques and plants best suited to local environmental conditions.

Soil erodibility. Contrary to an opinion widely held by agronomists, tropical ferralitic soils, and to a lesser extent tropical ferruginous soils, especially those with a high gravel content, seem less vulnerable than many leached soils in temperate regions. The striking damage found in tropical areas is in fact a result of the particular aggressiveness of tropical rains. The nomograph put forward by Wischmeier, Johnson and Cross in 1971 to allow rapid calculation of the index of soil resistance to erosion seems applicable so long as it is combined with a qualifying coefficient that takes account of the gravel or rock débris present in the tilled horizon (Dumas 1965). Lastly, it would seem that soils rich in swelling clay, such as vertisols, tropical brown soils and volcanic soils, require individual examination, for

TABLE 38

Assessment of measures to be taken to reduce erosion to tolerable levels (here E = 1 t/ha/yr): example of the Sudano-Sahelian, cotton-growing area of Mali

R	K	Max E risk t/ha/yr	Erosion control method	SL	C	P	E risk t/ha/yr
400	extensive system→0.3	120	(a) No control	0.4	0.8	1	38.4
			(b) Diversion ditch/50 m	0.24	0.8	0.5	11.5
			(c) Stone line/25 m	0.12	0.8	0.5	5.7
	intensive system→0.2	80	(a) No control	0.4	0.4	0.5	6.4
			(b) Diversion ditch/50 m	0.24	0.4	0.5	3.8
			(c) Stone line/25 m	0.12	0.4	0.5	1.9
			(a) + tied ridges	0.4	0.4	0.1	1.3
			(b) + tied ridges	0.24	0.4	0.1	0.8
			(c) + tied ridges	0.12	0.4	0.1	0.4
			(a) + mulch or live cover	0.4	0.01	1	0.3

they act in a very specific way and the equation therefore does not hold in their case. Analysis is still needed of the very specific manner in which runoff appears.

The topographical factor, particularly length of slope, certainly represents a weak point in the equation, for it should be adjusted according to type and texture of soil, and type of plant cover. However, until sufficient data are collected under natural or simulated rain, it can be used in most practical cases. The caveat is, however, important for the choice of erosion control techniques, which are too often based on reducing length of slope, an approach effective only for rill erosion and rarely for sheet erosion. Such reservations must be even stronger when the effect of topographical position exceeds that of slope, for example where headward erosion has its origin in the drainage network or the valley bottom.

Biological-type erosion control techniques – in other words, those encouraging soil cover – are therefore the most effective, the least costly, and the best suited to conditions on the plains and largely undulating uplands of the old continent of Africa.

In conclusion, Wischmeier and Smith’s equation cannot be described as universal, for it applies neither to swelling clay soils, nor to volcanic soils, nor to mountainous regions with young landforms where linear gullying erosion is predominant, nor to Saharan and Mediterranean areas where exceptional rainfall has a decisive importance. Nonetheless, it seems well suited to forecasting erosion in most types of cultivated land in West Africa, particularly gentle to medium slopes on clayey-sandy, tropical, ferralitic and ferruginous soils.

IMPLEMENTATION OF WISCHMEIER’S EROSION FORECAST MODEL

The aim here is that of defining a production system (including productive crop rotation, feasible cropping techniques and effective erosion control structures) which will keep erosion risk below the tolerance threshold – generally recognized as between 1 and 12 t/ha/yr, depending on soil-type. **The Sudano-Sahelian, cotton-growing area of Mali can be taken as an example** (Table 38):

1. Rainfall = 800 m : mean R index = 800 x 0.5 = 400 t/ha/yr (Figure 17).

2. The K factor – indicating erodibility – for cultivated tropical ferruginous soils in the region ranges from 0.3 for degraded soils to 0.2 for an intensive system recycling a great deal of organic matter (Figures 20 and 21).

3. SL, the topographical factor. Supposing that cropping is on a broad pediment with a 2% slope 300 metres long:

   - Figure 22 shows that SL = 0.4;
   - if a diversion ditch is introduced every 50 metres, SL = 0.24;
   - if a diversion ditch is introduced every 25 metres, SL = 0.18;
   - if a low stone bund or a hedge is introduced every 25 metres, SL = 0.12,

   for each bund creates a 25-cm-high bank which reduces the gradient of the slope.

4. The C factor, for a continuous rotation, ranges from 0.4 to 0.8 depending on whether cropping is intensive or extensive (Table 29):

   - the addition of groundnut would change nothing (C = 0.4 to 0.8);

   - the succession of 4 years of cropping + 4 years of fallow would cut C by half

     $$\text{Ccscsffff} = \frac{0.4 + 0.4 + 0.4 + 0.4 + 0.1 + 0.01 + 0.01 + 0.01}{8} = 0.2$$

     (Ccscsffff = a crop rotation of cotton, sorghum, cotton, sorghum, fallow, fallow, fallow, fallow)

     In the long term, the risks have been halved thanks to the fallow, but four years of production have been sacrificed.

     In order to maintain production, another plot would have had to be cleared – a solution no longer possible in some areas of Africa, where population pressure causes landholding problems.

   - A purely biological solution is possible with the use of mulch or cover plants (C = 0.01, and E = 0.32 t/ha/yr) without resorting to either erosion control structures or ridging.

5. **Erosion control practices (P).** Calculations show that introducing erosion control structures is not enough; cropping practices and/or rotations must be altered. In the best of cases, with an intensive system, stone bunds every 25 metres and contour tillage, the erosion risk is still double the tolerance level (E = 1 t/ha/yr).

   If tied contour ridging is introduced, erosion ranges between 0.4 and 0.8 where runoff dissipation or diversion structures are adopted. Although this second solution is a mechanical one and hence more expensive, it is also easier to implement in a semi-arid region where the biomass is eaten by livestock and the rainy season is too short to grow pulses as a catch crop under cereals.

Chapter 6

Linear erosion

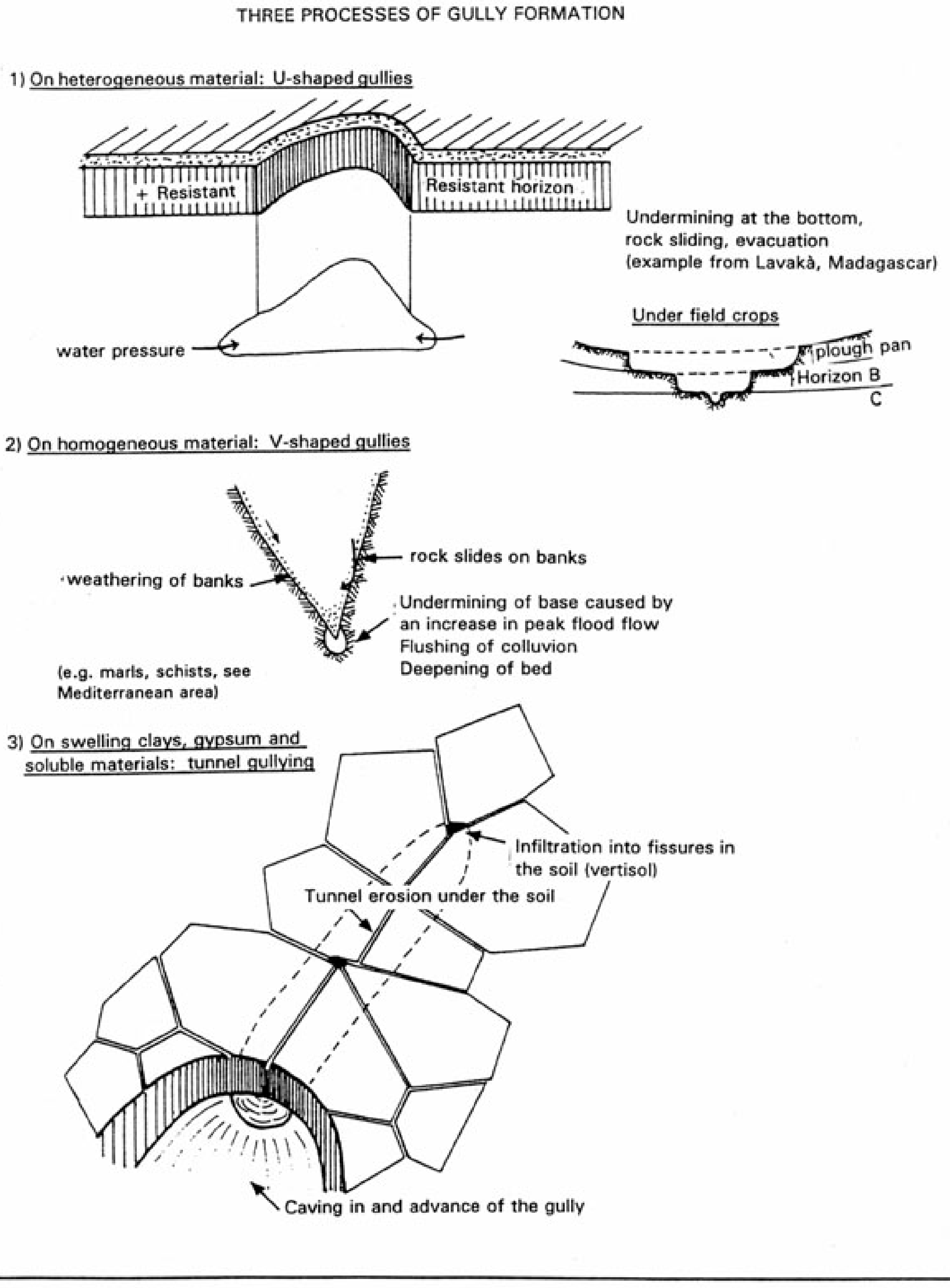
When rainfall intensity exceeds the absorption capacity of the soil surface, puddles form which are then joined up by rivulets of water, and when these rivulets reach a certain speed – 25 cm per second according to Hjulström (1935) – they take on an energy of their own. The energy such erosion generates is confined to and concentrated in flow lines on the steepest slopes, and no longer spread over the whole surface. Linear erosion is therefore an indication that runoff has become organized, picking up speed and acquiring a kinetic energy capable of cutting into the soil and carrying away larger and larger particles – and not only clay and silt as in selective sheet erosion, but gravel or pebbles and larger blocks once gullying begins.

There are some very well-researched manuals on the treatment of linear erosion (Hudson 1973; Gray and Leiser 1982; Cemagref 1982-88; Geyik 1986; Heusch 1988), as well as vast numbers of specialized articles (Boiffin, Papy and Peyre 1986; Watson, Laflen and Franti 1986; Govers *et al.* 1987; Laflen 1987; Meunier 1989; Poesen 1989; Deymier 1992; Combes 1992). The present work is concerned chiefly with controlling soil degradation and the onset of erosion. It will therefore give a brief description of the various types of gullying and their causes, followed by an explanation of treatment for medium-sized gullies within the reach of small farmers, and the principles to be followed by non-expert developers in order to avoid the main causes of failure (see the "Ten Commandments", page 216). The reader can consult the specialized works listed in the bibliography for further information on torrent and large gully control. The following chapters will approach mass movement and wind erosion in a similar manner.

FORMS OF LINEAR EROSION

Once runoff starts, lightweight particles are carried away – particularly organic matter, crop residues and animal faeces, as well as fine particles of clay, loam and sand. "Flood debris" can be seen on the ground, often made up of long, fibrous, organic matter, but also ribbons of sand, which are very frequent in wadis. Linear erosion [Plate 13] appears when sheet runoff becomes more organized, digging deeper and deeper into the ground. The results are described as **grooves** when the little channels are only a few centimetres deep, and **rills** when they are over 10 centimetres deep but can still be eliminated through cropping techniques. **Gullying sheet erosion** is when the channels are between 10 and 20 centimetres deep but as much as several metres wide, and real **gullies** are when the channels are at least 50 centimetres deep and, more specifically, when they can no longer be eliminated through cropping techniques. The gully category can then be subdivided. First, there are **small gullies**, where the bed is still overgrown with leafy – and especially shrubby – growth, and that can be quickly stopped by biological methods. On the other hand, in **large gullies**, which can stretch for several kilometres, the central channel contains rocky

FIGURE 53
Forms of linear erosion



boulders as evidence of large-scale sediment transport and a certain **flashiness**. Since the bottoms of such gullies are mobile, biological methods alone are no longer capable of stabilizing them, and cement sills and expensive mechanical methods will have to be used (Lilin and Koohafkan 1987, Mura 1990).

Gully shape is also important. Some are **V-shaped**, with an even slope down to the lowest point, others are **U-shaped**, with vertical sides, and still others develop **through tunnelling** and subsidence (Figure 53). **Large or torrential gullies** are those in which floods are so violent and frequent and sediment transport so extensive that there is no hope of establishing plant cover in their bed within a reasonable timeframe. Examination of the bed itself completes the diagnosis. The bed of a torrential gully is usually blocked with coarse alluvial deposits, and there is very little woody vegetation. On the other hand, in small gullies which will respond to biological treatment, alluvial deposits are finer and woody vegetation is still found in some sections – so long as the degradation of such vegetation has not been too much exacerbated by cropping (Lilin and Koohafkan 1987).

THE CAUSE AND PROCESSES OF LINEAR EROSION

The cause of linear erosion is to be sought in runoff energy, which depends on runoff volume and its squared speed.

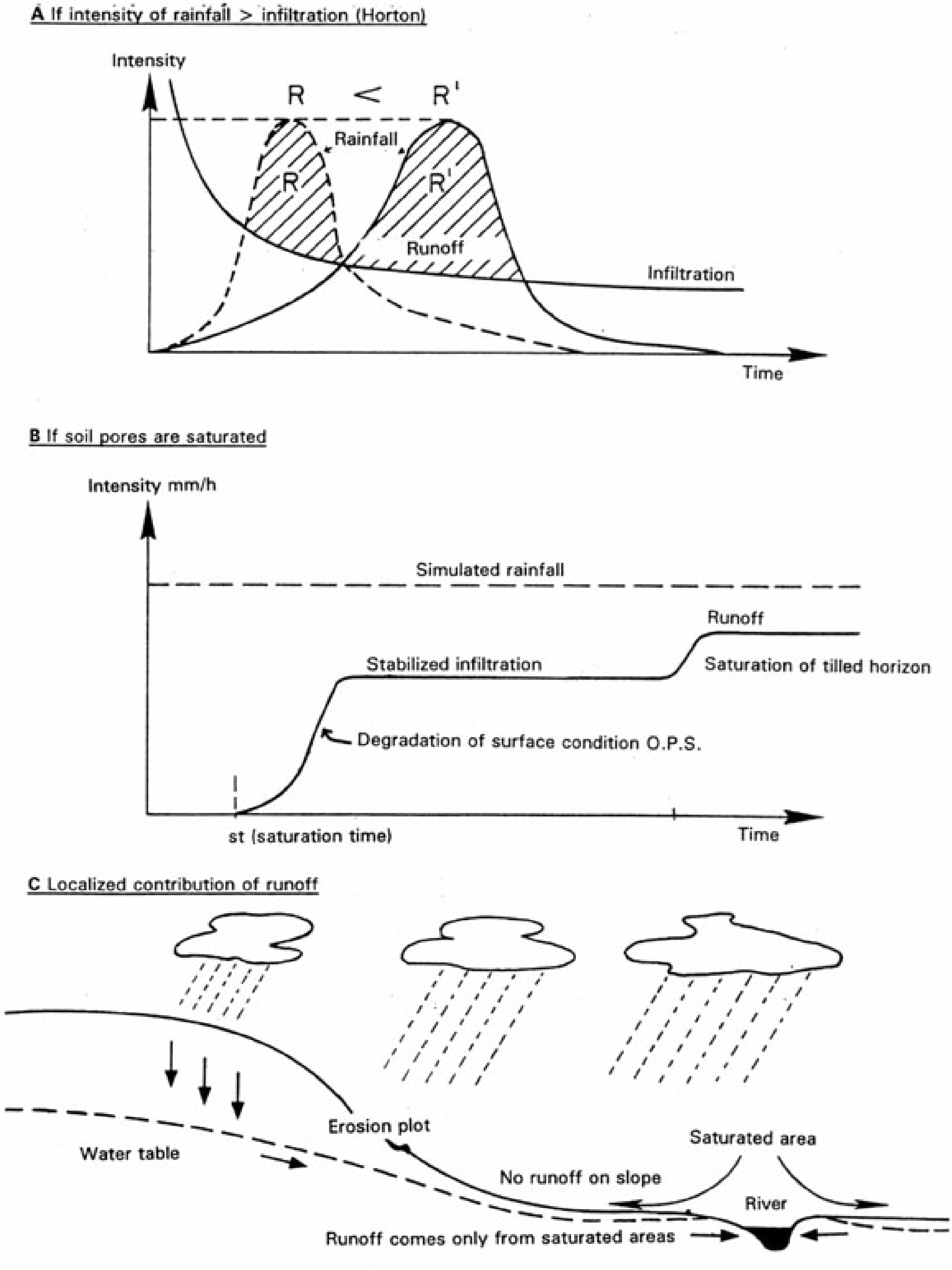
THREE THEORIES OF THE ONSET OF RUNOFF

1. **Horton's theory (1945).** Runoff starts when rainfall intensity exceeds soil absorption capacity (Figure 54a). Comparing infiltration to rainfall intensity, absorption decreases over time partly because capillary potential falls as the wetting front penetrates into the soil, and partly because soil structure at the surface has deteriorated. Rainfall generally has one or several peaks, and any volume of rain over the infiltration curve can be considered runoff. In the example chosen, even at similar intensity peaks runoff volume can vary considerably depending on when peak intensity occurs during the storm. The earlier this peak, the less runoff there will be, since absorption capacity decreases over time. However, hydrologists were unable to obtain any clear correlation between runoff volume for a watershed and rainfall intensity, and so another explanation had to be sought.

2. **Soil saturation theory.** Runoff starts when all the pores in the soil are filled with water (Figure 54b). In the course of a simulated rainstorm, if runoff starts after rain has soaked the soil, it will increase until it stabilizes at a level corresponding to the absorption capacity of the soil. However, if the rainfall persists (more than 100 mm), runoff may rise again, reaching a new plateau of stabilized infiltration. This simply means that the tilled horizon has reached saturation, so that the macroporous storage capacity of this horizon is filled to overflowing. If the underlying horizon is totally impervious, the amount of runoff will correspond precisely to that of the simulated rainfall; there may, however, be a certain residual absorption capacity corresponding to that of the plough pan. When the soil is totally saturated, any drop of rain will run off, irrespective of rainfall intensity.

3. **Theory of partial watershed surface contribution to runoff.** Figure 54c shows that the runoff measured at river-level depends on **the area of the saturated soil in the valley bottom**. If watershed surface runoff

FIGURE 54
Onset of runoff: three theories



is measured during the dry season, it is seen that the river reacts very quickly to rainstorms whereas no runoff is seen on the slopes! The volume of runoff is less during this dry period because only a narrow strip in the valley bottom is saturated – often only the minor bed. At the end of the winter, however, when the whole soil cover has been soaked to capacity, the slightest rainfall replenishes the aquifer, which will spread out sideways, saturating a greater area of the valley. As a result, **even if there is no runoff on the slope during the rainy season, the entire watershed will contribute to the volume of flow in the river through extension of the saturated area**, inasmuch as the groundwater is recharged directly by draining the entire basin.

Erosion control therefore takes a different form depending on the origin of runoff. If, as in the first case, runoff is a result of degradation of the soil surface, erosion control will primarily entail protecting this soil surface through plant cover, or delaying formation of a slaking crust. If, on the other hand, runoff sets in after saturation of the soil, the first step will be to control drainage. Plants will slow runoff and store it temporarily, thus reducing peak floods and the energy available to carry away solid matter. Lastly, if runoff appears only at specific places in the watershed, there is no point in setting up diversion bunds on the banks of steeper slopes, for very little runoff forms there. This explains the failure of many erosion control projects, which simply apply prescriptions developed in temperate regions under very different environmental conditions (for example, diversion ditches in Sudano-Sahelian areas).

THE PROCESS OF GULLYING

The kinetic energy of raindrops on a slope is more or less constant, depending on the wind-speed. Runoff, on the other hand, tends to accumulate and run together on a longer slope. If the peak flow increases, the soil surface will be cut and a rill will start to form. It will then deepen as the water-borne sediment abrades the bottom of the rill, the edges cave in, and the material thus dislodged is carried away.

V-shaped gullies are the form most common in nature, and tend to be found in relatively loose, **homogeneous material –** sandy-clay, clay, marl, or schist. The slopes of these gullies alter as the rock weathers: in cold seasons through the alternation of freezing weather and sun, and in hot seasons through the alternation of dry and stormy periods. In Mediterranean areas, weathering can reach 4 to 10 mm per year for marl and schist. Subsidence takes place during exceptional rainstorms. One or two storms per year are enough to carry away all particles accumulated in the gully bottom during the year, and for the solid load in the runoff to abrade the valley bottom.

During intermediate seasons, the fine matter accumulated on the slopes as the rock weathers slides down to the bottom of the gully, partly as a result of the impact of raindrops, partly through formation of small secondary rills, but most often through the mass sloughing of water-saturated particles. Since slope equilibrium has been far exceeded, no vegetation can take root. Erosion control must therefore concentrate on preventing further excavation of the bottom of the gully and re-establishing equilibrium.

U-shaped gullies are a second type common in nature on **heterogeneous material**. The base may be made up of very resistant material, in which case the channel will broaden as the sides cave in during exceptional flows. If, on the other hand, the resistant layer is found on the surface, runoff will cut deep into the material until it reaches a temporary or permanent water table, which will exercise lateral pressure on the base of the slope until it caves in (undermining the banks). Here again, the gully bottom must be stabilized and the sediment retained until the slopes attain equilibrium. In the agro-industrial farmlands of the Paris basin, there are also “boxed” U-shaped gullies which cut down through increasingly sticky silt from the seed bed down through the tilled horizon and plough pan into the compacted untilled B horizon.

Tunnelling is a third form of gullying, and is still more difficult to treat. It can develop on gentle slopes, in material with surface cracks, on soil rich in swelling clay (vertisols, tropical brown soils, etc.), or on marl rich in gypsum or other soluble minerals (frequent in the Mediterranean basin). During end-of-dry-season rainstorms, the water penetrates these cracked soils down to the weathered rock, percolating through the cracks to the bottom of the slope, where headwater-cutting can form gullies. As hypodermic runoff pours into cracks in the soil, these will gradually become tunnels, which will in due course cave in, forming headward-cutting gullies that can advance by several dozen metres during major rainstorms. Dry tillage is the only way of blocking these cracks and forcing the water to wet the whole soil mass instead of soaking primarily into the megapores.

FACTORS IN RUNOFF

FACTORS AFFECTING THE VOLUME OF RUNOFF

- **Rainfall is the primary element: cumulative rainfall** in cases where runoff sets in after saturation of the soil, or **the intensity of rainfall over 30 minutes** (Wischmeier and Smith 1960, Roose 1973), which is what affects rainsplash and the onset of runoff. On steep slopes in the Andes, the maximal intensity is counted over 15 minutes (Ecuador: De Noni, Viennot and Trujillo 1989).

  In Zimbabwe, Hudson claims that rain causes almost no runoff or erosion on very resistant oxisols when rainfall intensity is less than 25 mm per hour. There are therefore **intensity thresholds for rainfall** below which runoff cannot start on a permeable soil (Casenave and Valentin 1989, Raheliarisoa 1986). Using a rain simulator, Lafforgue and Naah (1976) demonstrated that in the case of **a rough soil surface** the absorption capacity of the soil increases with any increase in rainfall intensity. On the other hand, if the soil has a finely powdered, smooth surface, an increase in rainfall intensity has no effect on absorption. On fragile, loamy soil, infiltration decreases as rainfall intensity increases, for an almost impermeable slaking crust forms faster (Raheliarisoa 1986).

- **Soil moisture content prior to rainfall is the second element affecting the volume of runoff.** This factor is expressed either in terms of the lack of soil saturation before the rain (pores not swollen with water), or in terms of the number of hours before it rained, or by use of the Köhler index. The amount of rain absorbed is generally much higher for a dry soil than a moist one: while it may be 10 to 40 mm for dry soil, it will often be only 1 to 10 mm for moist soil. There is **an interaction between the condition of the soil structure and initial soil moisture**. Boiffin (1976) and Raheliarisoa (1986) demonstrated that simulated rainfall on a dry, loamy soil can degrade the soil surface faster than on already moistened soil.

· The third point affecting the volume of runoff is **the size of the catchment area** drained by the same channel (Zimbabwe: Stocking 1978).

· **The state of the soil surface** encompasses:

- soil surface structure;
- cracking;
- holes of biological origin;
- roughness.

Soil roughness mainly influences the amount of rain absorbed before the soil is saturated, but the influence of this factor decreases with steeper gradients, for the volume stored in puddles decreases on steep slopes.

When the soil surface is degraded, clods dissolve, and a **thin structural crust** forms on their surface, thus reducing infiltration to a few millimetres – or a few dozen millimetres – per hour. However, **the sedimentation crusts** that spread over the area, starting with the puddles between the clods, can be as thick as several centimetres and have extremely low infiltration capacity: from 0 to 10 mm/h. Runoff on a given plot will thus depend on the area covered by the various types of crust, and by the macropores that remain open between the clods on the soil surface.

· **The gradient of the slope.** This generally reduces the volume of runoff, for on a steep slope internal drainage is better, and a slaking crust forms more slowly as it is continually destroyed by runoff energy. **The length of the slope** also affects the volume of runoff, but although this volume, expressed as a percentage, theoretically remains constant all the way down the slope, in many instances of bare soil it seems that the runoff coefficient decreases as the slope lengthens (Roose 1973, Valentin 1978).

· **Cropping techniques** can increase absorption to a considerable degree. At Pouni in Burkina Faso, absorption on a bare, untilled soil was compared with that on the same soil when **crop residues** were dug in or when it was treated with **tied ridging**. Absorption of a 120-millimetre rainstorm rises from 35 mm to over 104. Also of interest here are French trials in the Pas de Calais region measuring the effect of **the number of passes of farm implements over the land.**

· The effect of **mesofauna** at Saria in Burkina Faso should also be highlighted. The final infiltration of a 100 mm sheet of water over 100 cm^2 was measured. Absorption was between 5 and 12 mm/h on crusted bare soil, about 60 mm/h where there were termite holes, as much as 90 mm/h after the slaking crust was removed, and finally 120 mm/h after the soil was dug to a depth of 5 cm. Holes made by earthworms, and in some cases termites, can have a considerable effect on infiltration, inasmuch as the flow in a tube varies to the fifth power of the diameter of the tube. The flow in a 2/mm pore will be 32 times greater than in a 1-mm pore. And the tunnels left by earthworms and termites are often over 4 mm in diameter.

FACTORS AFFECTING FLOW VELOCITY

The second factor that can help to reduce or increase the kinetic energy of runoff is **its velocity.**

- Runoff velocity depends on the depth of the runoff sheet and the slope and roughness of the channel. The slope increases the speed of flow and hence the advance of gullying, although gullying can very easily start on slopes of less than 1%.

- **The topographical position of the plot can also be a major factor** (Heusch 1970): water can drain away in the soil until it reaches the valley bottom, but gullying can develop where the groundwater emerges, later leading to headward erosion.

- Differences in height will also influence the depth of gullies: **the height from which water falls into the gully** causes a considerable **vortex energy**, which will accelerate erosion or the speed at which gully-heads advance. **Stocking**'s studies on the speed at which gullies advance in Zimbabwe should also be mentioned here. Having studied different types of gully on homogeneous soils, he observes that whatever the type of gully, erosion depends on:

  - the volume of rainfall, i.e. r in mm;
  - the surface area of the catchment in km^2, and hence the volume of runoff;
  - the height of the fall at the head of the gully (h).

  The equation is as follows:

$$\text{Gully erosion} = 6.87 \times 10^{-3}\, r^{1.34} \times s^{1} \times h^{0.52}$$

- **Plant cover has a complex influence on linear erosion:**

  - plant cover protects against the impact of rainsplash, hence prolonging soil permeability and reducing the volume of runoff;
  - its litter attracts mesofauna (which dig out macropores) and absorbs a considerable quantity of runoff energy;
  - the roughness of the soil depends on the number of stalks per square metre, so that a plant cover made up of grasses with many stalks is more effective than trees in protecting the soil against runoff.

- **The soil itself affects runoff and erosion in various ways.** Thus, **the roughness of the soil surface** slows down runoff and also affects the volume stored, while **the stability of the soil structure** affects the velocity of rainsplash and hence the amount of the rain absorbed before runoff starts. If the soil surface contains **gravel or larger stones**, there can be two opposite effects (Poesen 1989; Valentin and Figueroa 1987): if such stones are on the soil surface, they protect it against splash and also protect the underlying macroporosity, and hence have a positive effect on infiltration. On the other hand, if the stones are included in the sedimentation or slaking crusts, runoff will increase. **If soils are compacted**, they will be less pervious but **more cohesive**, and therefore more resistant to runoff. **If the soil profile is homogeneous**, erosion will produce a V-shaped gully, whereas **if soil resistance is irregular**, a U-shaped gully with vertical sides will form because erosion velocity depends on how well the material resists cutting.

In 1935 Hjulström studied soil erodibility as a function of soil texture and flow velocity, in canals. In a graph (Figure 19, page 92) showing flow velocity as a function of particle size, Hjulström demonstrated three levels: an upper **erosion level**, with a minimum of about 100 microns, a lower **sedimentation** level, and between the two a **transport** level. Erosion starts at a minimum flow velocity of 25 cm per second and with the texture of the bank soil at about **100 microns**, i.e., the size of fine sand, which is lighter than coarse sand and gravel and less cohesive than loam and clay. The minimum flow velocity for erosion is roughly **25 cm/s**. It therefore appears that the most vulnerable matter – fine sand in this case – is slightly coarser than in sheet erosion, where the most vulnerable matter is 10-100 ì (Wischmeier, Johnson and Cross 1971). This is why sheet runoff moving at under 25 cm/s carries away only fine particles and light particles detached by rainsplash, and not coarse sand. On the other hand, where runoff is concentrated, erosion is no longer selective and the speed and energy of the flow increase, digging out rills. When the slope gets steeper, runoff energy increases and exceeds that of sheet erosion. Energy becomes channelled toward the formation of rills and gullies, scouring the topsoil and draining all loose material across the breadth of the slope along these lines.

A further observation is that **the transport area in sandy textures is very narrow**, so that the shift from the erosion to the sedimentation level occurs as soon as runoff speed falls: **hence the sandy deposits that very often litter channels –** for example diversion ditches, particularly at the end of each spate. This is particularly striking in the case of rivers in the Sudano-Sahelian area of Cameroon, the beds of which are littered with coarse sand.

CONTROLLING RUNOFF AND LINEAR EROSION

This entails cutting runoff velocity and gradually reducing the volume of runoff.

ON FIELDS

The volume of runoff leaving a field can be reduced by adjusting cropping techniques and plant cover. Deep tillage allows better root growth, better water storage in subsurface horizons, and hence better development of plant cover, significantly reducing erosion and runoff. Another and opposite technique is never to leave the soil surface bare, till it as little as possible, and only along the seed line. Here again water is absorbed through the macropores created by mesofauna, and the level of erosion is very low. Where there are earthworms and termites, they will consume the litter deposited on the soil surface, dig out macropores, and maintain optimum absorption.

IN DRY VALLEYS

In dry valleys, small gullies and the bottoms of drained valleys, it is often enough simply not to till the soil or to **keep compacted land under grassland** to reduce erosion damage. Living obstacles such as hedges or dead obstacles such as bales of straw can also be set up in a V formation across such valleys. Another, but more expensive, solution consists of digging out **storm ponds** or building small **earth dams** to reduce flood flows and trap the suspended solid load in order to prevent mudflows from damaging inhabited areas. However, the expense of this method should be considered, for it immobilizes land and requires regular channel clearance.

BIOLOGICAL FIXATION OF SMALL GULLIES (cf. Lilin and Koohafkan 1987)

Small gully erosion varies considerably from one region to another depending on the extent of degradation. If woody vegetation still constitutes a protective armour for the valley bottom but is showing signs of weakness in some places, more attention should simply be given to preventive measures, and agricultural development curtailed in the bottom. Once the gully has started to cut into the bottom, the broken balance will need to be restored.

There are **two distinct aims of this type of intervention**.

The main objective will generally be that of **improving farm or forest productivity** by exploiting the alluvium that builds up behind each sill in the gully bottom. Since torrent phenomena are almost negligible, these deposits often have a high productive potential. As soil collects above the sill, fruit trees (for example: in Haiti – breadfruit, mango, coconut, banana; in Algeria – pear, apple, apricot, walnut, or poplar, ash, etc.) or water-demanding food crops can be planted.

The second objective is that of **reducing the solid load and regulating flows**. This aspect especially concerns sectors downstream of the area treated. Mindful of environmental conditions and the plant material available, the biological treatment of small gullies should be stressed. The basic instrument is a sill crosswise to the gully made up of living plants. This approach is based on the technique of hedges of large, close-planted cuttings used by peasant farmers to fence farm plots and protect them from livestock. The technique is widely used in Haiti, Rwanda and Burundi and is easy for farmers to learn, although it requires adaptation to the specific problems of gully treatment.

Various types of plant material are used in building a sill: large cuttings of woody species, and plants such as sisal and grasses to break the flow of the water and protect the lower side of the construction from undermining. Species must be chosen on the basis of their suitability for gully treatment: resistance to very swift-flowing water, jolting, bark-stripping, undermining and submersion; and a swift growth-rate. *Euphorbia lactea*, various sisals, *Bromelia*, *Glyciridia septium*, yucca, *Bambusa vulgaris*, guava, *Jatropha curcas*, *Cassia* and *Leucaena leucocephala* can be used in Haiti. However, this list of useful plants should be adapted for each region. The conditions each requires, as well as production methods for fragments or cuttings and rooted plants, will need to be spelled out.

After a hedge has been planted across the bed, **a filter** to induce deposit of the sediment load is formed by branches laid against the hedge. The height of this filter must be raised as the alluvial deposit and hedge grow in height. In Haiti, it is best to use cuttings between 1.2 and 1.5 metres high, 50 cm of which are below ground to stabilize the sills. In favourable conditions, the cuttings making up the sill can be planted directly across the bed without further care, in fairly close single or double lines with about 30 cm between cuttings. In some cases, recovery of the active gully-bed must start from the two banks – particularly when the colluvium is regularly swept away by floods as spring tides uproot plants during peak flows. Under these conditions, it may be possible to re-establish vegetation in the gully by using the trees growing on the two banks, for example by bending a slip down from either bank and attaching earth-filled woven baskets or old tyres in which cuttings have been planted. This favours the establishment of vegetation.

When gullying is already too far advanced, the technique is to build a small dry-stone sill before planting woody shrubs. As the sill silts up, it creates a favourable environment for the establishment of plants. It also spreads the sheet of water flowing down the gully during peak floods, thus helping to prevent the plant sill from being swept away. Where few stones are available, they can be replaced by **earth-filled salvage bags**, protected by a thin layer of gravel or cement, or simply earth – especially for plastic bags that disintegrate faster when exposed to the sun's rays. These barriers made of stones or bags of earth have a temporary rôle, with **the biological barrier then taking over** in order to control gullying. They need not be very high – 50 to 100 cm at the notch should be adequate – but they must be V-shaped so as to concentrate the flow down the stream of the gully.

Once these small structures are built they must be properly maintained:

- repair of weak points in the sill with supplementary planting;
- addition of a filter of plant residues;
- making sure that the water cannot flow *around* the barrier, by planting protective vegetation along the banks, reinforcing this if need be with branches;
- prevention of undermining below the barrier by limiting its height and planting certain species immediately below it: agave and fast-growing forage plants.

Generally speaking, government officers cannot be responsible for such upkeep. **The farmers can be expected to assume this responsibility if the barriers have a great enough effect on farm productivity in the gully bottom**. The distance between such correction sills in a small gully does not need to be calculated as precisely as for large, torrential gullies: alluvium is usually shallower, so that any localized cutting due to destruction of a sill develops more slowly into headward erosion than it does in the presence of deep alluvium in larger gullies. The authors of treatment projects therefore have a certain flexibility in the positioning of sills, which means that they can start the treatment where there are no land tenure problems, or where the landowners on the gully banks are willing to work together. In principle, priority should be given to the upstream sections, where the chances of success are higher as torrentiality is less. Once these sections have been treated, it will also be easier to treat the lower sections.

The second priority is that of treating gully sections that can lead to more appreciable results, for example a topographical situation allowing creation of a large alluvial deposit with a similar type of construction, proximity to the village and good access, thus facilitating surveillance and the removal of harvests.

LARGE, TORRENTIAL GULLIES (Lilin and Koohafkan 1987)

In large, torrential gullies, torrent-correction dams are the developer's basic instrument. Such treatment can have two objectives:

1. **Stabilizing the length-wise profile** of the gully in sections where there is a general tendency to cutting. The constructions primarily hold back the part of the hillside that would gradually be carried down into the gully (through undermining of banks and sliding) if the cutting continued; in other words, they stop headward erosion. The objective here is therefore not to hold back a great deal of sediment, but to prevent the gully from deepening.

2. **Holding back sediment** in transit sections where there is little cutting. Here retention becomes the main purpose, rather than a by-product as in the first case. Storage of alluvium (a) helps to prevent silting-up in dams further downstream, (b) improves water resources by spreading floods and storing ground water in the alluvium thus collected, and (c) protects inhabited areas against torrential wash.

The general principles to be observed in treating large gullies are as follows:

- The dams must have a long life-span, since plants cannot be expected to take over at once. They will be built in resistant materials – gabions, but especially masonry dams of large stones and cement.

- Plants play a major rôle even if the dams are the central element in this treatment. Establishment of vegetation on the alluvial deposits (except in the central part of the channel, which is left free to facilitate flow):

    - consolidates siltation, or the accumulation of sediment in the channel, and allows steeper slopes, which inturn means that more such matter can be stored;
    - channels and recentres flows, so that banks are not undermined and water does not flow around the structure;
    - produces wood, forage or fruit, depending on the choice of species used, in a place made unsuitable for annual crops by torrentiality.

- The structures must backstop one another, with spacing calculated on the basis of the equilibrium bed slope, i.e., the slope point at the gully bottom at which there is neither removal nor sedimentation. The principle of stepped torrent control must be respected if the intervention is to be lasting. Excessive spacing or the destruction of one structure will compromise the long-term stability of all the structures above, for headward erosion is particularly rapid when a mass of alluvium carpets the gully bed. Even when such erosion is slower because it has to cut through rock, calculations must be based on the long term, bearing in mind the intended sustainability.

Where spacing between structures is too great, the dam base is undermined and the cost of repair operations high (underpinning of the stonework, building an auxiliary dam). It is therefore better economics to space dams so as to minimize the risk of undermining.

When the aim is that of stabilizing the profile, the sections where cutting is important must be treated. Modest-sized structures are often enough to halt cutting. When the aim is that of trapping and storing sediment, operations are usually concentrated lower down, on more gently sloping sections, so that a greater volume of sediment can be trapped for a dam of the same height – although this second objective does also mean increased dam height.

The torrent control works described represent **a technique that is both expensive and fragile**. The high cost is due to the use of durable materials (gabions and stonework) and the need to build structures sturdy and large enough to withstand the various constraints and risks (jolts from boulders, shearing of unstable banks, overturning under the pressure of water, undermining, piping erosion, circumvention, etc.).

The fragility stems from the fact that destruction of one structure often leads to the destruction of those upstream as a result of headward erosion. Such treatment of a large gully is financially justified only if major economic interests are at stake and there is a sufficiently well-funded, well-staffed unit responsible for ensuring maintenance.

TREATMENT OF MEDIUM-SIZED GULLIES THROUGH MECHANICAL AND BIOLOGICAL ENGINEERING (Lilin and Koohafkan 1987)

When small gullies have deteriorated to the point where direct biological barriers are no longer feasible, but before the torrential gullying stage, biological action can be taken only after the gully-bottom has been stabilized by building sills.

The various principles for treatment of medium-sized gullies are given in the "Ten Commandments for Gully Treatment" (page 216). Since the sills do not have an indefinite life-span, a saving can be made on dry stone barriers where stones are scarce, and on gabions where these are still too expensive, by replacing them with sills in metal fencing, which generally cost about one-third as much. The successive establishment of vegetation is what, in the end, definitely stabilizes the gully. The first point is to fix sediment as soon as it is deposited, by planting rhizome grasses which will continue to grow as the sediment piles up, while unbroken, closely-planted lines of shrubs on the sides of the gully will help to recentre the flow. Then, when enough soil has collected, large fodder, fruit or high-value timber trees can be planted along the gully to stabilize the slopes. Research should be done to find the most suitable and productive species for the sides of the gully. A line of trees along the edge of the gully can also help to isolate this micro-environment, which is still fragile.

For small and medium-sized gullies, the use of plants attractive to farmers can also be fostered. The farmers can then be trained to maintain this system of gully fixing and control while at the same time producing forage, fruit and wood.

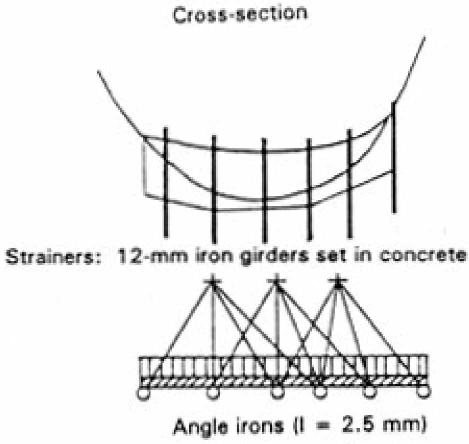
In Algeria, for example, the life-span of dams is very short – between two and ten years for small earth dams, and twenty to fifty years for large dams. Action therefore focused on rehabilitation of mountainous land and gully control (Figure 55). The general aim is that of stopping erosion, in other words blocking the process of gullying. Low dams are built in deep, narrow bottlenecks where raised sills then form. These can be gradually raised to the point where the slope and the banks reach equilibrium. It is a question of managing sediment. However, since treatment of a medium-sized gully 1 km long costs between 100 000 and 500 000 FF (US$ 20 000 and 100 000) and there are tens of thousands of gullies requiring treatment, feasibility studies are being done to reduce the cost and to make intervention more cost-effective (Roose 1989, Bourougaa and Monjengue 1989). At present, gabions are being built at the mouths of secondary gullies where they flow into main gullies, while the whole length of these secondary gullies can then be stabilized through use of sills made of light-weight wire mesh.

COST EFFECTIVE GULLY TREATMENT [Plates 14 and 15]

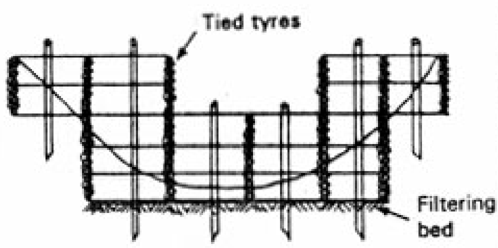
The very high cost of torrent control and gully treatment (between US$ 20 000 and 100 000/km), is only justified where there are dams, housing, roads or major constructions to be protected downstream.

FIGURE 55

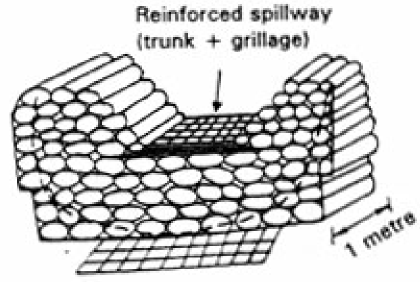
Various types of flexible, fairly inexpensive, pervious sills that are easy to build with local materials



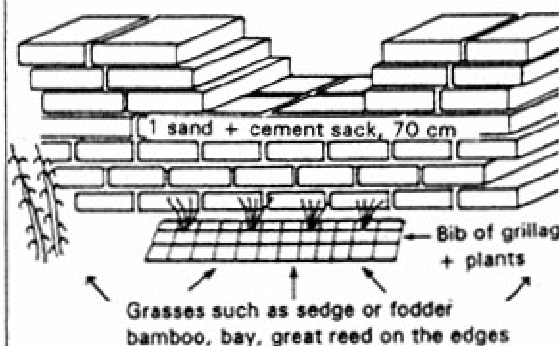
Sill made of galvanized iron grillage (0.5 cm mesh) attached to angle irons (45 mm) sunk 50 cm into the ground



Sill made of salvaged > 1 m Ø tyres fixed on angle irons sunk 50 cm into the soil. The old tyres are tied in place and filled with local earth.



In plastic bags 100 cm long x 60 cm wide x 1 mm thick



Sills constructed of thick plastic bags filled with local earth, with spillway reinforced by sacks of sand mixed with cement.

Cost of 4 m³ sill
(material + labour + transport)
at 90 dinars a day

1 dinar = 0,25 FF at June 1992 exchange rate

2200 dinars	in gabions
84%	in dry stones
34%	in iron mesh
21%	in plastic wind-break sheets
20%	in used tyres
(± 15%)	in plastic bags

in France = 500 FF/m³ of gabion

Prevention being better than cure, it is best not to wait until soils are deeply degraded, but rather to reduce runoff and erosion in the fields by developing production systems that provide good soil cover.

However, both small and medium gullies can be treated with simplified and fairly inexpensive sills (20% of the cost of gabions), using unsophisticated materials and the labour of local farmers who can quickly be trained (Figure 55).

The originality of this approach is that it not only stops the linear erosion that produces gullies and traps several dozen cubic metres of sediment behind the sills, it also maximizes the moisture stored in the trapped sediments so that green forage and trees will grow in the dry season, thus motivating farmers to manage their land and treat gullies correctly. This last point is vital in order to advance from an omnipresent State to a new stage of fostering the farmer initiative indispensable for sustainability in the rural sector.

The next stage consists of treating secondary gullies and then building small dams that can provide water for mountain farmers who are chronically short of water for their livestock and for the irrigation of small, highly-productive gardens.

TEN COMMANDMENTS FOR GULLY TREATMENT

1. Until **infiltration on the catchment area has been improved**, no attempt should be made to block a gully (otherwise it will simply find another bed); a stable channel should be planned that can evacuate the peak flows that occur every ten years (or even less frequently).

2. Mechanical and biological treatment of a gully may be done gradually from one to six years, but must take account of the whole watershed from the outset. Biological fixation of a gully will consolidate the sides and bottom once they have been stabilized by various types of sill: if this order is reversed the plants will be stripped away along with the soil by floods.

3. Sills must be positioned carefully, according to the objective. If the purpose is simply that of raising the gully bottom so that the sides achieve the natural equilibrium, a key narrow section should be chosen where a number of light sills can rest on solid sides. If the purpose is to save as much sediment as possible or to rehabilitate arable land, the best choice is gently sloping places, the confluence of secondary gullies, or sections with sloping banks, and a solid, heavy structure that gradually builds up.

4. The spacing of the sills depends on the slope of the land. The downstream spillway must be on a level with the base of the sill above, according to the on-site equilibrium bed slope (1 to 10% depending on the nature of the gully bottom, in a stable area with neither removal nor sedimentation). Initially, the spacing can be doubled, with intermediate sills being built when the first generation is filled with sediment: **it is important to stabilize the trapped sediment immediately** with low plants in the centre of the flow and trees on the sides.

5. Hydrostatic pressure should be offset by providing drainage for the sills in the form of grids, baffles, or loose stones.

6. The sills must be anchored in the bottom and sides of the gully by a foundation trench to avoid piping and circumvention. A sand and gravel filter at the point of contact between loamy-clay soil and the stone sill will be needed to prevent uplift from carrying away fine particles and piping the structure.

7. The wings of the sill - which should be higher than the spillway - should keep the water-course centred along the axis of the gully. The spillway itself must be reinforced with large flat stones with or without cement, or with scrap iron, so that it resists the tearing force of the sand, gravel and stones that tumble down gully bottoms at considerable speed.

8. The energy of the water as it falls from the spillway must be broken by a cushion (riprapping, gabion, metal grid + tufts of grass) or by a subsidiary dam to avoid piping under or actual overturning of the sill.

9. Livestock must be kept away from the treated section, for they would quickly destroy sills and degrade plant cover. However, fruit and forage - and in due course wood - can be harvested in exchange for upkeep of the structure.

10. Mechanical treatment is not complete until the source of the sediment has been tamed, and the gully heads and sides stabilized. Vegetation should then establish itself naturally if the equilibrium profile has been reached, although nature can be assisted by quickly covering the sediment with grass and fixing it with ecologically appropriate, productive trees. Simply managing sediment must be followed by getting the most out of the system thus treated.

Gullies can become "linear oases".

Chapter 7

Mass movement

While sheet erosion attacks the soil surface and gullying affects drainage lines on a slope, mass movement involves massive erosion of a large volume of the soil cover. This chapter will outline the general principles for means of preventing and controlling mass movement that are within the reach of peasant farmers. The view is that only the State has sufficient technical, financial and legal means to control sloughing and landslides (which can often cause real disasters), and to impose restrictions on the use of land under the greatest threat from mass movement.

FORMS OF MASS MOVEMENT [Plate 12]

The many forms of mass movement can be divided into six main groups (Figure 56):

- **Creep**

  This is a relatively slow sliding of the surface layers of the soil cover, generally without detachment, and is widely observed on steep slopes where young forest saplings are bent and the base of adult trees crooked. In agroforestry areas, livestock treading on slopes can also lead to a stepped formation flanked by a network of fissures (Moeyersons 1989a, b).

  Another form of creep – that of dry mechanical erosion – is caused by cropping techniques, and has been treated separately. Like sheet and rill erosion, these various processes eventually scour the hill-tops and clog slope bottoms.

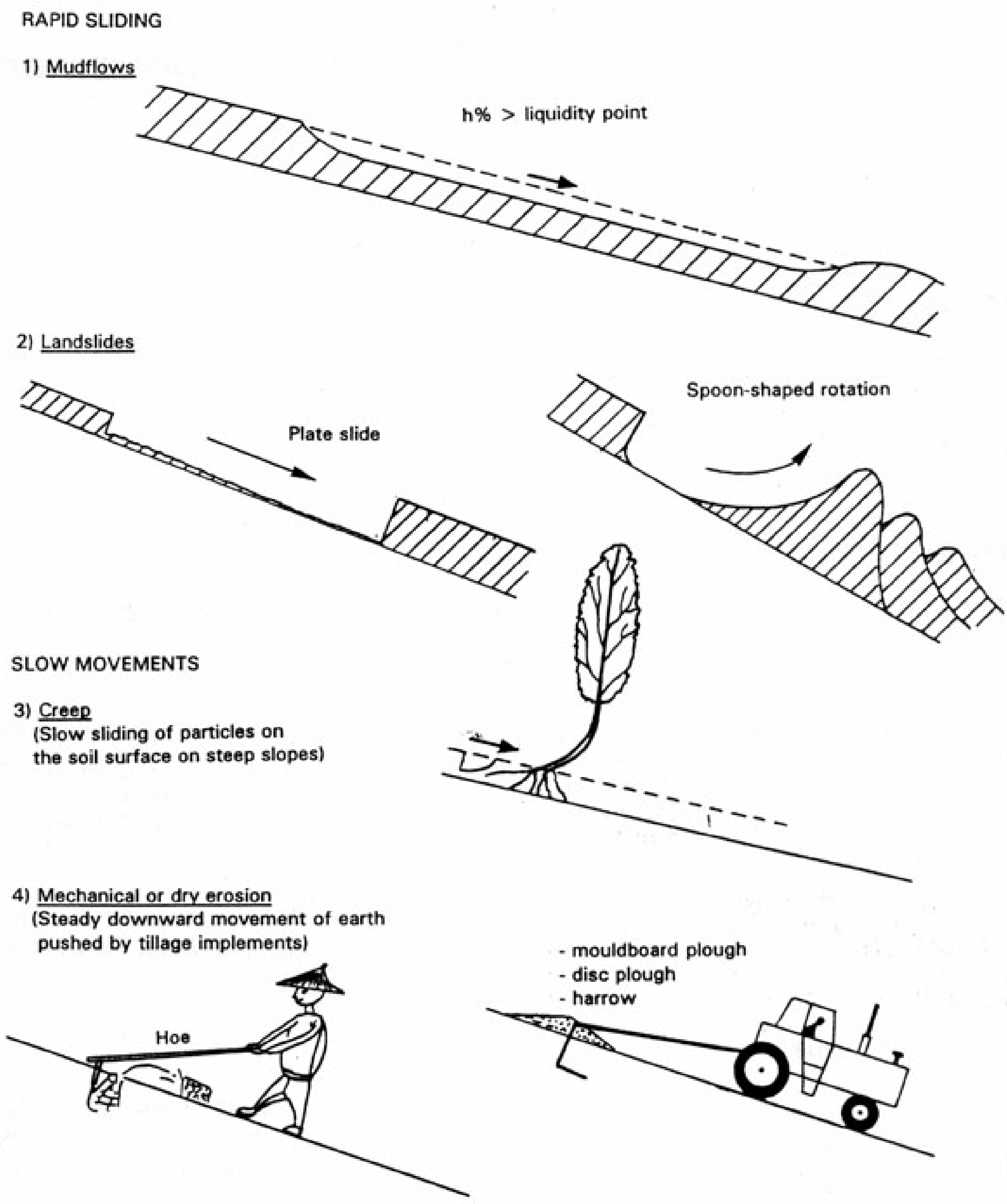
- **Rapid sliding**

  Sliding or sloughing of **plates of earth** is the sliding of a thick or thin layer of overlying material over a more compact horizon (often weathered rock) which acts as a slide bed-plane. This is a very common occurrence on schist where the dip parallels the slope of the land, on gneiss, and on marl in process of weathering.

- **Sheepback slopes**

  These are soft forms appearing in wet conditions when the surface horizons pass the point of plasticity and move slowly, like toothpaste, between the root networks holding the topsoil in place, and the compact, impervious horizon made up of a material such as weathered marl or clay.

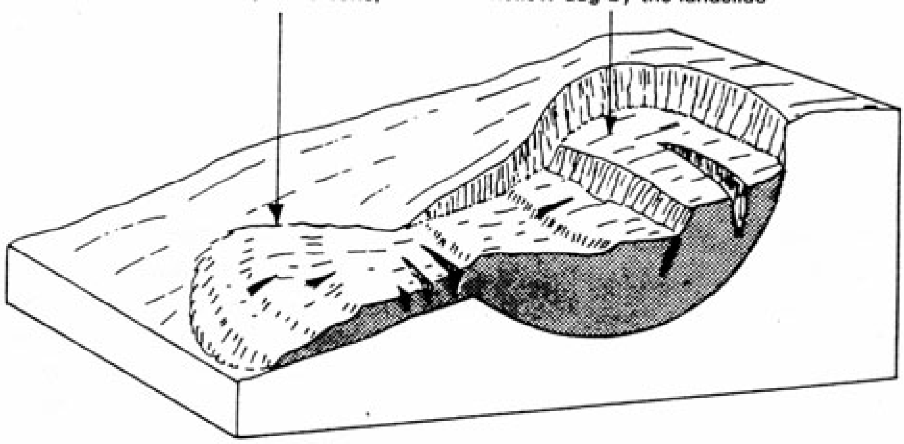
FIGURE 56
Forms of mass movement



· **Mudflows** (or torrential washes)

These are high-density mixtures of water and soil which have passed the liquidity point and can carry away large masses of mud and impressively sized rocks at high speed. When such flows occur, they start as a channel and end as an outwash fan (or débris cone) of material with a wide variety of textures. Fine material

FIGURE 57
Rotational spoon-shaped slide (cf. Neboit 1991)



is subsequently removed by water erosion, either sheet or rill, leaving behind a mass of gravel and blocks of rock of very varied sizes. Such phenomena often appear following a plate slide or in a gully when an exceptional rainstorm clears away weathering débris that has been collecting for some years (Temple and Rapp 1972).

- **Rotational spoon-shaped slides** (Figure 57)

  This is a slide in which the soil surface and part of the mass rotate as they slide, so that a counterslope appears on the slope. There is often a whole series of such slides, giving the landscape a sheepback appearance. There is usually a moist area in the hollow of the spoon where moisture-loving plants grow (*Carex*). After very wet periods, runoff often sets in on the sides of the counterslope, gradually gullying it out of existence and leaving only a dip in the slope which is difficult to distinguish from an ordinary gully.

- **Local forms**

  This category covers rock slides, the undermining of banks, and slope subsidence leading to localized sliding. These are very frequent at gully heads: they cause the upper part of the lips of the gully to slide, and move the gully upwards through headward cutting. They are also found in wadis, particularly in the concave sections of meanders.

CAUSES AND PROCESSES OF MASS MOVEMENTS

The cause of both slow and rapid mass movements is an imbalance between the soil cover, stored water and plant cover, and the friction they exert on the sloping substratum of weathered rock on which they rest (maximum slope of 30° to 40° = 65%). This imbalance can manifest itself progressively on one or more slide planes following wetting, or when the soil cover goes beyond the point of plasticity (creep with deformation though without actual breaks) or liquidity (mudflows).

Such imbalance most often occurs suddenly in answer to one or both of two kinds of event: earthquakes and very heavy cloudbursts (over 75 mm in 2-3 hours) (Temple and Rapp 1972). As water races through fissures or megapores (tunnelling) and down to rotten rock, hydrostatic pressure builds up at a certain distance from the crest (5 to 95 m at Mgeta in Tanzania) or at the confluence of underground trickles of water. This pressure can push away the formed soil mass, detaching it from a fragile level of rotten rock; hence the very frequent plate slides on schist, gneiss and porous volcanic material deposits over impervious rock (for example, volcanic ash on granite domes in Rwanda).

This imbalance can be created by earthquakes, cracking as frost and thaw alternate, the dessication of swelling clay, rock weathering, wetting of the soil cover to the point of saturation, wetting of the slide bed-plane so that it becomes slippery (as in the case of silt from weathered mica), the presence of rocks with preferential fracture planes (argilite, clay, marl, schist, micaceous rocks, gneiss). Human beings can cause more such mass movements by altering the external geometry of a slope (by terracing, cutting into it to build roads or houses, overloading it with landfill, altering natural flows, or by the erosion that occurs at the foot of a slope after deviation of a watercourse, etc.). Vegetation also has an effect. In their study of a site subject to débris-slide and mudflow, Temple and Rapp (1972) showed that 47% of cutting occurs on cropped fields (maize + millet + beans), 47% on fallow and grazing land, and less than 1% on the highest-rainfall forest zones. Even free-standing trees seem to have an effect, for only trails where no trees were planted show signs of sliding. One row of trees would be enough to avoid the process. However, some major slides occurred in the highest-rainfall forest zone (R 2 000 mm) which received 185 mm in 72 hours on 23 February 1970. Reforestation is therefore not a sure-fire defence against landslides, and the type of (forest) probably also plays a part. Convex slopes (weathering in orange-half forms) and deeply scoured valleys will also be susceptible to landslides (Temple and Rapp 1972; Avenard 1989; Moeyersons 1989a, b).

Risk factors

According to Ferry (1987), the decisive factors in soil cover resistance to sliding are expressed in Coulomb's equation:

$$s = c + (p - u) \text{ tangent } f$$

where
- s represents resistance to shearing
- c soil cohesion
- p normal pressure at the surface of the movement due to gravity
- u pressure of interstitial water in the soil
- f internal friction angle
- tangent of f, the friction coefficient.

Sliding takes place when the shearing constraint exceeds soil resistance or when the plasticity or liquidity point is reached. Creep is often seen when the soil cover is thick, the slope steep, and the climate very wet. Plate sliding is more likely in the presence of gneiss, schist or volcanic ash deposits on convex schist or granite slopes where a dip follows the direction of the slope, when soil cover is not very deep, on steep slopes (> 60%), or again when there is an impervious level or a steeply sloping and excessively lubricated contact plane.

Slopes with small ridges, bunds or sheepbacks are generally found in moist, marly sites, as are rotational landslides. Undercutting of riverbanks and the banks of gully-heads or sides is generally linked to flows which undercut soil cover to such an extent that they cause rock slides. Tunnels formed as gypsum or salt dissolves, or dug into the soil cover by rodents, can also collapse when water pours into them. Undermined banks are frequent at turns in the river and in meanders.

MASS MOVEMENT CONTROL

Mass movement control tends to be both expensive and far from simple. Unlike sheet or linear erosion control, mass movement control often means **preventing rainwater from soaking into the soil**, adding to the weight of the soil cover and rapidly reaching the slide bed-plane. The surface is therefore drained to evacuate runoff to less vulnerable zones, generally the convex sections of a slope. The zone over the slide bed-plane can be drained in depth to prevent interstitial pressure from detaching the soil cover from the stable zone beneath the slide bed-plane.

Another method is that of **drying the land by increasing plant evapotranspiration**, for example by planting eucalyptus or other plants with a high evapotranspiration capacity. However, it is important to prevent such vegetation from becoming overwhelming, so shrubs must be kept on the edges of fields. If trees are introduced they must be coppiced, i.e., the vegetation must be kept young as it will then evapotranspire and produce maximum biomass. Very tall trees should not be kept on slopes where risks of sliding are high. When the slide bed-plane is close to the soil surface, tree roots can oppose strong mechanical resistance to shearing of the soil cover, whereas when the potential slide surface is too deep for the roots to reach, such resistance is no longer operative: overloading slopes with trees may even add to slide risks. Moreover, trees can shake in the wind, transmit vibrations to the soil and produce cracks that favour localized infiltration of runoff water down to the slide bed-plane. Quick-growing species with tap-root systems are preferable, and clear felling is to be avoided, for it destroys the whole root framework in the soil cover at one time. Trees not only increase resistance to shearing through the mechanical action of their roots, they also alter the water content of the soil: evapotranspiration is high in a forest and this keeps the interstitial pressure of water in the soil cover lower – which is why there is a sharp increase in soil humidity after clear felling.

Preventive methods are the most important. Infrastructures should not be built on unstable slopes and, if there is no other choice, the cuts and fills that upset slope equilibrium must be kept to a minimum. If, for example, a slope has to be cut into for a road, the embankment must be strengthened by providing the abutment with a riprapping mask or a supporting wall which counters rotational sliding and improves drainage on the slope. There should be a ditch uphill of the road to intercept runoff and prevent it from infiltrating the traction cracks in the soil cover above the cutting. Drains level with the weathered rock of the threatened zone will reduce hydrostatic pressure.

If cracks are observed on the soil surface, for example between micro-terraces formed by untethered livestock, **surface tillage** can help infiltration water to spread over the whole soil cover, and thus delay the advance of the wetting front toward the slide bed-plane and improve evaporation of the water mass (Rwanda: Moeyersons 1989a, b). When a road is built on a steep slope, it is a good idea to start stabilizing the road plate by planting and coppicing eucalyptus on the banks above and below it, or planting grass and ensuring it is not removed. A drained wall can also be built, with foundations well-anchored in the rock. Lastly, on very steep rocky slopes in mountainous areas, sheets of wire netting can be thrown down to break the fall of rocks.

In Tanzania, Temple and Rapp (1972) showed that mass sliding in plates is very rare in forest zones (1%), and that even isolated trees can reduce its occurrence, particularly along roads. However, reforestation is not an infallible solution, or even a method that can be widely used in mid-altitude mountain areas (like Mgeta) with high population densities (170 to 510 inh/km^2) and where people depend on rich and well-watered land for their livelihood (staple food crops and vegetables for the towns). At the most, they can be advised that the annual crops grown on small step terraces 1 m wide would be best combined with lines of trees on the ridges (eucalypts), on the banks around fields (fruit trees) and along river-banks (bamboo, eucalyptus or other local species) (Rwehumbiza and Roose 1992).

In Rwanda, zones subject to land-slides on slopes of over 45% are often planted to eucalyptus and left as pasture land. Houses are built on a flat space dug out of the convex side of a stable slope, and a double line of eucalyptus dries the bed-plate along the principal tracks by drawing up water.

CONCLUSION

Mass movement control must be primarily preventive: e.g., mapping vulnerable zones, drawing up a land use plan, banning building work or any modification of slopes, and protection in the form of coppice forests. However, it is not always possible to avoid cropping in these fragile mountain areas, which are often more densely populated than the surrounding lowlands because the climate is healthier (malaria-free) and the land better-watered.

Landslide control calls for expertise and major funding in order to drain slide bed-planes - and this is beyond the reach of small farmers. State investment in such measures are only justified where vital structures are at risk: road networks, villages, dams, etc. There are, however, some measures well-known to farmers long familiar with the region: the use of trees - particularly eucalyptus and bamboo - to dry out the ground and stabilize the slow movement of soil cover on steep slopes and along river-banks. Careful choice of species should make it possible to transform these inhabited landscapes into a stable landscape dominated by hedges, as has been done by the Bamiléké (see Chapter 10).

Lastly, the relative risks of the various erosion processes in each zone must be carefully evaluated before erosion control is undertaken. Sheet erosion control (which tends to improve infiltration) and the digging of diversion ditches on slopes steeper than 25% (which drain the surface horizons but can lead water more quickly down to slide bed-planes) are often the source of huge and even more catastrophic land-slides. Temple and Rapp (pers. comm.) report that after a single rainstorm of 100 to 186 mm in three days (23-25 February 1973) in Tanzania, the overall damage caused by about a thousand landslides was estimated at 500 000 FF (US$ 100 000), with six dead, nine houses destroyed, 20 goats drowned, and 500 hectares of crops wiped out; 14% of the farms lost their harvests, roads were cut by floods for six weeks, etc.

Hoeing with a Manga hoe. This implement allows surface tillage of the soil after the first rains in order to destroy both the slaking crust and the young weeds. Later, a slight adjustment allows hoeing and ridging of widely spaced crops (cereals, groundnuts, cotton, etc.). Saria Station, Burkina Faso. [Photograph Dugué]

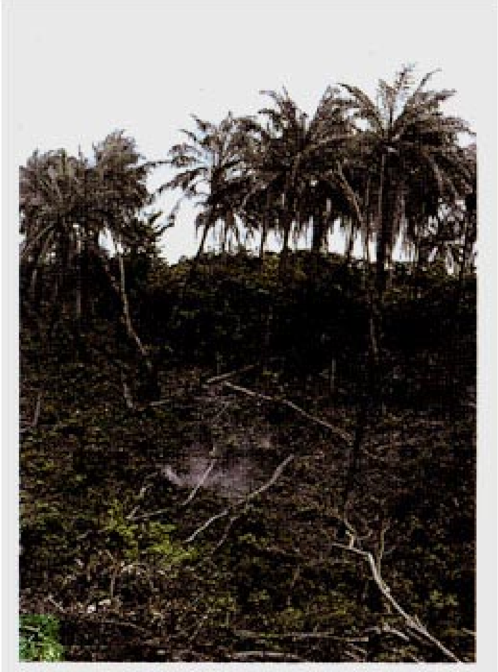
On a gentle slope, tied ridging allows some 50 mm of rainfall to be stored, improving infiltration by this amount. In Sudano-Sahelian zones it allows better crop-water saving in low-rainfall years, whereas in wet years, the crops can become waterlogged and produce less than on the control plot. In the long run, this technique leads to the removal of fine particles (clay, loam, alluvium and organic matter) from the surface horizon. Puni, Burkina Faso.

Ridging with digging in of organic matter. After a short fallow the farmer first rakes over the biomass so that it dries, then collects it along a line and buries it under a thick ridge of earth to form a contour line. Stones are piled on the closest edge of the field. Salagnac, Haiti.

Draining ridges. On steep slopes (20 to 40%), slightly oblique ridging with a spillway every 10 m breaks runoff energy and collects a large amount of well-aërated humus-bearing soil for growing root vegetables (cassava, yam, potato, sweet potato, etc.). However, the simple action of tillage tends to shift soil downwards, thinning it. Additionally, during the heaviest cloudbursts, runoff can overflow and gouge gullies in or around the fields. Mount Okou, Cameroon. [Photograph Bedel]

Karité stand in a Sudano-Sahelian savannah area. When farmers prepare the soil (for cereals, cotton, groundnuts, etc.), they keep about forty useful trees per hectare (fruit, forage, medicine, timber, litter-improving, etc.). Note also the attempts at water and fertility management (line of stones, grass and branches, corrugation of the soil to trap water and manure). Yatenga, Burkina Faso.

Traditional selective clearance. Fire is an indispensable tool in traditional systems for disposing of woody vegetation progressively and selectively. In the foreground note the soil, which remains covered and retains its root network, and in the background, the forest fallow, which regenerates the soil in the course of 12 years, under a continuously harvested natural palm stand. Fresco, south-western Côte d'Ivoire.



Lakou, agroforestry "Garden A." Around the home on the freehold land, the farmers often plant hedges to protect an intensive household plot + fruit trees, taking advantage of the proximity of the stable and household waste. The positive interaction between trees, livestock and crops is optimal here. Salagnac, Haiti.

Forage trees planted along the risers keep the soil in place and provide large amounts of forage prized for its nutritional qualities. These nitrogen-rich foods are essential to the digestion of dry coarse forage during the dry season. Gulmi District, Nepal. [Photograph Ségala]

Alley cropping between Leucaena *hedges. The use of live hedges means that soil fertility can be maintained by immobilizing 10 to 20% of the usable area - a partial solution clearly unable to meet the challenge of a doubling of the population in 20 years. Ibadan, Nigeria.*

Cropping under cover of 200 Cedrella *or* Grevillea *trees. By removing trees of different ages and pruning low branches and surface roots, cereals and other foodcrops with a staggered growth cycle can be produced under their cover. Ruhandé Arboretum, Butaré, Rwanda.*

In the Sahelian zone of Niger, only the valleys are covered with trees (Acacia albida), *which send their roots down to tap the groundwater. Their protection is vital to reducing the ill-effects of drying winds on crops. Tahoua Valley, Niger. [Photograph Oumarou]*

Fruit and vegetable garden in the Sudanian zone of Côte d'Ivoire. After selective clearance, a good number of karité, locust bean, kapok and other useful species are left on the slopes. The Sénoufo use the bottom lands for rice fields, and traditionally build fruit and vegetable gardens surrounded by an earth bank. Many varieties of fruit tree are grown here, together with some bananas. Korhogo, Côte d'Ivoire.

Contour channels on calcareous bluffs. The hills are covered with shallow, grey rendzinas. The small plots are rented out to "rich city folk," and their edges are marked by contour channels, which quickly fill with sediment, so that they are now of use only as paths on these very steep slopes. Since the whole approach has never increased yields, the local small farmers do not maintain it unless paid to do so. Clearance is general, except around houses. Bouchereau, Jacmel.

Individual cistern. Rural development started in the Jacmel region with the building of cisterns to catch rainwater from roofs or small cemented areas. The water has allowed improvements in family hygiene and reductions in the time and labour entailed in fetching water, and is also used to water livestock and a small vegetable and fruit garden. Jacmel.

Gully garden. Once it becomes "worn-out land," the slopes are scoured down to the rotten rock and left to fallow (RAK) grazed by livestock. Only the bottom lands are still productive where dry stone walls have been built to trap water and sediment. Jacmel.

Stabilized tracks and communal cisterns. One of the first development activities in mountain areas is the creation of tracks. However, these tracks are often the cause of serious gullying, and they have therefore been paved so as to collect runoff from the slope in a sand trap, from which it flows into a large communal cistern. The water is used for livestock watering, household purposes, and irrigation of a small off-season household vegetable and fruit garden. Salagnac.

Water management on the Salagnac toposequence. A little below the track, the soil is deeper, and cassava is grown on mounds in combination with beans and maize. Lower still, on the shelf where the houses are located, the red soil is much deeper and is intensely cropped (multi-storey gardens). Such plots are in danger of gullying by runoff from the scoured hilltops, so that it is important to catch this runoff on the track. Salagnac.

Plot-bordering hedges. In the foreground, large cuttings, which act as hedges to protect the cultivated plot on the left from passers-by. The project has tried to improve these hedges by introducing forage and fruit species. In the background, the stony surfaces (or "worn-out land") where runoff concentrates. Salagnac.

In the Nippe area, the weathering of basaltic soils has given birth to an undulating landscape covered with fertile vertisols. Traditionally sorghum is sod seeded, and vetiver, which is very resistant to overgrazing but not to gullying of the valley bottoms, is planted on the edges of the fields. Mangoes produce masses of fruit, and are used to feed pigs. Since the ravages of swine fever, the dried foliage has been used as forage, but many mango trees have been sold for timber. Petite River, Nippe.

In mountain areas, runoff and linear erosion (E = 100 t/ha/yr) scour the soil down to the cangahua, a hardened layer unsuitable for cultivation. Cayambe Basin, altitude 2 800 m. [Photograph De Noni]

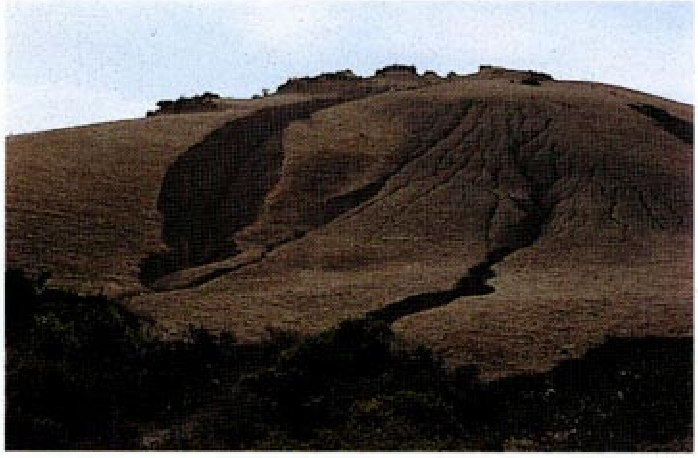
Station to measure runoff and erosion risks, soil surface conditions, and yields as a function of natural rainfall on control plots (bare or under traditional crops) and improved plots (1 000 m^2). Mojanda, altitude 3 300 m. [Photograph De Noni]

Low contour walls built of blocks of cangahua or grass clods according to local practices have turned the landscape into gradual terraces, and reduced water erosion to acceptable levels (under 5 t/ha/yr). [Photograph De Noni]

Watershed management by the local rural community. High yields on the experimental plots encourage the farmers to invest in land husbandry; if they sign a contract undertaking to maintain the works, they can receive a loan enabling them to purchase sufficient inputs to double yields. When they repay the loan after a year, another family is granted the same loan, so that a small amount of aid eventually benefits a whole community. Pedro Moncayo, altitude 3 300 m. [Photograph G. Noni]

Marls and soft rocks are very susceptible to water erosion. Following clearance of steep slopes, extensive cereal cropping and centuries of overgrazing, the hill has lost 1 metre of soil, and sheet and rill erosion are clearly visible. The form of the tree trunk also indicates mass movement.

On the nearby marly hill, the effects of sheet erosion can be seen at the top, and those of rill and gully erosion on the steep slopes, while the wadi eats away at the foot of the hill, causing the banks to slide.



Sheet erosion carries only a few tonnes of sediment down to the bottom of the hill, whereas gullying and wadi streambed displacement carry hundreds or thousands of tonnes of sediment right down to the dam. This should influence the choice of sites and strategies for erosion control intervention at the watershed level.

With a view to developing mountain farming, international aid projects introduced fruit tree crops, which considerably increase small farmers' income. However, apricot trees lose their leaves in winter, so that these orchards provide very poor protection to the soil during the rainy season. On this plot with a 35% slope, 15 to 30 cm of soil has been lost after 30 years. Ouzera, Algeria.

With a view to reducing runoff and erosion risks and improving income still further, the INRF-ORSTOM research team has established grass buffer strips under the trees, combining this with rotations (beans and cereals) that cover the soil during the rainy season and complete their cycle before summer starts. Without reducing fruit yields, this system assured an additional crop of grain, produced straw useful for animal husbandry, and cut erosion risks. It aroused considerable interest among neighbouring peasant farmers. Algeria.

Half-orange landform in the gneissic regions of Vietnam is perfectly developed in terms of management of water, biomass and fertilizing elements. The top and the steep slopes are protected by a crop of tea. Runoff irrigates sugar cane and a rice field before flowing into a pond that is surrounded by a collection of useful trees. Tilapia provides food for people, hens and pigs, and the latter recycle banana and sugar-cane residues, so that their dung fertilizes both rice field and pond. In this way, nutrients can be recycled several times per year. Bac Thai, Viet Nam.

On these fields in the Sudano-Sahelian zone of Burkina Faso, there are stone lines to curb the velocity of water, a stand of acacia, and heaps of dung which will be dug into the soil: a mineral supplement is indispensable. The interaction of all these ways of managing water, biomass and nutrients allows hopes of a relatively productive and sustainable agriculture. Burkina Faso. [Photograph Dugué]

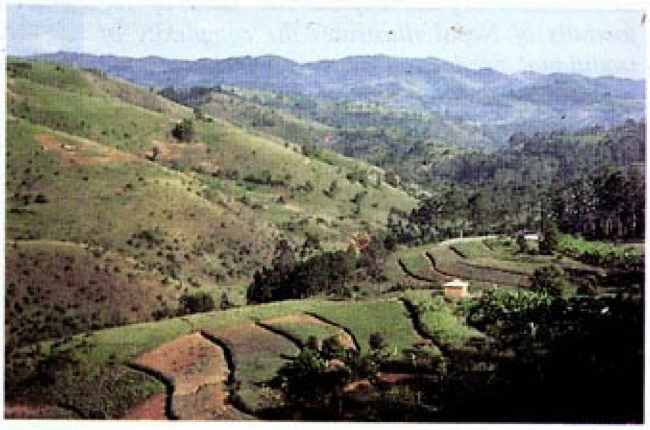
Land husbandry in Nepal. The case of the foothills of Nepal illustrates the complexity of traditional production systems which combine sophisticated water management on irrigated terraces on the slopes or in the valley bottoms, agroforestry and animal husbandry in order to propagate fertility on cultivated gradual terraces. Gulmi District, Nepal. [Photograph Ségala]

Multi-storey gully garden. Runoff on the basaltic slopes causes gullies, which can easily be controlled with sills of earth protected by plastic bags. The sediment that collects is immediately planted with a wide range of fruit trees, bananas, cane sugar and various forage shrubs. Such gully gardens are eventually intensively farmed as "linear oases." Petite Rivière, Nippe, Haiti.

Risers of blocks of rock or tufts of grass have been built in order to treat the steep slopes of the Ecuadorian Andes, reducing water erosion to under 5 t/ha. In order to make the most of this system, a whole series of other inputs were necessary, such as chemical fertilizers, improved seed and pesticides. This technological package made it possible to both stabilize the slopes and intensify farming. Ecuador. [Photograph De Noni]

Jessours *in Tunisia. In semi-arid zones where plants cannot take root on slopes, small dams of earth or gravel can be built to trap runoff and sediment. Cereals are then planted under various fruit trees (palms, olives and figs). Matmata region, Tunisia. [Photograph Chassany]*

The authorities forced groups of peasant farmers to dig blind ditches (0.5 x 0.5 x 10 m) to store runoff water. These ditches require a great deal of work (250 days/ha to install + 50 days/ha to maintain) without increasing production. Unmaintained, they fill with sediment, causing gullying or landslides. The majority of these ditches have now vanished, leaving risers and gradual terraces. Central uplands of Rwanda.



Runoff diversion terraces. This method does not reduce soil degradation or increase yields, and requires maintenance. When exceptional rainstorms occur, the water overflows the terraces, causing gullying (on the left in the photograph), whereas a plot protected by clover (on the right) shows no trace of erosion. Biological methods prove much more effective than mechanical terracing. Capetown, South Africa.

Grass banks to dissipate runoff energy: runoff cannot cut a gully unless its velocity is over 25 cm/s (Hjülstrom). Rather than concentrating runoff water, it is better to develop techniques that leave a very rough soil surface (rough tillage, mulching) and pervious erosion control structures (grass banks, hedges, stone lines) that can slow down the water and spread it out as a sheet. CVHA Project, Burundi.

Earth bunds sealing off a tank. In Sudano-Sahelian zones of Burkina Faso, villages are in dire need of water at the end of the dry season. With small earth dams, runoff water from the hills can be trapped to water livestock and a small irrigated garden. Yatenga, Burkina Faso.

Mulching degraded land allows restoration of both infiltration capacity and fertility through the action of termites which redistribute the organic matter in their galleries. Yatenga, Burkina Faso.

Multi-storey garden irrigated by a bouli, *a small earth dam. With the runoff water collected by a modest dam of this kind, livestock can be watered after the onset of the rainy season, and a small early vegetable garden irrigated. Sabouna, Burkina Faso.*

Development of terraced rice fields along the slope is based on the possibility of gravity irrigation. The seasonal availability of water and the altitude then decide whether one, two or three crops should be grown per year. Gulmi District, Nepal. [Photograph Ségala]

In the zaï method, 3 tonnes of sun-dried faeces or corral soil must be dug into the pan. The concentration of water and available manure restores productivity on this degraded land, even in the first year. The organic matter not only contributes a minimum of mineral elements but also provides the microflora needed for assimilation of the nutrients in the soil.

A fallow of legumes grown as a catch crop under the cereal is another solution, allowing an increase in biomass, bringing nutrients to the surface, and protecting the soil during early storms. However, it is possible only in Sudanian areas where rainfall is over 1 000 mm and distributed over more than 5 months of the year.

Compost pit irrigated by runoff water. This system consists of building a field compost pit, thus eliminating the need to transport crop residues and compost. Unfortunately, the time needed for decomposition (18 months) and the quality of the organic product leave much to be desired. In future, efforts will be focused on setting up "compost-dung-rubbish" heaps or pits near the dwellings, which will allow each family to produce 5 m^3 of a compost that is well-decomposed and recycled even by the following season. Ziga, Burkina Faso.

Under coffee trees, a thick mulch (25 t/ha/yr) retains soil moisture in the dry season, protects the surface against erosion, lowers competition from weeds, and concentrates nutrients from all over the farm. The trick is to produce enough biomass without upsetting the whole farm.

Maintaining field fertility by adding dung, a practice that is part of a complex foddering system. There is a real transferral of fertility from uncultivated to cultivated areas. Gulmi District, Nepal. [Photograph Ségala]

After a short fallow, the farmer brings tethered livestock a forage supplement, the residue of which will be recycled directly during tillage. Jacmel, Haiti.

The transport of dung is one of the factors that limit its use to the immediate vicinity of dwellings, i.e. home gardens. [Photograph Ségala]

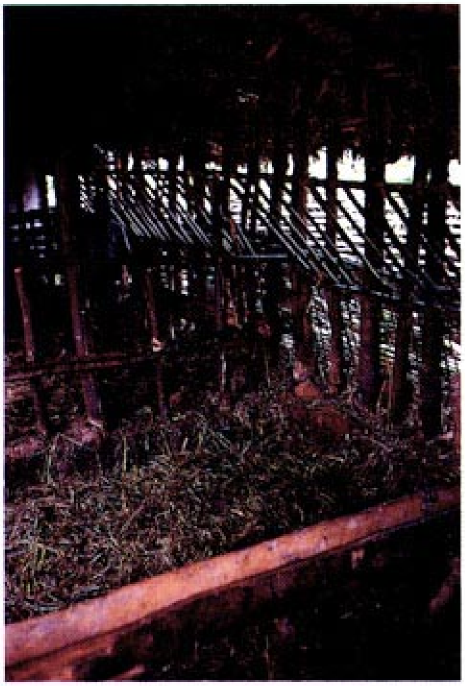
Dung contract. Farmers in the African savannah traditionally propose that herdsmen have their livestock graze on crop residues in exchange for leaving them on the fields during the night. This produces localized dung, possibly in considerable quantities, although it is poor in nitrogen, since the faeces are exposed to the sun and are trampled by the animals. Boukere, Burkina Faso.

Night corralling. When the livestock are herded into a corral for the night, they produce so much dung that nothing more will grow there. Powdered faeces crushed by the animals' feet and mixed with varying amounts of soil from the corral are removed. The quality of this product, which is unfermented (and hence full of seeds ready to germinate), can be improved by the addition of a litter of coarse straw. Production of this improved dung can be as high as 1.5 t/ha/cow/yr. Southern Mali.

A movable corral can also be made using barbed wire, thus improving distribution of dung on cultivated fields.

Dung stable. In farms using animal traction, a pair of oxen are often stabled under a rudimentary roof that allows storage of crop residues. Combined with the urine and faeces, the litter is then taken to the dung pit where it ferments, lowering the content of live weed seeds. When household refuse, ash and other organic waste are added, a farmer can produce up to 5 t/yr of good-quality composted manure, especially if he digs in a mineral supplement (N, P, Ca) with it to compensate for soil deficiencies. Kaniko, southern Mali.

Village compost-dung pit which could be made more efficient if the pit were surrounded by trees. The roots would recover nutrients in solution now carried away by drainage water, the litter would return nutrient-rich biomass, and the shade would maintain an environment favourable to decomposition. Yatenga, Burkina Faso.



The top system is a stable where the livestock are kept permanently on litter. Watered daily and trodden down by the animals, the litter is quickly transformed into good-quality manure. CVHA Project, Bugaramé, Burundi.

*Paddock surrounded by contour hedges (*Leucaena*, eucalyptus, etc.). The stable is joined on to the house. CVHA Project, Bugaramé, Burundi.*

Grass lines and step microterraces on steep slopes. The lines of Pennisetum *that can be seen in the foreground do somewhat slow erosion on these 60% slopes. In the middle ground on the right are micro-terraces 50 cm deep dug into the topsoil and protected by grass risers. This network of grass keeps the soil in place while producing foodcrops on slopes of up to 80%. Note also the eucalyptus stands in areas where there is a risk of sliding. Ruhengeri region, Rwanda.*

Radical terraces in Rwanda. In order to absorb all the rainfall and maintain the fertility levels needed for intensified cropping, radical terraces were built. This involved building risers with clods of grass from the land, removing the topsoil, building the terrace with a 4% reverse slope, and shifting the topsoil back onto this almost horizontal surface. Unfortunately, since the subsoil is sterile, apart from the necessary investment of 1 000 working days per hectare for the terracing, the method requires 10 tonnes of dung, 3 tonnes of lime, and 300 kg of NPK if it is to produce viable results. It is therefore unaffordable for most Rwandan farmers. There are also many hills where it would be dangerous to build such terraces, because the slopes are susceptible to landslides. Rwanda.

Grass bank with bananas planted below it. Some experts hope to reduce the density of bananas between erosion control structures in order to intensify foodcropping. Meanwhile, banana is a cost-effective crop because of the organic residue dug into the planting hole. Burundi.

The grass bank retains the earth pushed by runoff and above all by tillage. Central uplands, Burundi.

Chapter 8

Wind erosion

There is considerable wind erosion in West Africa in dry tropical zones where annual rainfall is below 600 mm, the dry season lasts more than six months, and steppe-type vegetation leaves large stretches of bare soil. It can also develop elsewhere when the soil is being prepared and large amounts of surface matter are crushed fine.

PROCESSES [Plate 16]

The wind exercises a pressure on solid particles in repose. This pressure is exerted above the centre of gravity on the surface exposed to wind and is opposed by a friction centred on the base of the particles. The two forces combined tend to rock heavy particles (0.5 to 2 mm) and make them roll.

Moreover, the difference in speed between the top and bottom of particles means that they are drawn upwards. The lighter particles rise vertically until the gradient of velocity is too low to bear them, at which point they fall back, pushed by the wind, following a subhorizontal curve. As they fall, these grains of sand transmit their energy to other grains of sand (as in a game of bowls) or degrade loamy-clay aggregates, releasing dust (Heusch 1988).

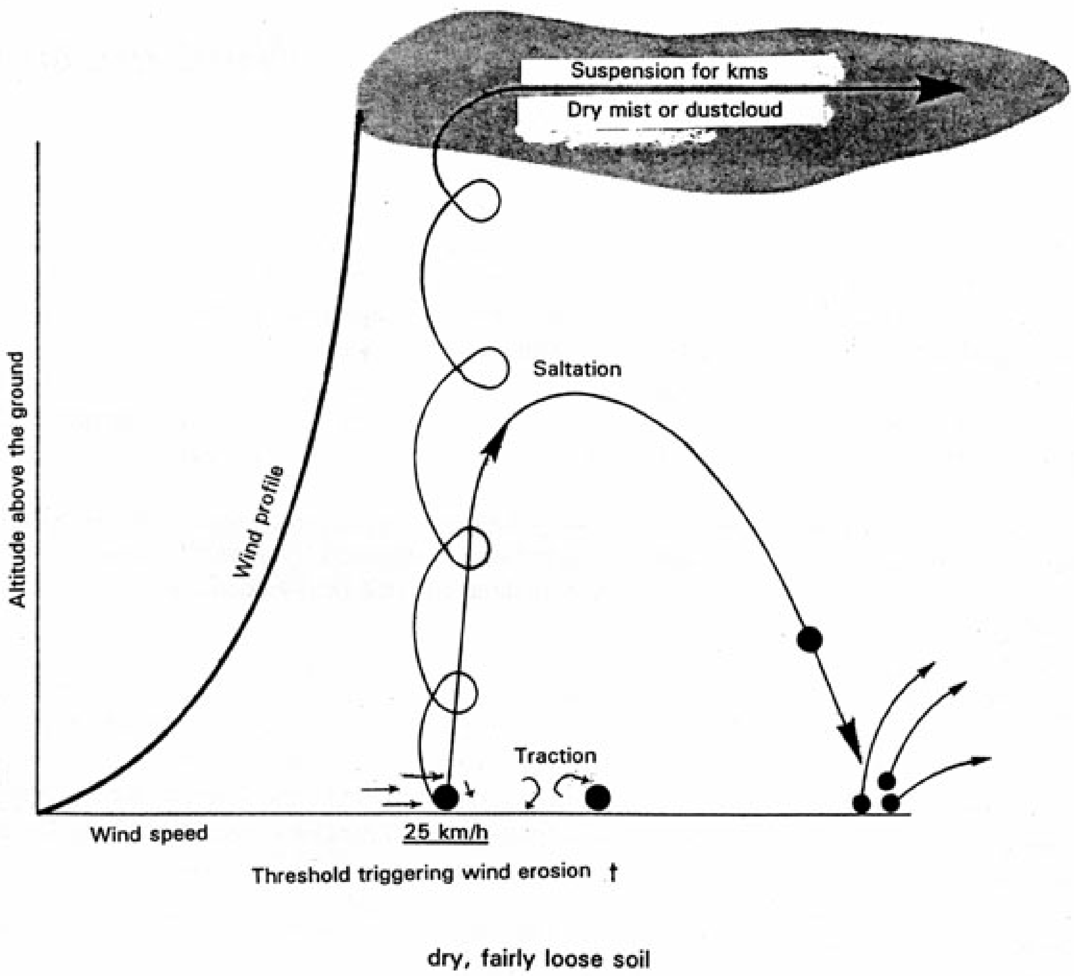
The three processes described below can be observed in the field when the wind-speed exceeds 15 to 25 km/h (or 4 to 7 m/s) depending on air turbulence (De Ploey 1980, Mainguet 1983, Heusch 1988) (Figure 58).

- **Saltation** of fine sand (0.1 to 0.5 mm): in this process, sheets of sand raised by violent wind travel several dozen metres over smooth surfaces, leaving sheets of ripplemarked sand on the ground or small mounds of sand trapped by plant tufts. These sand sheets lash at rocks in desert areas, giving them a typical mushroom shape (corrasion), and cause serious crop damage.

- **Deflation**: in this process light particles of soil (clay, loam and organic matter) are carried away in suspension. This dust is sucked up by vortices as high as several thousand metres, and then dispersed as a dry mist, or it may travel several thousand kilometres as a dust cloud. This category covers both wind-borne loam torn from periglacial loess steppes, and the Sahara dust that falls in Montpellier three times a year and once or twice a year in Paris.

- **Creep:** grains of sand 0.5 to 2 mm and too heavy to be sucked very high are thrown off balance by gusts of wind, and rolled and dragged over the soil surface to the tops of dunes, which can advance several metres per hour in this way in strong winds.

FIGURE 58
Three processes of wind erosion: suspension, saltation, traction



1. Suspension : cloud of superfine silt (e.g. dust in dry season = dust bowl) rising as high as 10 km and extending over hundreds of km
2. Saltation : fine sand grains, ϕ ≃ 100 μ
   major ill-effects: moving dunes - damage to crops and other vegetation
3. Traction along the ground:
   - coarse sand rolling along the surface of dunes
   - fine sheets of sand

FORMS OF WIND STRUCTURES

The form of dunes depends on the prevailing winds.

If the prevailing winds come from only one direction, the dunes can be **straight**, paralleling the coast (formed by the winds that sweep across the beach at low tide) or crescent-shaped, with the side toward the wind gently sloped. In the second form, the wind pushes grains of sand up to the top of the gentle slope, and they then fall on to the steep slope inside the semicircle. Dunes advance more slowly as they grow in size. According to studies by Bourgoin (1956) along the route of the Mauritanian railway, dunes 3 metres high will advance between 40 and 80 metres per year, dunes 12 metres high will advance between 12 and 35 metres, and those 24 metres high, between 8 and 17 metres.

In order to avoid the risk of sanding-up, lines of communication are not taken through areas with live dunes. A 50-cm bank with a very gentle slope (1/5 to 1/10) is also built so that the wind speeds up as it crosses the road, preventing it from depositing sand. The wind-speed can be increased still further at particularly vulnerable points by setting up 3 x 1 m deflecting panels at a 60° slant, or triangular cross-sectioned sand mounds 8 metres from the road, with the top and sides covered with a 20- to 50-cm layer of gravel.

If the prevailing winds are multidirectional, sand dunes can sometimes stretch several hundred kilometres; lying at a tangent to the wake of an obstacle, the **Silk** is oblique with respect to what could be termed the annual wind. During storms, sand travels along the dune, parallel to this structure, which continues growing in the same direction (Mainguet 1983). The profile is of two steep slopes of moving sands, meeting in a sharp ridge.

There are also pyramidal dunes (*ghourd*) with several ridges leading down from the top, as evidence of multidirectional winds.

There are also hollowed dunes – corridors between two dunes where the wind pours through and digs out *yardangs*. The sheets of sand carried between the dunes in this way will be trapped by tufted plants, gradually forming what are called *nebkas*, which continue to grow, eventually forming larger and larger dunes.

The material often comes from matter previously removed by water erosion – inland or marine sediment, products of weathering or disintegration of coarse-grained rocks, or else from soil finely powdered by tillage techniques, particularly the ill-advised use of disc ploughs, especially on volcanic soil (for example the basaltic soil of Nicaragua or the loam of the Great Plains in the United States).

EFFECTS OF WIND EROSION

- The first effect is the winnowing of light particles. Wind erosion is very selective, carrying the finest particles – particularly organic matter, clay and loam – many kilometres. The build-up of this alluvial matter stripped by the wind from the periglacial steppes gave rise to the fertile loess soils that cover large areas of Europe and North America, where highly productive farming has developed.

- The most spectacular forms are dunes – mounds of more or less sterile sand – which move as the wind takes them, even burying oases and ancient cities.

- Degradation of sedimentation crusts on the surface of stripped soils, or the weathering of rocks at their base where they are in contact with the soil (abrasion).

- Sheets of sand travelling close to the ground (30 to 50 metres) can degrade crops (particularly millet or cotton seedlings in semi-arid zones).

- Lastly, wind erosion reduces the capacity of the soil to store nutrients and water, thus making the environment drier.

FACTORS AFFECTING THE EXTENT OF WIND EROSION

- **Aridity of climate.** Wind erosion can also take place in high-rainfall climates when certain months of the year are particularly dry (but only if the soil is tilled with techniques that crush the surface fine). It tends to be slight in Africa, however, except where rainfall is less than 600 mm; there are more than six months without rain; potential evapotranspiration exceeds 2 000 mm; soils have been left bare; and the vegetation shifts from savannah to steppe, with patches of bare soil.
  Wind-speed also has to exceed about 20 km/h or 6 m/s over dry soils. Wind erosion phenomena will increase proportionately in the presence of strong, regular prevailing winds or gusts.
- **Soil texture.** Loamy sand, rich in particles between 10 and 100 microns in size, is the most vulnerable soil (Bagnold 1937). More clayey soil is much stickier, better-structured, and hence more resistant. Coarse sand and gravelly or rocky soils are also more resistant, since the particles are too heavy to be removed by wind erosion. The optimum size for wind erosion is about 80 microns.
- **Soil structure.** The less structure-improving matter a soil has on the surface (organic matter, iron and free aluminium, lime), the more fragile it will be, while the presence of sodium or salt often leads to formation of a layer of dust on the surface, which fosters wind erosion.
- **State of the soil surface.** If the soil surface is stony, forming a “pavement”, the risks of wind erosion are lower – as, for example, in *regs*.
  A rough surface, left by cloddy tillage or ridges perpendicular to the prevailing wind, slows down the wind at ground level, thus reducing saltation.
- **Vegetation.** Stubble and crop residues in the soil cut wind-speed at ground level.
- **Soil moisture** increases cohesion of sand and loam, temporarily preventing their erosion by wind.

WIND EROSION CONTROL

Wind erosion control is carried out on two fronts: reducing wind-speed at ground level, and increasing soil cohesion, thus improving soil resistance to wind.

INCREASING SOIL COHESION

Applications of organic matter in the surface horizons improve soil structure.

Spraying the soil with refinery sludge, heavy oil or bitumen and plastics industry waste (for example, diluted glue) binds particles to the soil surface making it difficult for the wind to remove them (Gand University experiments).

Where there is enough water, supplementary irrigation can be an effective and financially viable way of reducing erosion problems. Irrigating the soil prior to the normal rainy season is enough to allow favourable tillage conditions and establish plant cover before the destructive tornadoes which generally come at the start of the rainy season.

INCREASING ROUGHNESS OF THE SOIL SURFACE

This entails cropping techniques that leave large clods on the soil surface or ridges perpendicular to the direction of the prevailing wind – although ridges must not be more than 40 cm high or the wind will lop off their tops, thus speeding up erosion.

Another very effective control method is that of leaving crop residues in the fields. In Burkina Faso, for example, when millet and sorghum stubble is cut at a height of 1 metre and left vertical to the soil surface, it traps a large amount of dust, together with leaves that tornado winds have blown off the trees.

INCREASING PLANT COVER

Wind-speed can also be cut by increasing plant density. Since this is clearly not easy in arid zones, it is particularly important to ensure sound crop residue management, keeping residues on the ground so as to increase roughness and protect the soil surface, rather than ploughing in, which would only slightly improve soil structure and resistance to wind. In the semi-arid tropical conditions of West Africa, the large natural stands of *Acacia albida* so prevalent in cultivated zones generally provide fairly effective protection against wind erosion in these fragile areas by cutting wind-speed at ground level, and also shedding leaves onto the ground. Unfortunately, most of these stands are made up of between 25 and 40 very old trees per hectare and are in urgent need of regeneration. Planting 100 to 150 young trees along the defence lines against water erosion would give a good density of adult trees. In areas subject to violent blows from a regular direction, hedges and **wind-breaks** are well-known methods.

WIND-BREAKS

Their role is twofold: they cut wind-speed to reduce both evaporation and wind erosion. The effect of cutting wind-speed by 20% is operative over an area 10 to 12 times the height of the barrier before and behind it.

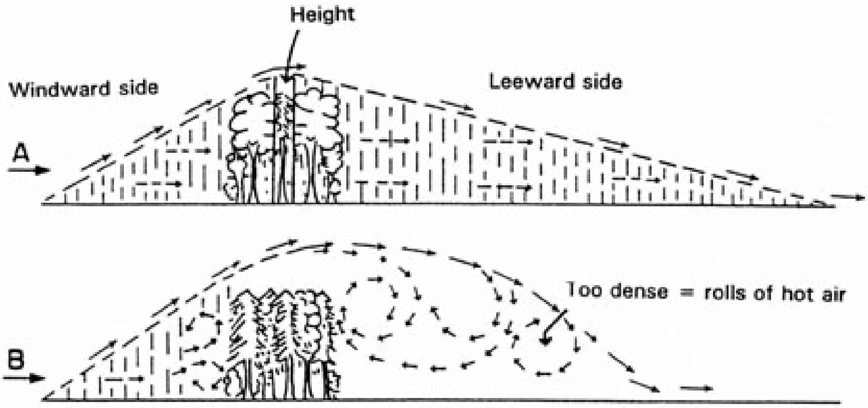
This protection depends on the permeability of the wind-break, for relative impermeability reduced speed more, but over a smaller area. According to Heusch (1988), if the speed is cut too much by very close planting, the temperature rises and crops are scorched along the wind-break. It would be better to regenerate a stand of about 40 adult trees to cut the wind-speed more regularly.

In principle, wind-breaks reduce evapotranspiration by up to 20% (although the water consumption of the wind-break itself can offset this positive effect), hence the attraction of wind-breaks around irrigated crops. In the Keita Valley in Niger, a marked rise in yields (+27%) is seen except in the direct vicinity of the wind-breaks, where the millet suffers from root competition with the roots of the wind-break (shade and competition for water).

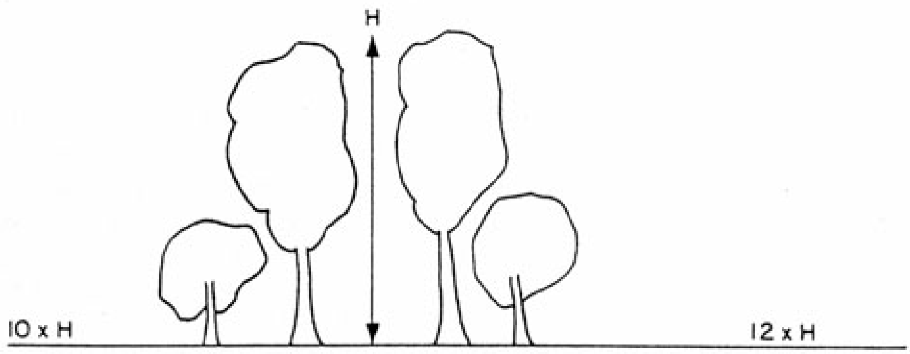
The best arrangement would be two rows of tall trees surrounded by two rows of low trees, making up a 10-metre strip (Figure 59b), half of which is logged at a time. The cropped area between wind-breaks can be as wide

FIGURE 59

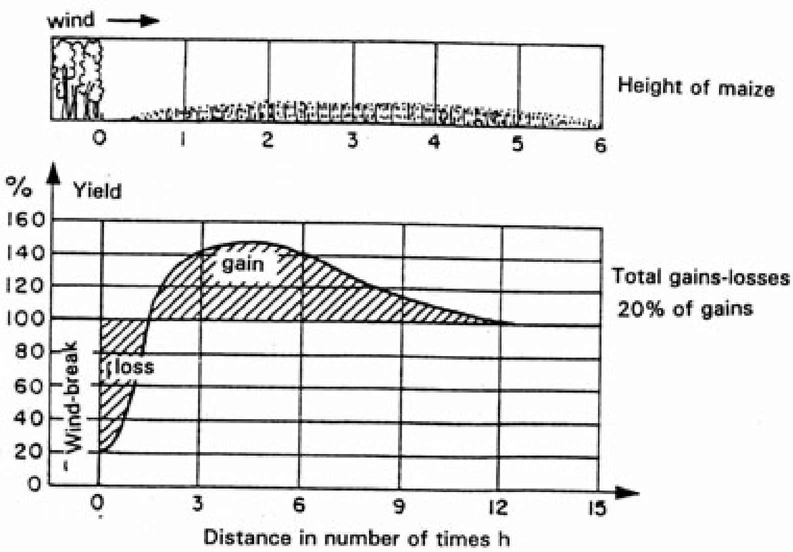
(a) Influence of a wind-break on the wind (cf. Combeau 1977)



– Wind flow through and over a moderately penetrable (A) and dense (B) protective screen



b. Influence of a wind-break on production of a cereal grain (cf. Guyot 1963)



as 100 metres if the tall trees are over 5 metres. Root competition is reduced by breaking the young horizontal roots of the trees from the first year onwards by raking the tillage furrow. It is particularly important to repair breaches in a hedge to keep the wind from pouring through at these points (the Venturi effect) and considerably reducing effectiveness.

When the trees are cut, it is best to leave two metres above the ground so that livestock do not destroy new shoots.

The most commonly grown tree species in Africa are eucalyptus, *casuarina*, *neem*, various acacias, tamarisk and cypress – although cypress is susceptible to a serious disease. Reeds of various kinds can also be useful.

A wind-break does not have to be very thick: the thicker it is, in fact, the more impervious – and thus the less effective – it becomes. At a distance of 10 times the height of the barrier, the wind-speed on the leeward side is 56% the speed of the local wind behind a line of reeds, 72% behind a 20-m thick wind-break, and 83% behind a 600-m wide forest strip (Combeau 1977).

In Niger, Renard and Van den Beldt (1991) noticed that huge quantities of sand were trapped in the strips of *Andropogon* surrounding their trial plots, and they therefore suggest that farmers should surround their fields with a double row of *Andropogon*. Elsewhere, low crops such as groundnut and cotton are protected by interspersing them with rows of millet and sorghum, which can reach a height of 4 m. Lastly, although the initial objective of wind-breaks is that of reducing evaporation caused by the wind, they also help to reduce the amount of solid wind-borne matter. The wind must be able to pass through them and not set up eddies, and they must combine species with complementary forms and heights and in sufficient numbers, so that they can be logged in succession and regularly renewed (Figure 59).

DUNE FIXATION

The point of dune fixation is to eliminate the source of sand and to keep the dunes in place, using both mechanical and biological methods. In places where dangerous winds come from only one direction, wind erosion can be stopped by rows perpendicular to this wind at distances of 20 times the height of the rows. So if millet or sorghum stalks 1 to 1.5 metres high are used, rows should be spaced every 20 metres, or the wind will take up sand between these lines of defence. This means that large amounts of material are needed (millet stalks, oleanders which grow in wadis, palms, or prunings from the forest trees or shrubs found in the region), and the removal of this material helps to degrade the area. If – as is often the case – the dangerous winds come from a variety of directions, the use of grids of permeable plastic sheeting with a 5- to 10-mm mesh and a height of 50 to 80 cm is indicated. The stronger the winds, the smaller the grid, ranging from 5 x 5 m to 8 x 8 m in normal conditions. Some plastic sheeting, scorched by UV rays, turns to dust after two years, and is therefore to be avoided, while some black UV-resistant plastic can be used for two years on one site and then moved to another. The main problem is to stretch it and to have solid enough stakes to hold it (12-mm reinforced concrete posts). As soon as this grid is in place and the soil surface has become more stable, a variety of grasses and shrubs must be planted inside it to restore plant cover and definitively stabilize the dune.

Another inexpensive method well suited to West Africa is that of sowing rows or grids of millet or some other fast-growing plant in the rainy season, thus giving the soil further stability. If the survival of these fragile planted plots is to be assured, it is obviously vital to protect them against grazing and fire, although after five years some light and well-supervised grazing may be possible.

In France, the first attempts to stabilize coastal dunes were made in the 16th century, when the town of Bayonne had a sand-loving plant sown on the live dunes at Cap Breton, followed by reforestation with sea pines. In 1786, Bremontier, a public works engineer, initiated measures to fix the sandy heaths near Arcachon, by having branches of broom spread over the sand, and sowing with pine. These attempts were so successful that work then continued until 1876, covering 80 000 ha and costing 9.6 million “gold francs” plus 3.5 million for the creation and upkeep of a long, protective coastal dune to cut the wind-speed and allow the pines to grow.

This protective dune 50 metres behind the high water mark has a bank with a 20% slope facing the west winds and planted with *Ammophila arenaria*, then a flat top, with a palisade on posts along its axis, then a crumbling bank of sand. When the fence is about to be capped by deposits, it is raised again with a gin, until the dune eventually reaches a height of 10 metres (in 10 ± 2 years). In front and to the sides, wattling marks off the area to be stabilized, and seeds are broadcast inside this area, after which the soil is covered with branches of pine, gorse, heather or broom laid one over the other like tiles on a roof, with the thick ends of the branches pushed into the ground towards the wind.

One hectare will take 25 kg of pine seed, 15 kg of broom seed, plus gorse and *Ammophila*, 120 000 15-kg bundles of branches, and 120 days of work, plus the cost of creating the fence (Heusch 1988, p. 184).

CONCLUSION

It is interesting to see how similar wind and sheet water erosion are in terms of the processes involved, the effects on the soil, and the factors and control methods. Indeed, an equation very similar to the USLE has been drawn up to forecast wind erosion. Wind erosion assumes significant proportions only when the wind carries a load of sand grains which bombard the bare soil surface, and sheet erosion occurs when rain splashes on naked soil. Both forms of erosion selectively carry off fine particles from the soil surface, and both are eliminated by mulching the soil or by providing an adequate plant cover. Both processes lead to a reduction in fine particles in the surface horizon – or scouring of the whole horizon in the most extreme cases. The factors that can be brought into play are soil cover, pervious barriers that allow the medium (water or air) to filter slowly, and improvement of the structure, cohesion and roughness of the tilled horizon. The control methods are therefore very similar: hedges, wind-breaks, keeping crop residues on the soil surface, thick plant cover, coarse tillage, mounding or tied ridging, reduction of the length of fields exposed to prevailing winds or runoff, organic or mineral applications (lime or gypsum), etc. This is why this publication is confined to general principles, referring readers to the many manuals giving details of plant species suited to local dry conditions.

PART THREE

Case studies

LAND HUSBANDRY ENCOURAGES REGIONAL DIVERSITY IN EROSION CONTROL DEPENDING ON ENVIRONMENTAL, SOCIAL AND ECONOMIC CONDITIONS

In **Part One** of this work the variety of forms that erosion can take in terms of both space (the effect of scale) and time has been emphasized.

It was shown how serious the economic impact of erosion can be for a regional community, especially in terms of downstream damage caused by peak runoff flows, deterioration in the quality of water, and siltation of reservoirs and river beds as suspended load is deposited. Degradation of cultivated land and loss of productivity on soil exposed to erosion vary widely depending on soil type, amount of rainfall and topographical position. An historical review of erosion control strategies shows that for thousands of years humanity has demonstrated a capacity to adapt to changes in environmental and human circumstances – in this case, to erosion crises. However, the acceleration of demographic, social and economic change in recent decades has led to a new erosion crisis, with causes that vary from those in large-scale field-crop regions (excessive mechanization, ill-suited to local conditions) to those in semi-arid, extensive agropastoral regions (degradation of plant cover and of organic matter in the soil) or densely populated mountainous regions (increasingly intensive farming with no balanced input of nutrients).

Erosion control is thus not simply a technical problem (and in any case effective techniques are still unavailable in many places), but is in fact primarily a human problem. This has led to proposals for a new approach based on solving immediate needs (increased productivity of both land and labour) while guaranteeing the future through the best management of available water, biomass and nutrients.

In **Part Two** the five main types of erosion are briefly examined, noting the causes and factors determining the extent of each, and outlining some of the principles of erosion control. (Specific methods have been described in detail in many manuals: CTFT 1969; Hudson 1973; Heusch 1988; Hurni 1986.) Closer concentration was placed on the difficulties of controlling sheet and rill erosion – in other words, the initial forms, which farmers can control on their plots.

The success or failure of such control generally depends on measures taken at the field level, and it is here that peasant farmers' skill is demonstrated in making the best of their physical, social and economic circumstances, developing widely varying techniques for managing water and soil fertility.

Wischmeier and Smith's empirical model has been used to provide a consistent framework for analysis of the causes and contributing factors in sheet (and rill) erosion. The value and limitations of this empirical model have been pointed out: its systematic approach allows definition of the risks of sheet erosion on fields with an average slope (1 to 20%) and a less empirical approach in suggesting a range of methods for reducing average soil loss over a 20-year period to a theoretically acceptable level; it takes no account of exceptional rainfall (typhoons with strong winds, tropical tornadoes with 500 mm of rainfall in one to three days), interactions between different functional sections of a toposequence (water accumulation on the lower part of a slope), steep slopes (> 20%) where the energy of runoff supersedes that of rainsplash, or, most especially, regional variations in cultural, social and economic conditions affecting the choice of soil conservation methods.

This is the reason why this **third part** expands the picture of the variety of problems and approaches to conservation to include a wide range of environmental conditions (temperate, semi-arid Mediterranean or Sudano-Sahelian climate, subequatorial forest or over-populated mountainous zone, etc.) and human circumstances (developed or developing countries, population pressure varying from 10 to 700 inhabitants per km^2). A set of case studies by French-speaking experts working in very different regions is used to demonstrate the ways in which land husbandry can meet present needs for increased land and labour productivity, while improving the rural environment. Since land husbandry is a relatively recent concept, the choice of examples is still limited, and the perspective is not yet broad enough to draw any definitive conclusions from these trials.

Chapter 9 compares the environmental conditions and soil degradation problems along a whole bioclimatic sequence starting from the subequatorial zone of southern Côte d'Ivoire, crossing the Sudano-Sahelian zones of Mali and Burkina Faso, and ending with the Sahelian zone of West Africa.

In Chapter 10, J.M. Fotsing describes the development of the Bamiléké bocage in south-western Cameroon, where erosion is inversely proportionate to intensification of agriculture.

Chapter 11 reports the present state of research on the integration of agroforestry and subsistence farming among very dense populations (150 to 800 per km^2) farming the steep slopes of the Milles Collines region of Rwanda.

Chapter 12 moves to Haiti, describing the implementation of a land husbandry approach based on the people's participation in a whole system of rural development.

In Chapter 13, a Franco-Ecuadorian team analyses the situation of peasant farmers on the volcanic Cordilleras of the Andes, and describes solutions recently developed by these farmers.

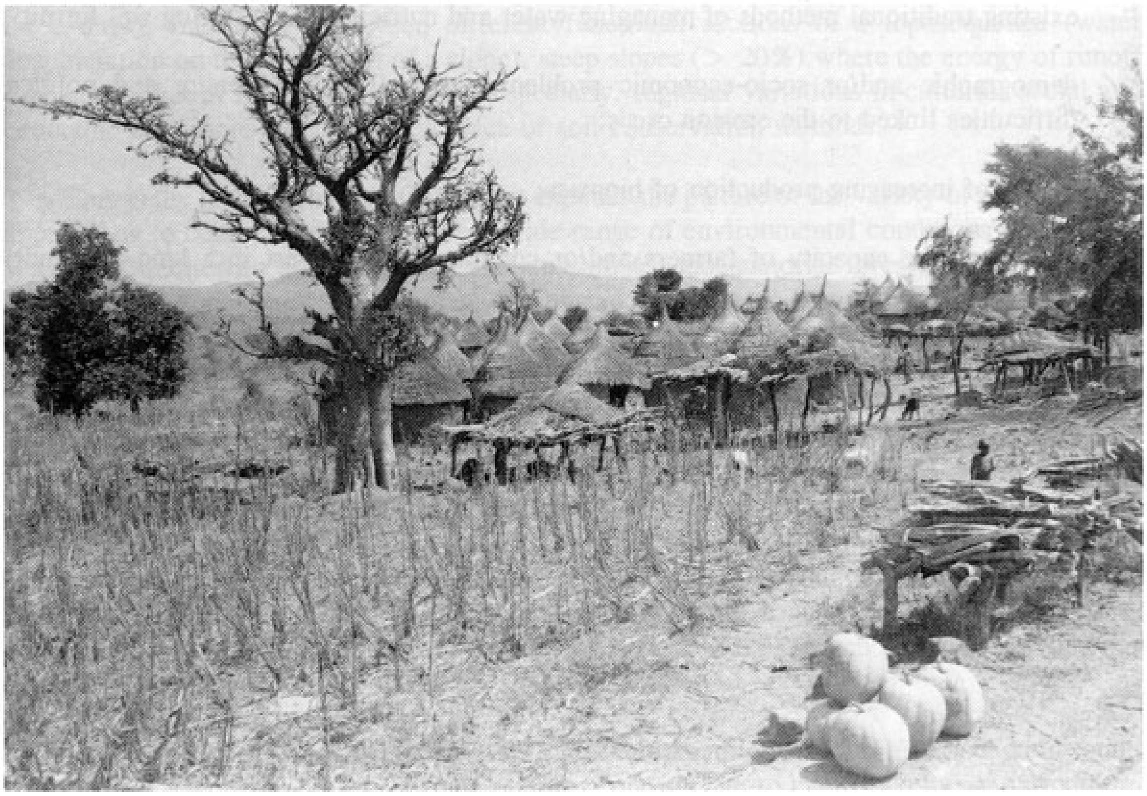
Chapter 14 gives the initial results of an INRF-ORSTOM Franco-Algerian team's research, which seeks to define erosion risks and develop intensive farming on the steep slopes of the semi-arid Mediterranean mountain regions of northern Algeria.

Lastly, in Chapter 15, J.F. Ouvry, an agricultural scientist working with AREAS, describes the problems involved in the management of surface water in intensive field-crop areas on the temperate plains of northern France.

This aim will have been achieved if at the end of this third part the reader has become aware that it is not enough to apply solutions that have had some (unverified) positive effects in some other part of the world.

No erosion control measures can be envisaged without close analysis of:

- the comparative risks of different kinds of erosion;
- existing traditional methods of managing water and nutrients and restoring soil fertility;
- demographic and/or socio-economic problems, as well as land-tenure and political difficulties linked to the erosion crisis;
- means of increasing production of biomass;
- costs, and the capacity of farmers and/or communities to invest in a land husbandry strategy.



Chapter 9

The wide range of erosion control strategies in West Africa: from subequatorial forest to Sudano-Sahelian savannah

AN EXAMPLE OF AN AGROCLIMATIC SEQUENCE

If a line were drawn from Abidjan to the Sahel a wide range of traditional farming systems would be found along this line.

In the Guinean forest zone of Côte d'Ivoire, there are small mounds on which cassava, maize, groundnut, okra, etc. are multicropped.

In the Sudanian tree savannah of northern Côte d'Ivoire, the Sénoufo shift huge amounts of soil, forming very large mounds (about 80 cm high) to grow tubers (yam, cassava). In following years the fields are ridged with crop residues placed in the furrows and covered with soil from the mounds.

Three hundred kilometres further north, the Miniana in the Koutiala region of Mali reduce tillage to a fairly hasty ploughing following by two surface hoeings.

Another three hundred kilometres further north, the Mossi of the Sudano-Sahelian tree savannah region of Ouahigouya practice direct drill seeding and then flat-hoe.

Lastly, in the sandy zone of northern Yatenga, the Peuhl practice surface sod seeding on untilled ground, and then use hoes to make mounds between the plants in order to concentrate water around the millet planting holes.

This wide range of farming techniques is not the outcome of chance, but of the long adaptation of each group to the environment in which it lives. The longer people have been settled on a given site and the harsher their living conditions, the more they will have developed strategies for managing water, biomass and soil fertility that are suited to their environmental, social and economic situation. It would seem that where farmers have developed very few special techniques, this is often because they have recently migrated from a place with very different problems. For example, in Cameroon the Capsiki, farmers in the Mandara mountains near Mokolo, build bench terraces and low stone walls on steep slopes in an extremely densely populated area. When these people are shifted to the under-populated Sudanian zone of south-eastern Bénoué, beyond Tchollirá, they completely abandon their techniques for water and soil fertility management.

Traditional farming techniques are usually very well adapted to the environmental conditions of the locality – as can be seen by comparing the water balances of the various areas.

These traditional strategies have now been largely abandoned, and are indeed no longer adequate for coping with the problems of soil degradation arising from population pressure: the population is doubling every twenty years in Sahelian savannah and mountain zones. Fortunately, part of this population is migrating into Sudanian zones, thereby relieving pressure on land in the very vulnerable Sahelian zones. Nonetheless, study of traditional strategies provides **a good basis for the development of new strategies of water and soil fertility management** in order to counteract soil degradation, runoff and erosion, which are all closely linked. The failure of a number of erosion control schemes would quite probably have been avoided if traditional methods had been studied more closely and an erosion control strategy more in tune with local environmental, social and economic conditions had been proposed in place of the generalized imposition of methods developed during the 1930s for mechanized farming in the United States.

The following pages briefly describe ten different situations, with the treatment used for each, depending on the type of land management, general environmental conditions (especially the water balance for each type of crop) and social and economic conditions (especially population pressure) [Plate 10].

EROSION CONTROL IN THE SUBEQUATORIAL FOREST ZONE OF THE ABIDJAN REGION OF SOUTHERN CÔTE D’IVOIRE

TRADITIONAL FARMING TECHNIQUES

Following gradual land clearance over five years, Ebrié farmers build small mounds 30 cm high in February, well before the rainy season. These mounds allow them to plant a combination of crops that are complementary in both time and space: on the one hand, cassava cuttings, which take a very long time to cover the ground, and, on the other, very fast-growing crops such as maize, groundnut, okra and tomato, which cover the mounds quickly, are harvested in three or four months, and then leave growing space for the cassava. Mounding has several purposes: apart from drainage and the accumulation of humus so that the tubers grow well, it also organizes drainage and collects fertilizing elements around the crop. And this mixed cropping means that the soil is covered for two years.

A bush or tree crop – coffee, cacao, palm or rubber – is also often introduced under this cover of more or less annual crops. When the soil is exhausted, it is abandoned to fallow or the tree crop, making sure that the understorey is cut back under the trees. The number of shade trees may be reduced after a short while, but palms and kola trees are retained.

ANALYSIS OF LOCAL CONDITIONS

Such landscapes are composed of convex hills, with typical half-orange forms and convex slopes which may reach 40% at the edges, and flat, sandy, hydromorphic lowlands. Soil on the hills is ferralitic, sandy-clayey, and very resistant to sheet erosion (K = 0.10). This soil is permeable but very acidic and chemically impoverished.

Annual average rainfall is about 2 100 mm, spread over ten months; the maximum monthly rainfall is in June, with 700 mm, and annual drainage is 1 000 mm. Evapotranspira-tion is low (1 200 mm). Daily rainfall may reach 250 mm once every ten years.

HAZARDS

At the top of gently sloping hills there are two risks:

- soil degradation from the rapid mineralization of organic matter, rainfall impact, and skeletonization of the surface horizon;

- acidification due both to abundant drainage and to leaching of fertilizing elements.

On steep, convex slopes, the previous hazards are combined with that of gullying. And in the valley bottoms the hydromorphic soil is prone to waterlogging in the rainy season and parching in the dry season. As these areas are often peaty and sandy, the soil is very acid, which has to be corrected.

SUGGESTED IMPROVEMENTS (Figure 60)

The neatest solution to the problems of degradation of organic matter and acidification is to cover the soil permanently with tree crops, with a cut-back under-storey grazed by livestock to some extent. **On gently sloping uplands** root and tuber crops providing less ground cover may be planted (cereals, cassava or various food crops), the aim being to cover the soil in order to minimize surface degradation and slow down runoff.

The second point is to fertilize root and tuber crops with staggered applications of both organic and mineral fertilizer: drainage is so copious during the rainy season that most of the nutrients added to the soil are drained off in June and July, unless the crops are able to take up and store them in their tissues.

The third point is to restore the amount of organic matter in the soil, either by cutting the under-storey, digging in crop residues, or, better, keeping crop residues on the surface and mulching.

It is important to plant early and closely, and to plan both mineral and organic applications – which must be staggered in view of the risk of removal by drainage, the poor storage capacity of the soil and the physiological needs of the crops, rather than deficiencies in the soil. Lime is needed if the pH is below 4.8, in order to avoid aluminium toxicity.

On steep slopes, apart from the risks outlined above, it is essential to ensure a permanent cover of pastureland, or, if possible, tree crops with an under-storey of legumes (a mixture of *Pueraria* and *Centrosema*). If there is no choice but to grow food crops here, either the whole slope should be mulched, or hedges should be planted and the prunings used to cover the ground with a permanent light mulch.

FIGURE 60
Erosion control in a subequatorial Guinean forest environment, e.g. the Abidjan region

Analysis	Rainfall	2100 mm/yr	Max. monthly rainfall =	700 mm
	Rainfall 1/10	250 mm/day	Monthly PET	1200 mm/yr
	R_{USA}	1200	Heavy drainage about	1000 mm/day

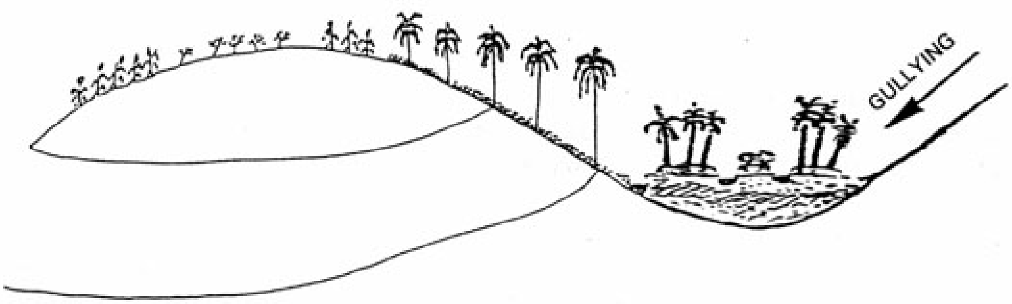
Ferralitic, permeable, acid, sandy-clayey soils

heavy erosion

heavy leaching

Hazards

Sheet erosion		
Rainsplash	Idem	
Skeletonization	+	Siltation
Leaching	Gullying	Waterlogging
Acidification	Scouring	Acidification



Improvements

Convex uplands

- Cover the soil: plant early + thickly + mixed cropping
- Fertilization adjusted to meet crop needs
- Management of organic matter; cover plants/mulch
- Supplementary organic and mineral fertilization in staggered doses

Steep slopes

- Permanent soil cover, under-storey of legumes. Palms, rubber, coffee, cacao
- If root and tuber crops are unavoidable, hedges + light mulch + staggered fertilization

Valleys

- Surface drainage
- Interception of lateral inputs
- Dry-season irrigation
- Management of organic matter + staggered mineral supplements
- Bananas + horticulture

In the valleys, the problem is that of organizing drainage of excess water during the rainy season, digging lateral channels to catch water from slopes, and providing irrigation during the dry season, especially for banana plantations and horticulture. Staggered applications of organic matter, lime and mineral nutrients must be planned, taking account of the risk of their removal by drainage.

EROSION CONTROL IN THE HUMID, TROPICAL, SUDANIAN SAVANNAH OF KORHOGO IN NORTHERN CÔTE D'IVOIRE

TRADITIONAL FARMING TECHNIQUES

After selective, gradual clearing by burning over several years, the Sénoufo build large mounds as high as 60 to 80 cm to grow yam or cassava.

During the second, third and fourth years, the farmers place weeds, crop residues and assorted biomass elements between the mounds, covering them with earth, taking half a mound from either side. This forms new large ridges on which they intercrop maize, sorghum and groundnut with various secondary crops such as tomato, tobacco and okra.

The fields form a patchwork of small ridged plots with tied edges. When rainfall is excessive, the water runs into a drainage ditch, which unfortunately often turns into a gully. The direction of the ridges is seen as irrelevant, varying from one field to another.

The Sénoufo have a long tradition of agroforestry, and when they are clearing land, they retain a whole series of trees of recognized value: locust bean, karité, kapok, baobab, *Daniela olivieri* and many others. As the years pass, they protect the stumps of these trees while cutting them back to allow food crops to be grown.

In the hydromorphic valley bottoms, the Sénoufo grow irrigated rice, digging a feeder channel down the side of the valley, with side offtakes for excess water, and central drainage capable of carrying off large amounts of water during the wettest months.

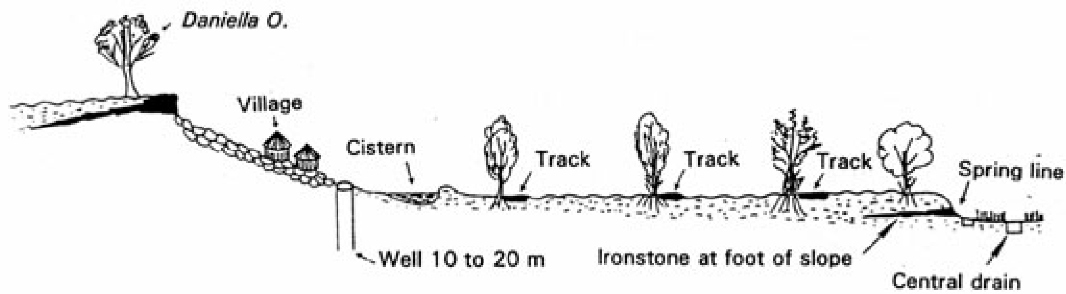
ANALYSIS OF LOCAL CONDITIONS

Average annual rainfall ranges from 1 000 to 1 400 mm. The heaviest monthly rainfall can reach 400 mm for an annual volume of drainage of 400-200 mm. The aggressiveness factor is very high at 700 to 500 – and at ten-yearly intervals rainfall in a single day can reach 140 mm. Risks of leaching and erosion are therefore considerable, although reduced by a luxuriant vegetation.

The landscape is composed of lateritic tabular hills or granite domes surrounded by scree slopes of large rocks and long sloping pediments of red or ochre ferralitic soil, with gradients decreasing from 5 to 1%. The soil in the valley bottoms is hydromorphic, sandy and humus-bearing. Traditionally this low-lying land was used as a reserve supply of green forage for livestock during the dry season, but in the past 50 years a large proportion has been given over to irrigated rice, increasing the danger of overgrazing on the slopes. The soil on the hills is ferralitic, very desaturated, often gravelly, and resistant to erosion, but acid and chemically very impoverished. Although the whole profile is ferralitic in type, the top horizons are at present in the process of changing into more ferruginous tropical

FIGURE 61
Diagram showing improved use of a granitic landscape in Sénoufo country (Korhogo): example of farming requiring drainage in a Sudanian zone

Ironstone plateau	Scree slopes with large boulders	Gravelly pediment	Sandy-loam pediment on red → ochre → grey hardpan	Bottom lands subject to prolonged runoff
Extensive rangeland + crops on large mounds		Reserve of fragile land	Intensive cropping block with reserve of stumps of useful trees	Rice fields + fruit and banana gardens
slope < 0.5%	< 20%	8 to 3%	3 to 1%	1 to 0.1%
			Ridging on gentle slope leading to spillways	
			Rows of trees ± hedges	



Ferralitic soils — very poor in organic matter and bases, deficient in N and P; highly desaturated due to strong drainage, and risk of waterlogging for two months; often gravelly, drying out fast

Hazards

- Degradation of organic matter; acidification of plateau land
- Gullying at foot of hills and starting at villages + tracks

- Temporary waterlogging: rotting of tubers
- Sheet erosion → rills → gullies
- Leaching of nutrients, acidification

- Flooding in August + September
- Silting up with material carried down in gullies

Improvements

- Organic and mineral fertilization of deep upland soil
- Reforesting the remainder, rangeland (cashew, teak, eucalyptus)
- Downstream: villages + wells
- Cisterns on drainage lines to irrigate small fruit gardens

- Blocks of mixed crops on ridges
- Gently sloping large ridges, tied or untied, with rainfed rice in the furrows
- Drainage on the edges by grassed spillways, used as tracks in dry season
- Agroforestty: hedges and rows of trees every 25 to 50 m to form gradual banks
- Fenced livestock paddocks with hedges

- Central drainage: lateral irrigation of rice fields + fodder in the dry season
- Off-season fruit trees bordering household plots

soils. Toward the foot of the slope is a spring line, and below this is the greyish, hydromorphic and generally sandy-clayey soil used for rice growing.

HAZARDS

The soil on the hills has a good structure and good drainage. It is exposed to risks of **acidification** through use of fertilizers, **degradation of organic matter** (like all tropical soils, and **leaching** caused by extensive internal drainage. If this soil is mechanically tilled it gradually loses most of its organic matter and its resistance to the impact of rainsplash, becoming prone to erosion and runoff. On steep slopes, in heavily populated areas with overgrazing and late fires, gullies tend to develop on the lower part of slopes. On the central cropped pediment, apart from the dangers of soil degradation, acidification and leaching, sheet erosion can turn into gullying. Moreover, the runoff from the hills can also waterlog the surface soil and rot tubers.

SUGGESTED IMPROVEMENTS (Figure 61)

In the ironstone uplands, scree slopes and broad gravel pediments, forestry potential can be improved by planting cashew, teak and forage trees.

Small fruit gardens, irrigated from wells, can be planted around dwellings, which are very numerous in this region. Indeed, below the gravelly layer there are alterites which stay moist almost to capacity on the fields throughout the better part of the year. Cisterns could be dug at the foot of this zone to lighten the task of drawing water for livestock and village use (permanent water tables lie at a depth of between 10 and 30 m).

So far as the cultivated section is concerned, it is best to keep small ridged fields on gentle slopes, tying them to some extent, and possibly sowing rainfed rice in the furrows. Grass strips with trees (which will act as green stakes) or hedges should be planted around fields to keep out wandering livestock. Spillways also have to be built to carry off excess water during the wettest months, and to act as grassed pathways for removal of produce during the drier months.

Rice fields can be laid out in the valley bottoms with two side channels collecting water flowing from the spring lines and river water upstream. The centre of the valley is the central drain through which the river flows, and this will carry off excess water. Fruit and vegetable gardens can be created on the edges of the valley, not far from the spring lines. Lastly, it would be wise to plan a dry-season fodder crop on the rice fields and in the wetter parts of the valley, planting hedges in order to control livestock more effectively.

EROSION CONTROL IN THE TROPICAL SAVANNAH ENVIRONMENT OF THE KOUTIALA REGION OF MALI: strictly rainfed farming

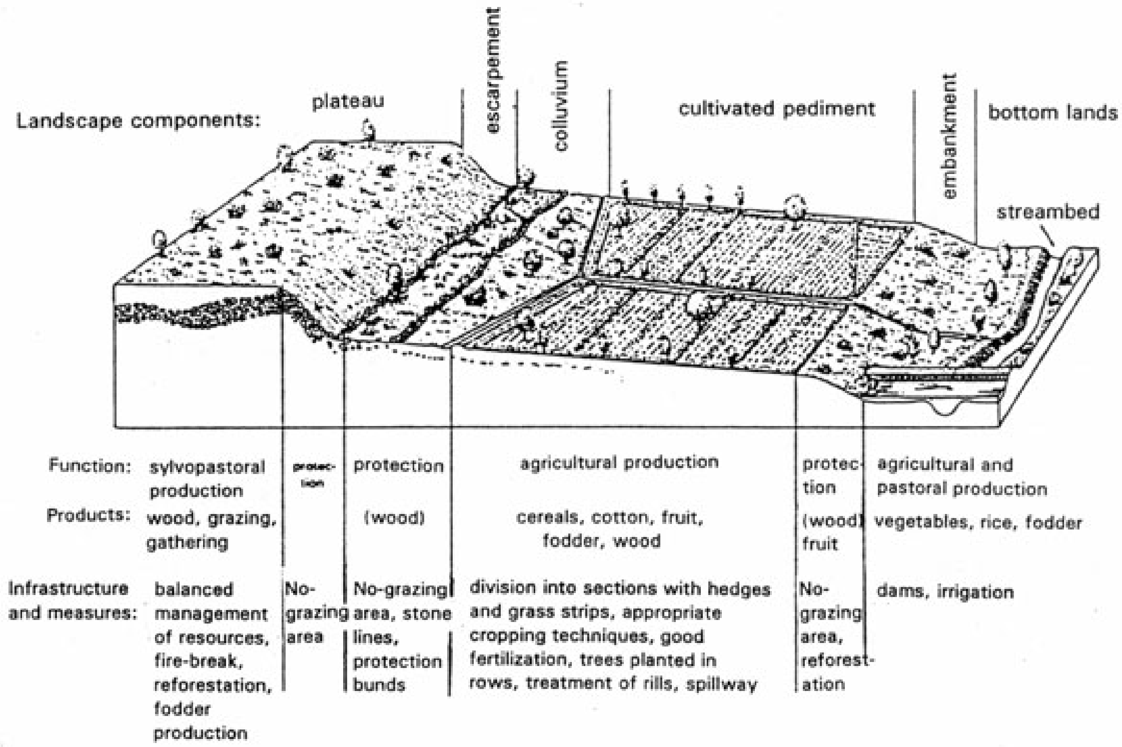
TRADITIONAL FARMING TECHNIQUES

In times past the Minianca traditionally used the sandy and even the gravelly land at the top of hills, building their villages on lateritic ironstone in order to avoid being surprised by possible enemies. Nowadays, with mechanization and animal traction, they prefer to farm the loamy-sandy sloping pediments, and tillage is confined to one passage with the plough and two with the hoe, mounding at the same time.

Animal husbandry is always extensive. During the rainy season a shepherd (often an outsider) takes the village animals to the grazing lands. During the dry season livestock live off crop residues and any greenery remaining in the valley bottoms.

In the evening cattle are gathered in paddocks protected by a dead hedge. Dried dung trodden into powder by the animals’ feet accumulates in these paddocks. Wood requirements have so far been met by taking it from the

FIGURE 62
Diagram showing improved use of a hillslope in Minianka country: an example of rainfed farming proper (cf. Hijkoop, Poel and Kaya 1991)



rangeland. In the cultivated area there is still a stand of karité, locust bean, and occasionally *Faidherebia albida*. The valley bottoms are still little used, except for rice production where wide enough, and fodder at valley heads in the dry season. The farmers are aware of the steady degradation of their environment due to the increasingly intensive cropping of cotton and cereals, and are anxious to protect the cultivated areas from runoff from rangelands and the considerably degraded lateritic hills.

ANALYSIS OF LOCAL CONDITIONS

Rainfall gradually decreases from 1 000 to 700 mm. Maximum monthly rainfall is 250 mm, and drainage decreases from 200 mm to practically zero. Wischmeier's R_{USA} erosivity factor varies from 350 to 500, and the highest daily rainfall at ten-yearly intervals is 120 mm. The ferruginous, tropical, loamy, fairly unacidic, undesaturated soil is fragile and vulnerable to rainsplash. As in the previous cases, the landscape is composed of lateritic hills or granite domes followed by scree slopes, and in this case very long sloping pediments (several kilometres) ending in steep banks or valley bottoms of varying widths, degraded through overgrazing.

HAZARDS

The dangers on the gravelly soil of the hills come from degradation of the vegetation through overgrazing, which leads to a reduction in infiltration. Concentration of runoff leads to deep gullying which can severely scour the slopes. On the cultivated sloping pediments, apart from soil degradation through mineralization of organic matter and rainsplash, there is also gullying from the hills, the deposition of stretches of sand and gravel, and the skeletonization of the surface horizon from very frequent tillage. In the hydromorphic zone in the valley bottoms, the risks are those of degradation through overgrazing, gullying of the bed, and siltation from gullies spanning the entire cultivated area.

SUGGESTED IMPROVEMENTS (Figure 62)

Runoff on the ironstone uplands must be checked by stone lines, grass and forage bushes regenerated, and fodder resources restored. At the bottom of this area, cisterns could be dug in front of the protection dikes that now collect runoff water over 400 metres and lead it toward spillways to divert it during the excessive rains of August. The spillways double as paths during the cotton harvest in the dry season.

In the zone of the broad sloping pediments, grassed spillways are needed to divert runoff and to bring out the harvest. Plots must be bordered by hedges and trees, organic matter and nutrients balanced on plots, and full absorption encouraged through deep tillage followed by tied mounding. In the valley bottoms fertility must be restored through organic manure and fodder crops to improve the production of fruit and vegetables. And in the rice-growing sections, a second, dry-season crop could be grown, allowing deep-rooting plants to draw on water stored deep in the soil. This last section can be improved by using bunds made of earth and clumps of grass to help level each plot perfectly. The main problem in these lowlands is often the flooding caused by heavy rains, and a central channel is therefore needed to drain the whole valley bottom.

EROSION CONTROL IN THE SUDANO-SAHELIAN SAVANNAH OF THE OUAHIGOUYA REGION OF NORTH-WESTERN BURKINA FASO: runoff farming

TRADITIONAL FARMING TECHNIQUES

Mossi farmers behave like pioneers, clearing and burning nearly all the trees, save a few acacias, *Sclerocarya birrea*, baobabs, etc.

At the time of the first storms of the rainy season, and without tilling the soil, they drill-seed sorghum on the best land and millet (plus some groundnut and cowpea) on sandy or gravelly land, in holes every metre. They resow as many as five times if necessary and then hoe once or twice. On the sandy soil in the north, hoeing is combined with clearing around the roots, thus improving infiltration around the clumps of millet.

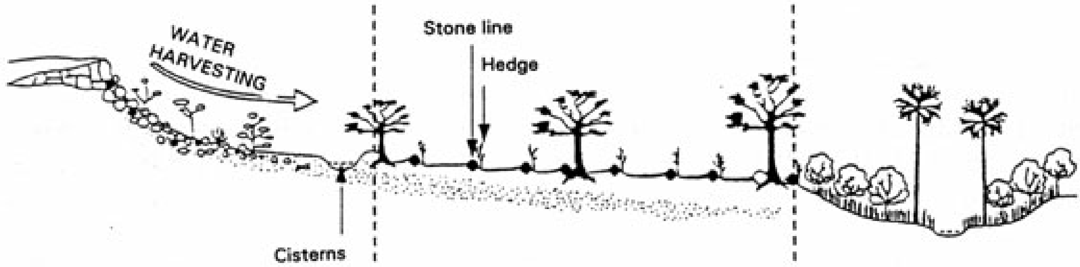
The farmers treat exhausted soils with applications of organic material (2 to 5 t/ha of dried, powdered paddock dung and household ash) or a mulch of cereal stalks and branches of pulses unattractive to livestock, such as *Piliostigma reticulatum* and *Bauhimia refuscens*, and then leave the land as grassland.

They use the zaï method to restore exhausted land, catching runoff in a small pit that contains some organic manure. The tunnelling activity of termites allows this organic matter to trap 100 mm of water after the first storms (Roose and Piot 1984; Roose and Rodriguez 1990; Roose, Dugué and Rodriguez 1992).

FIGURE 63

Diagram showing improved use of a granitic landscape on the Mossi Plateau: runoff farming

Ironstone plateau	Rocky scree	Gravelly pediment	Cultivated sandy-loamy pediment	Bottom lands - sandy uphill, silty-clay below
Slope < 0.5%	< 20%	5 to 2%	2 to 0.5%	0.9 to 0.1%
Extensive communal rangeland + wood		Reserve of fragile land	Block of intensive cropping	Pasture in the dry season, rice or sorghum, fruit gardens, ± irrigated



Gravelly lithosols, to some extent ironstone on deep alterites	Tropical ferruginous soil, increasingly deep, on hardpan, increasingly hydromorphic with depth	Hydromorphic ± sandy

Poor soils: deficient in N and P, sometimes Km Ca, Mg and trace elements: pH 5 to 6.5

Fragile soils: slaking crust, poor infiltration, plough pans, poor in organic matter

Restoration of soil fertility (see saï): tillage + spot manuring + N, P, K supplements + control of runoff + sorghum or strong-rooting legumes

Improvements

Uncultivated water harvesting area

- Storage of runoff.
  - ½-moons, microcatchment.
  - cisterns for cattle, and for irrigating a garden
  - hill lake in a favourable location
- No-grazing area (5-year contract).
  - forage trees along the subsoiling line.
  - grass behind the stone lines.
  - protection against fires.
- Grazing organized by the community herder.

Rainfed crops

- Slowing runoff.
  - hedges + trees along edges
  - stone lines
  - lines of *Andropogon* grass, every 10 to 25 m.
- Creating a bocage against the wind.
- Dense, early sowing, tied mounds to enhance water storage.
- Irrigated gardens behind the cisterns.
- Cattle passage corridors.
- Rotation of cattle paddocks.
- Manure/compost pits near dwellings.
- Supplementary fertilization as required by crops

Irrigated crops + off-season fruit gardens

- Spreading flood water.
- Trapping fertile sediment.
  - filtering dikes
  - bunds build of sods/rice fields
  - small village reservoir.
- Recharging groundwater to increase security in periods of drought.
- Avoiding large trees, which draw too much on groundwater.
- Maintaining a forage zone to act as a filter.

The traditional use of ***boulis* or water tanks** several dozen cubic metres in size, with the earth being dug out and spread downhill in a half-moon shape, also allows them to collect some of the runoff from the hills to water livestock near the rangeland and irrigate a small garden (Dugué 1988). Where land is short, the Mossi farmers use a system known as ***zipelle*** in which stone lines are arranged in a honeycomb pattern to rehabilitate eroded, bare and crusted surfaces where even natural vegetation can no longer grow through lack of infiltration. These lines of stones, grass or stakes slow down runoff and encourage the deposition of organic matter and coarse, permeable sediment. From the second year, the sandy horizon so formed is tilled, manured and planted – and as much as 800 kg/ha of sorghum is often harvested (Wright 1985).

As in the previous case, livestock are moved to the rangelands during the rainy season. After the harvest, the animals are fed crop residues, but are then left to shift for themselves, wandering over the area at will.

ANALYSIS OF LOCAL CONDITIONS

Annual rainfall decreases from 700 mm in the south to 400 mm in the north. Maximum monthly rainfall rarely exceeds 100 mm, and drainage is only occasional – between 50 mm and zero. Rainfall aggressiveness decreases from 400 to 200 on the R_{USA} scale, and the maximum rainfall in a single day over a ten-year period rarely exceeds 100 mm. The landscape is very like that in the previous case, but is composed of lateritic hills or granite domes, and very long, broad, sloping pediments with valley bottoms of varying breadths. On the hills, the gravelly lithosols are ironstone to varying degrees over deep alterite, and contain very little water. On the other hand, the deep alterites under the gravel sheets are moist throughout the year. The broad, sloping pediment is composed of leached, tropical, ferruginous soil, loamy-sandy on the surface and more clayey at depth. The valley bottoms are hydromorphic and sandy or loamy.

HAZARDS

As little is stored in the gravelly lithosols of the lateritic hills, overgrazing leads to degradation of the vegetation, which in turn reduces the activity of mesofauna, forms slaking and sediment crusts on the soil surface, and encourages heavy runoff leading to gullying. The cultivated sections often present an advanced degradation of soil fertility, acidification and skeletonization of the surface horizon, which becomes very sandy, easily eroded and vulnerable to rainsplash. Sand and gravel from gullying on the hills are also deposited on these sections. The soil has a very depleted stock of nutrients, so that crops must be nourished as and when needed. The general degradation of the soil in the valley bottoms through overgrazing and cropping with no restoration of organic matter or nutrients is also to be deplored. Added to this, the gullies upstream lead to gullying of the river bed and/or generalized siltation of the valley bottom. The broad bottom lands are difficult to manage, since they are flooded for several days during the heaviest rainstorms two years out of three.

SUGGESTED IMPROVEMENTS (Figure 63)

Improvement of the rangelands on the ironstone hills and gravel pediment may be achieved by reforestation with the help of forage shrub species, if a partial ban on grazing can be organized for five years. Such improvements can be assisted by slowing runoff with stone lines and replanting grass, first scratching the dry ground with a pronged subsoiler, and spreading organic débris (twigs, bark, straw) or stones to trap water, sand and seeds. If the soil is too degraded, subsoiling along the tree-planting lines can have a lasting effect, at least on the gravelly pediment. Lastly, runoff storage can be improved either by building half-moons or total absorption ditches, or by digging out the cisterns known as *boulis* to obtain water for livestock or for irrigating a small garden.

With respect to the cultivated area on the loamy-sandy pediment, stop-wash lines can be set up every 20 to 25 m, and hedges planted around the fields, with trees every 5 m to build up a stock of karité, *Acacia albida* and various pulses. The stop-wash lines can be made of rows of stones or grass, the long-term objective being the creation of a landscape in which sufficiently large crop fields are surrounded by hedges so that livestock can be kept on the fields during the periods when the animals eat crop residues, or off them when the soil has been prepared and the crops are growing.

In the irrigated valleys, filtering dams built at valley-heads will spread flood waters, trap some of the water and sediment, replenish the water table, and increase food security by providing off-season water to vegetable and fruit gardens. Where the valley is larger, with a catchment area of several square kilometres, earth bunds can be built to retain enough to provide water for the village. This method of semi-pervious microdams improves yields and contributes to the food security of these very poor regions which have practically no cash crops. Furthermore, the suggested improvements are very inexpensive and within the reach of any farmer.

EROSION CONTROL IN THE NORTHERN SAHLEIAN ZONE AROUND THE DOTI MARCHES IN BURKINA FASO: valley farming

TRADITIONAL FARMING TECHNIQUES

In this zone with under 400 mm of rainfall, conditions contrast greatly with those in Sudanian zones. Rainfall is more erratic and falls on a small area. While there are several methods of collecting rainwater or runoff to grow trees and cereals in the wide runon areas in the Mediterranean environment of the northern Sahara where rain falls during the cold season, water conservation strategies are few and less easily apparent in the tropical Sahelian zone where rain falls in the hot season. Strategies focus on choosing crops according to the soil (millet on sand, sorghum on loam and in the bottom lands, and irrigated gardens around the wetlands) and on taking advantage of storms when these occur (very light tillage, but with repeated sod-seeding, requiring very little seed [3 kg/ha] or work [9 h]) with large areas being sown, although a good proportion may be abandoned when it comes time to do the hoeing.

A frequent survival strategy is short-distance migration in order to gather wild crabgrass or water-lily bulbs. Homes are on the cultivated fields from November to August, near granaries and milking places. Herds are systematically moved to temporary pastures.

This region depends essentially on the extensive pasturing of herds, which are moved as seems most advantageous. The use of crop residues and even animal excreta as fuel demonstrates the severe lack of wood in this zone.

ANALYSIS OF LOCAL CONDITIONS

Rainfall varies from 400 to less than 150 mm, the maximum monthly rainfall is roughly 175 mm, drainage is calculated as nil, the erosivity factor is under 200, highest daily rainfall in a ten-year period is 80 mm, and the population density drops sharply to less than 10 per km^2.

The landscape is composed of dioritic hills followed by a broad, sloping, sandy, then loamy, pediment, terminating in the region of the pond. Small dunes form around clumps of grass and bushes on the sandy pediment. Some old *Faidherbia albida* and other thorny vegetation still survive on the loamy pediment, especially where the water table is not too far down. Soil is lithomorphic on the mountains and sandy on the dunes, with sub-arid, brown-red soils around the marshes. Traditional techniques entail flat-sowing millet on sand and sorghum on the clayey lowlands, and using the slopes as extensive pasture. Gardens are planted in the lowlands, with a certain amount of flood recession cropping all around the pond.

HAZARDS

The main risk in the sandy zone is wind erosion along with degradation of vegetation from both overgrazing and the wind erosion. Rainsplash on the sloping loamy pediments results in very extensive runoff, which digs small gullies.

SUGGESTED IMPROVEMENTS (Figure 64)

In this extremely fragile environment, it is dangerous to advise the development of an agropastoral system to match population growth. Development appears to be blocked today, since almost all the possible land is now being farmed. Fallow periods are disappearing, the soil is becoming exhausted, and the cost of inputs (mineral fertilizers and short-cycle varieties) is only economically viable in years when rainfall is abundant and well distributed. However, the following measures could be tested on an area such as that at Ségué in northern Yatenga:

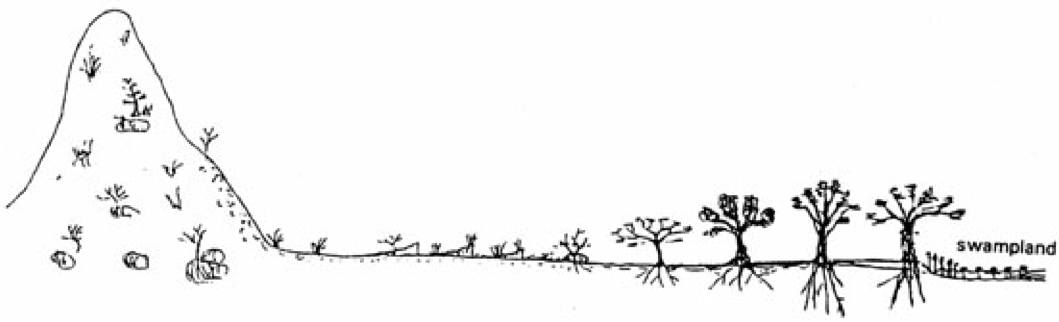
- planting hedges or thorny fodder species in sandy areas (*Balanites*, *Acacias albida*, *Acacias nilotica*, etc.);
- microcatchment water-harvesting for small ridged fields on loamy pediments;
- agroforestry in the bottom lands (stone lines, hedges, forage and fruit trees);
- organizing the shores of ponds and marshlands for diversified intensive cropping (fodder for dairy production, cereals, vegetables and some fruit trees).

However, it is clear that agricultural production is restricted to the lowlands and that animal husbandry with short-distance nomadism is better adapted than cropping to this very fragile Sahelian environment.

FIGURE 64

Diagram showing improved use of a Sahelian landscape (R > 400 mm): example of an agropastoral system in which intensive farming is confined to the valley: valley farming

Water harvesting area and rangeland	Rainfed random crops under old trees	Intensive irrigated or falling-flood crops
dunes or sandy deposits	loamy pediments	edge of the valley or swampland



lithosols	red-brown semi-arid soils	fairly fertile hydromorphic soils

Poor soils: deficient in N and P, poor in organic matter, risk of salinization

Fragile soils: slaking and erosion crusts
permeable if covered by a sheet of sand
quickly becoming sealed on loams

Hazards: rainfall impact on soil → scouring wind erosion on sand	splash erosion, degradation of organic matter and gullying	hydromorphism, surface salinity

Improvements

- Large area for water harvesting - Extensive rangelands - ½ moons or zaï for planting millet and shrubs	- Supplementary irrigation from groundwater fed by runoff - Larges *Acacia* with roots down into groundwater	
- Some millet cropping on the sandy deposits	- Millet-groundnut or cowpea rotation	Intensive irrigated fruit and household plots
- Harvesting runoff to form small ponds to water livestock - Stabilizing the sandy deposits with bushes so as to minimize the risks of damage to neighbouring crops from sheets of wind-blown sand	- If possible, thorny hedges: *Acacia*, *Euphorbia balsamifera*, or perennial grasses - *Andropogon*.	Fodder crops in and around swampland

TABLE 39

Variety of environmental conditions along a bioclimatic belt in West Africa, and range of suggested control methods (cf. Roose 1992)

Ecological zone Rainfall Case studied	Guinean forest 2500 to 1200 mm in 2 seasons (Abidjan)	Southern Sudanian 1400 to 1000 mm in 1 season (Korhogo)	Northern Sudanian 1000 to 700 mm Koutiala	Southern Sahelian 700 to 400 mm Ouahigouya	Northern Sahelian 400 to 150 mm Mare d'Oursi
Mean annual rainfall Monthly rainfall max. Daily rain 1/1 1/10 1/100 Max. intensity 1/1 1/10 Rain erosivity R_{USA} PET (mm) Calculated drainage	2100 mm 700 mm 135-230-280 (mm) 90-120 (mm/h) 1260 1250 mm 1200-800 mm	1350 mm 318 mm 76-119-169 (mm) 75-106 (mm/h) 675 1660 mm 470-160 mm	900 mm 250 mm 62-107-166 (mm) 60-80 (mm/h) 420 1750 mm 180 to 10 mm	725 mm 207 mm 55-101-146 (mm) 59-78 (mm/h) 360 1905 mm 50 to 0 mm	535 mm 177 mm 49-79-109 (mm) 32-45 (mm/h) 260 2000 mm 0 mm
Diagnosis of risk: - leaching, acidification - sheet erosion - gully erosion - waterlogging	 + + + + + + + + + + bottom lands	 + + + + + + + + + slopes and bottom lands	 + + + + + + + + bottom lands	 + + + + + + + + bottom lands	 - + + (on pediments) + + (on pediments) bottom lands
Soils on the slope	very desaturated ferralitic SC ± gravelly very acid	- ferralitic, desaturated ± gravelly - or vertisol/brown soil on basic rock	- ferruginous leached SC ± gravelly - or vertisol/brown soil on basic rock	- ferruginous leached SA ± gravelly - or vertisol/brown soil on basic rock	- ferruginous, little leaching, sandy on dunes - or brown-red sub-arid soil
Vegetation	Closed rainforest + *Panicum*, etc.	Tree savannah, *Daniella, Parkia, Butyrospermum* + *Andropogon* + various	Tree savannah, *Parkia, Butyrospermum* + thorn species + *Andropogon* + various	Shrub savannah with *Combretum*, Baobab, acacia + thorn species *Andropogon* + various *Pennisetum*	Steppe or bush boabab, acacia, *Balanites, Ziziphus* annual grasses
Farming systems	Cover farming Complete/Full/Total infiltration	Drainage farming during the 2 wettest months	Rainfed farming = total infiltration of rain	Runoff farming	Valley farming: concentration of water and crops in valleys
Population density (pop/km^2)	20 to 40	30 to 100	30 to 50	70 to > 100	10 inhab/km^2
Traditional techniques	- multicropped cassava + maize + herbs on small mounds - coffee, cacao, oil palm, kola, under shade - forest fallow	- yams on large mounds - maize + various herbs on average ridges - millet → groundnut on degraded soil + ridges - crops combined with useful trees - drainage between plots	- flat-grown crops + 1 weeding + 1 mounding, sorghum/cotton or millet/ groundnut/cowpea - passage of water from hills - rain infiltration on fields - low stone walls or stone lines	- sod seeding on the flat after burning, then 1 weeding and 1 mounding: sorghum or millet/groundnut/cowpea - mulching, zaï, boli - stone or grass lines - levelling sandy dunes	- sod seeding on the flat + 1 weeding and loosening around roots - millet on sand - sorghum on pediment and clayey-loamy bottom lands - extensive grazing on slopes - household plot on bottom lands - flood recession crops on ponds
Treatment proposed	Land husbandry - management of OM + NPK = f. of crops + lime if pH <4.5 - soil cover + close, early planting + multicropping + tree crops + cover plants - grass banks or hedges on slopes - drainage of bottom lands	SWC (1964-68) Reforestation or ironstone Buffer strips on slopes Stabilization of gullies Protection of rice fields	Land husbandry 1985-91 - rangeland improvement - regeneration strips - lines of stones or cotton stalks - protection bunds uphill of block of crops - hedges + trees around fields - grassed spillways - treatment of bottom lands	SPR of GERES 1960-65 - then SWC ORD + FEER - Land husbandry CIRAD + CRPA 1986 = rangeland improvement + l;ivestock ponds + gardens + stone lines + *Andropogon* + hedges around fields = treastment of gullies and roads + improvement of bottom lands	Land husbandry - forage shrubs in ½-moons - improvements to rangelands - ponds for livestock - runoff harvesting on pediment/hill - filtering bunds on pediment or gully - fodder crops on bottom lands

CONCLUSIONS

The above overview of this bioclimatic sequence indicates that development of farming techniques tailored to the water balance should go hand-in-hand with appropriate water management methods for erosion control (see Table 39). This makes it easier to understand one reason for the failure of the many SWC and SPR projects which have stubbornly applied the model developed by Bennett at another time, in a temperate climate, and under intensive mechanized farming.

It is also easy to understand traditional farmers who not only fail to maintain imposed erosion control schemes but actually destroy them when they come to realize that they are unsuited to their special farming conditions.

Analysis of both traditional strategies and the monthly water balance could provide a basis for future land use planning projects, which must focus on improving such strategies with the active involvement of farmers and herders.

This is a challenging, long-term research and development task, in which the human aspects are as important as the technical ones. Multidisciplinary teams will therefore be needed to monitor and evaluate such projects.

Chapter 10

Development of the Bamiléké bocage

EXAMPLE OF TRADITIONAL ADAPTATION TO STRONG POPULATION PRESSURE

THE SITUATION

Situated in Central Africa between 5° and 6° N, the Bamiléké uplands occupy 6 196 km^2 to the south of the highlands of western Cameroon (Figure 65). With an average population of 168 per km^2, reaching 600 in some places, it is one of the few tropical regions supporting such a large population on traditional rainfed farming. Analysis shows that the farming techniques are relatively effective in maintaining fertility and controlling erosion. However, current changes in the region are leading to a simplification of techniques in areas long occupied and to an expansion of these same farming methods to recently developed areas. Heavy population pressure, increasing numbers of dwellings and contemporary social and economic demands may well have adverse effects on a fragile environment; even the relatively unaggressive rainfall tends increasingly to accumulate on the surface, and the ensuing runoff threatens farmed slopes. What is the answer? Is it possible to envisage a heavily populated, productive and stable mountain area? The partial success of the Western Province Rural Development Project – which included digging erosion control ditches, building bench terraces on the slopes, and applying mineral fertilizers – encourages consideration of solutions based essentially on local know-how in an environment with considerable agricultural potential.

DIAGNOSIS: RELATIVELY FRAGILE ENVIRONMENTS

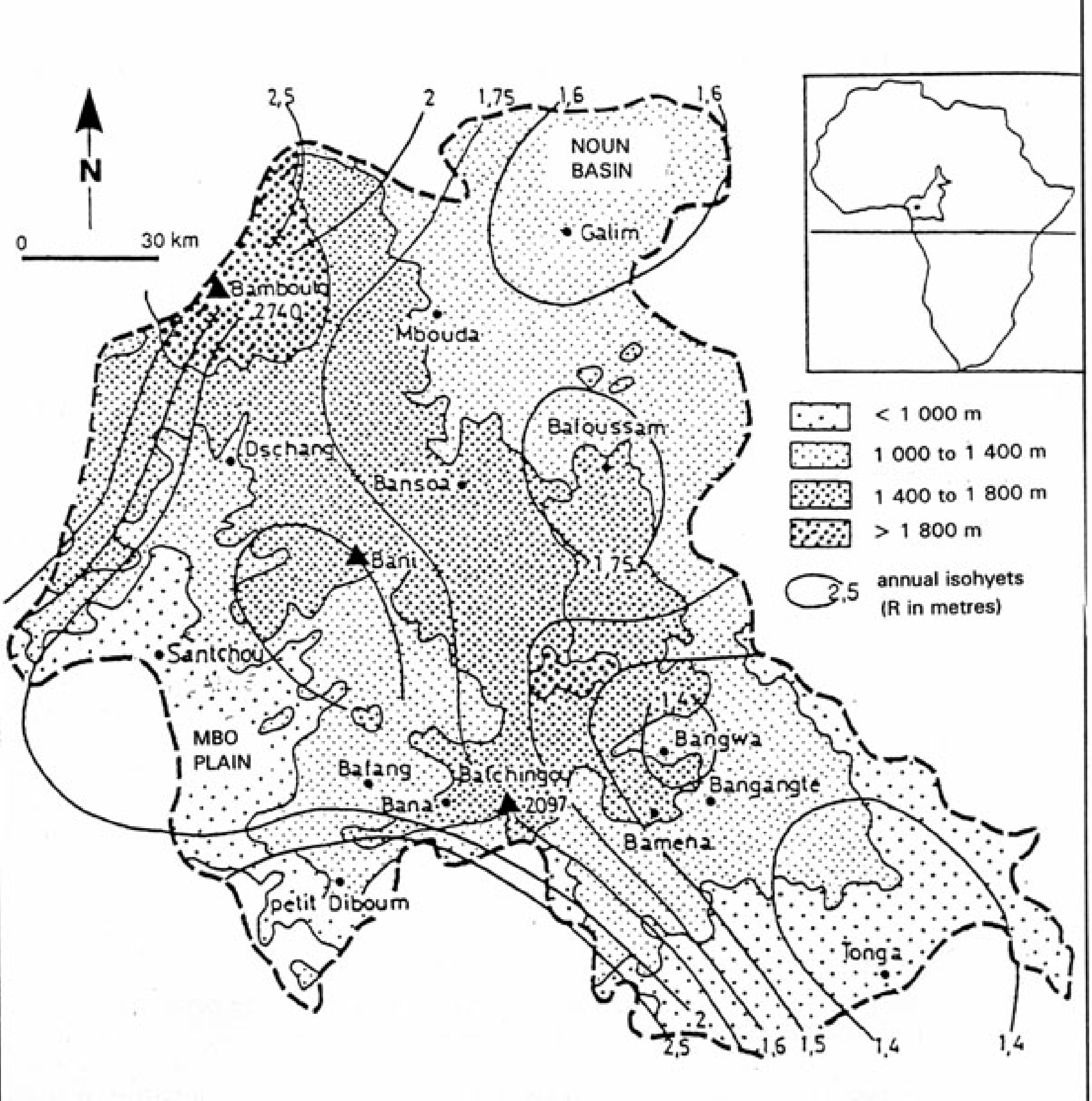
UNDULATING LANDFORMS MARKED BY STEEP SLOPES

The Bamiléké region is a high plateau at an average altitude of 1 450 m. It can be divided into three main sections, ranging from 700 to 2 740 m (Figure 65).

Up to 1 100 m, the peripheral plains (Noun in the east and Mbo in the southwest) occupy nearly 20% of the area. The flat surface is relieved by small gentle hills (less than 12% slope).

Between 1 100 and 1 600 m, the uplands constitute the main relief pattern, accounting for more than 70% of the region, with two distinct types:

FIGURE 65
Relief map showing rainfall distribution (cf. Suchel 1989)



- the granito-gneissic plateau in the south, with polyconvex or half-orange landforms, and occasional granite outcrops;
- the basaltic plateau in the north, with more even landforms, in which the land between the rivers has flattened, rounded or elongated hillocks, separated by narrow valleys; slopes steeper than 25% and those between 12 and 25% are predominant.

Above 1 600 m, the mountains (less than 15% of the area) exhibit a more rugged topography, with 75% of their area on slopes of over 25%. This category covers the small granite mountains rising to less than 2 100 m in the south, and the volcanic Bambouto chain in the northwest which rises in steps to a maximum of 2 740 m.

UNAGGRESSIVE RAINFALL ON VULNERABLE SOILS

The climate is subequatorial monsoon in type, chiefly moist and cool, with one rainy season from mid-March to mid-November. Annual rainfall is everywhere over 1 400 mm (Bangangté 1 457, Bafang 1 731, Bafoussam 1 796, Santchou 1 727, Dschang 1 919, Baranka 2 500), although it decreases considerably from west to east, and also from south to north due to altitude. The peak rainfall levels are in August and September; in Bafoussam, for example, they reach 90 to 116 mm in March, April and May, and 118 mm in August. However, hourly intensity is low (15 to 40 mm/h). Temperatures are kept down by the altitude (in Bafoussam maxima are between 23° and 27° C).

Soils can be divided into three groups (Champaud 1973, Segalen 1967):

- ferralitic soils derived from basalt are the most widespread, with very favourable physical and hydric properties – great depth, high porosity, friability without gravel, a high clay content, and surface permeability; hardened ferralitic soils with occasional outcrops of ironstone;
- relatively unevolved soils derived from basic soft volcanic rock (ash, lapilli), very rich in organic matter, nitrogen and exchangeable bases, and very permeable;
- hydromorphic soils – sandy and deficient on granite, peaty on basalt and alluvial deposits – are found in the marshy lowlands; they are not particularly fertile, but the presence of water, flat topography and high organic matter content makes for good farmland.

Soil texture is very varied, with silt content ranging from 10 to 30% and clay from 10 to 70%. However, whatever the soil make-up, local variations depend on the position in the toposequence. Generally speaking, soils are deeper, finer and more fertile on the lower slopes than on the higher reaches. The traditional farming techniques and organization of farmland reflect these local variations.

STRONG POPULATION PRESSURE, ALTHOUGH VARYING IN ACCORDANCE WITH GEOLOGICAL SUBSTRATUM (Figure 66)

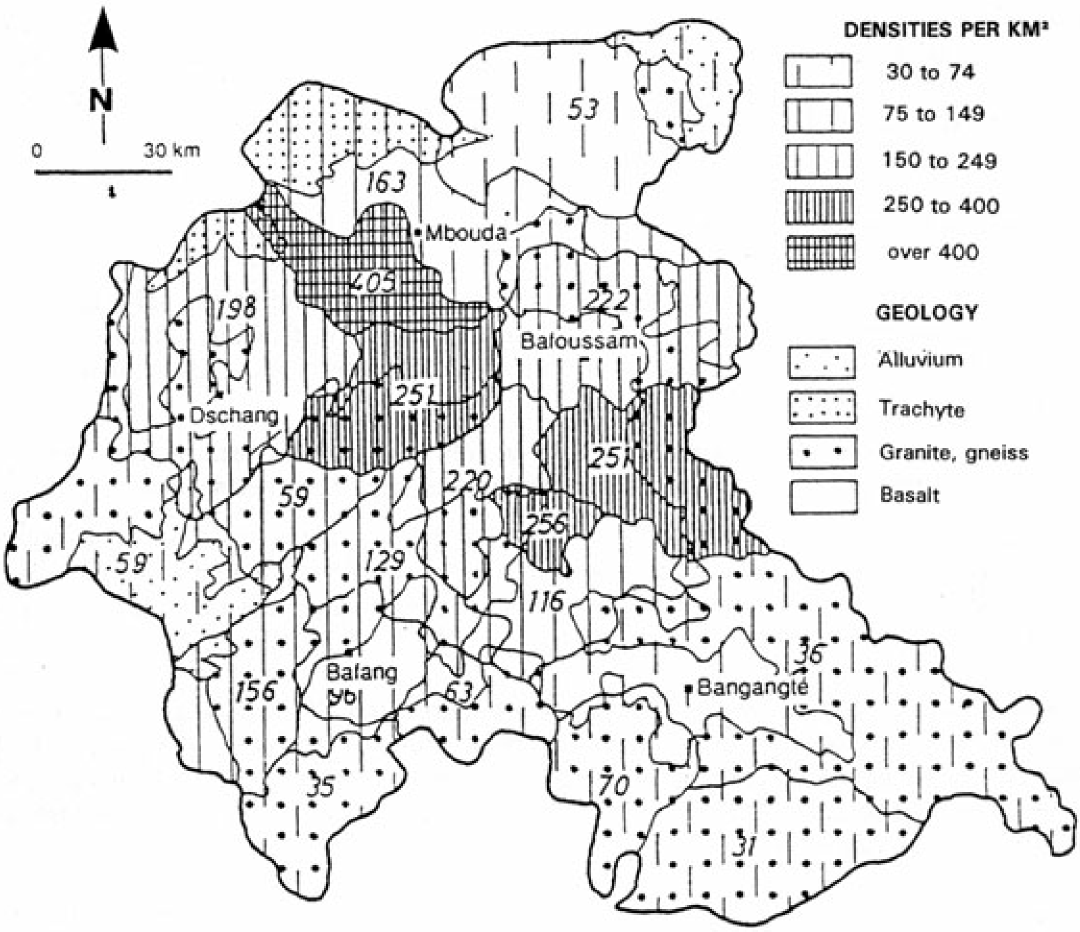
The Bamiléké country has been inhabited for a long time and is densely populated, with an average of 168 per km^2 (1987). This figure means very little, however: density everywhere in the basalt region is higher than 200, in some areas approaching or even exceeding 1 000 (Ducret and Fotsing 1987), while outside the basalt region it rarely exceeds 150, with the lowest densities in the alluvial zones and in mountain areas.

Population pressure is accentuated by the fact that dwellings are scattered, and also by the inheritance system: one male inheriting the entire family landholding. Non-inheriting sons therefore become founders of new lineages and have to find land for themselves elsewhere. With an annual growth rate of 3.2%, there is no let-up in pressure on land, despite a massive exodus toward the towns.

EFFECTIVE TRADITIONAL TECHNIQUES

Land use in the Bamiléké country combines and/or juxtaposes agriculture and animal husbandry. Agrarian systems are fairly complex, and the associated improvement techniques vary according to the predominance of agriculture or livestock, as well as the permanence of human settlements. Both intensive and extensive systems are found.

FIGURE 66
Geological map showing population distribution (cf. 1987 Census)



TRADITIONAL INTENSIVE SYSTEMS (Figure 67)

These are seen in the inhabited regions of the uplands, where family farms have three kinds of land essential for family autonomy (lowland, slope and hilltop). Intensive polyculture is combined with small animal husbandry (sheep, goats, pigs, poultry) in a bocage landscape. Family farms (generally less than 3 ha) spread down a whole slope, with a varied range of crops grown from the hilltop down to the valley.

The higher parts of the slopes are used either as pasture for sheep and goats (*Pennisetum purpureum*, *Panicum maximum*) or for food-crops (temporary or permanent) with groundnut intercropped with maize, sweet potato, beans and yam. Where density is lower, fire is used to clear land and renew fodder.

FIGURE 67
Traditional use of space (large-scale map of one section of the granite plateau)

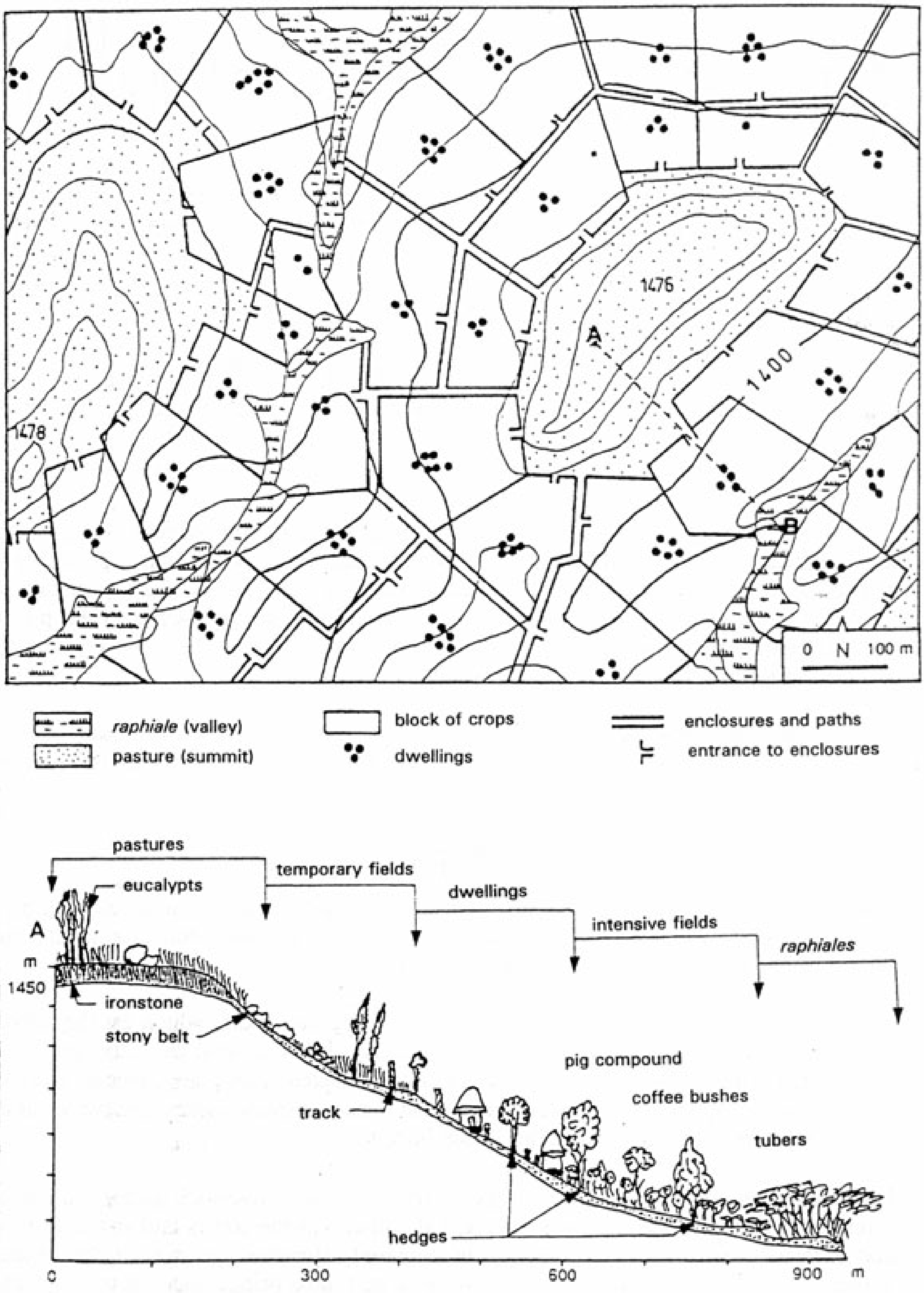
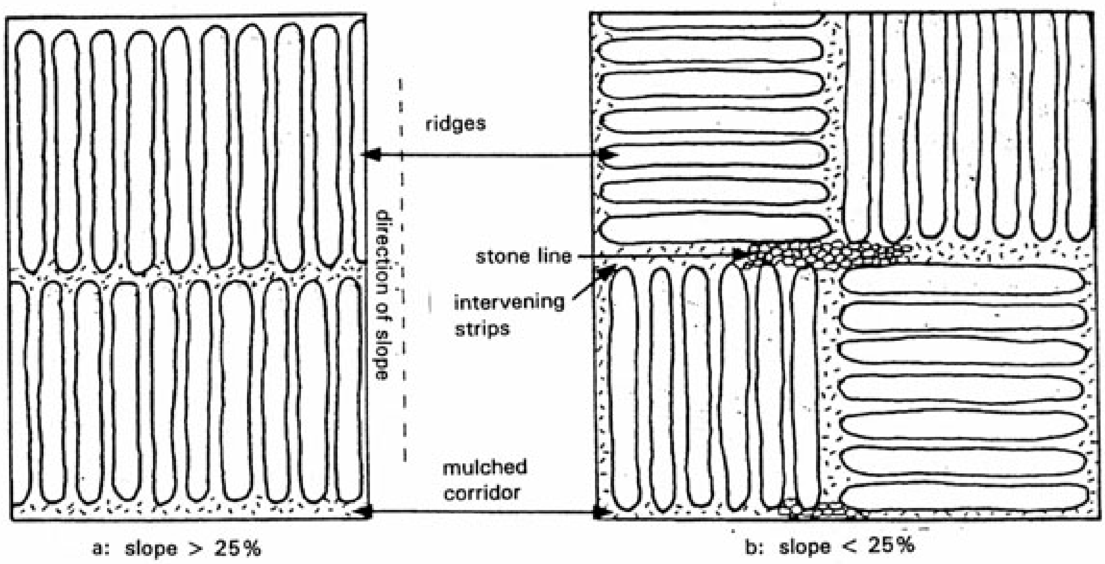


FIGURE 68
Direction and layout of ridges on a plot



The middle sections contain houses and multi-storey multicrop gardens. In the shady coffee plantations, maize, groundnut, yautia, cassava, taro, yam, vegetables, various herbs and banana are combined with coffee, or with fruit or forest trees around the houses and pig pens. On plots kept exclusively for food crops, a second-season crop (beans, sweet potato, potato) follows the maize harvest. The generalized presence of trees – between 120 and 130 per hectare – gives the countryside a luxuriant look.

The lowlands are kept for raffia palms, *Raphia farinifera*, bordered by small fields of tubers (yautia, taro, yam, cassava, etc.) combined with some banana trees and various vegetables.

There are various techniques for preserving soil fertility.

- **The use of a fallow period** allows natural reconstitution of soil nutrients. On intensive food-crop fields there is a short fallow between cropping seasons, while groundnut fields on the hilltops are left fallow for one to two years.

- **Mixed farming:** plots left fallow are grazed by sheep and goats, which eat the harvest residues and leave manure. The pig pen is regularly shifted around the settlement, with the vacated space being used for crops. Manure collected from places where livestock regularly gather (piggeries, chicken coops, goat pens and small poultry enclosures at the start of the sowing season) is spread in the furrows.

- **Digging in organic matter under ridges**: harvest residues, livestock manure, domestic refuse, ash and any other organic matter that can enrich the soil is laid in the furrows and earthed over as the fields are being prepared. However, as not all the organic manure is transformed during the cropping season, tillage brings undecomposed matter back to the surface, and this provides partial protection for the soil.

- **Recycling the biomass**: this is particularly effective when ridges and furrows are alternated, with the ridges carrying the crops and the furrows receiving domestic refuse and cleared weeds which will in due course fertilize a future ridge. In this way, one part of the soil is rested and reconstituted so as to receive crops in the following season.

- **Eco-burning**: this consists of piling up the weeds cleared from a plot, covering them with earth, and then setting them alight through a hole in the side. The slow combustion preserves all the ash from the incineration, protects it from rainfall, and promotes soil fertilization.

Erosion control methods are similarly varied.

- **Combining several crops on the same ridge**: this safeguards the stability of the ridge, provides good soil cover, and reduces erosion – which explains how large ridges laid parallel with the slope effectively withstand runoff.

- **Practising two cropping cycles**: confined to food-crop plots, this ensures a permanent soil cover, especially when the crops from the first cycle remain partially present on the fields.

- **Combination trees and crops**: fruit or forest trees provide the shade needed by certain crops, curb wind speed, and maintain soil moisture. Their litter protects the soil from raindrop impact and slows down erosion.

- **Keeping harvest residues on the fields**: maize stubble is left standing and groundnut haulms are left in furrows, thus providing a mulch for the soil and protecting it from the sun during the dry season, and from the ill-effects of runoff.

- **Planting hedges to fence off the cultivated area:** the "control hedges" and "closure hedges" are used to lead livestock from the vicinity of the houses up to the communal pastures on the hilltops. When reinforced horizontally with raffia ribs, they are effective in checking the flow of water and trapping suspended sediment. These forest hedges also break the wind speed. Made up of fast-growing species which can be grown from cuttings (*Ficus* spp., *Markhamia lutea*, *Polyscias fulva*, *Harungana madagascarensis*, *Podocarpus milanjianus*, *Dracaena arborea*, *Hymenodycton floribundum*, *Datura stamonium*, *Veronia* sp.), they are a major source of firewood, provide stakes for climbing crops, and also a secondary source of forage for small livestock.

- **The size and layout of ridges on cultivated plots** (Figure 68): this varies according to topographical position, type of crop and depth of soil (except that the length of the ridge is sometimes determined by plot size):

    - on steep slopes with shallow soils, small ridges (50-70 cm wide and 20-30 cm high) are laid parallel to the steepest slope in staggered rows from the top to the bottom of the slope. The ridges are completely covered by crops, and so this arrangement is very effective in controlling runoff, channelling rainwater, cutting water velocity and reducing erosion;

    - on gentle and medium slopes, large ridges (70-90 cm wide and 30-40 cm high) are laid out in a patchwork pattern, though with a slight preference for ridges parallel with the contour. Ridges parallel and perpendicular to the slope are therefore often found on the same plot.

Laying ridges parallel to the slope is well suited to the central regions where the short length of slopes, the high infiltration capacity of the soil, and continuous cropping prevent both the concentration of rainwater on the surface and fast surface flow. On the other hand, the technique is unsuitable in mountainous and granitic regions where infiltration is lower and the slope more pronounced.

USE OF LAND RESERVES AND MARGINAL LAND

Steep slopes, swampy or hydromorphic plains and mountain areas have long received little consideration from traditional development, although they have been farmed without title by Mbororo herders and indigenous farmers.

- **On grazing land in mountain areas, semi-sedentary** Mbororo herders raise cattle and sheep. The abundance of grass means that only a short transhumance is necessary in the dry season. Some herders practise intensive agriculture around their semi-permanent campsites, co-operating with the indigenous Bamiléké in order to take full advantage of the dung from night corrals (Fotsing 1990).

- **On new farmland**, farming techniques are hasty, land improvements perfunctory, and intercropping extremely simplified. Preference is given to market-garden crops (potato, onion, garlic, carrot) or food crops yielding quick returns (maize, beans), which provide scant ground cover.

This is an openfield landscape, scorched in the dry season, dotted here and there with a few fruit trees. The only wooded land is some pioneer eucalyptus rows which serve little purpose in erosion control since they are located at valley heads and on flat land where there is little risk of erosion.

HAZARDS

RECENT CHANGES IN AGRARIAN SYSTEMS

- **In intensively farmed areas**, “land hunger” linked to strong population pressure leads to fragmented family farms and a shortage of space. Sons and brothers are increasingly being settled on the higher sections, and plots leased to the emigrés for secondary dwellings. In the districts of the basaltic Bafou plateau, the building density is 3.3 dwellings per hectare with an annual rate of increase of about 3%, with population density at the tolerance threshold (more than 1 200 per km^2). Space is less crowded in the granitic area, where there has been considerable outmigration for a long time, and the annual rate of increase in building is lower (1.5%), as is the density (0.82 dwellings per ha) (Ducret and Fotsing 1987).

  On constantly shrinking farms – 1.3 ha on average – market gardening simplifies the hedges and fewer trees are grown. The fallow period tends to disappear, and the use of mineral fertilizers becomes widespread for all crops. Mineral fertilizers are supplemented by off-farm livestock, particularly poultry manure. The disappearance of hilltop grazing land has reduced sheep and goat raising to penned and staked systems. The adoption of soybeans, Z 230 maize and Cardinal potatoes – varieties popularized by the UCCAO (the Central Union of Western Agricultural Cooperatives) – confirms the tendency to diversification and completes the saturation of the agrarian space.

· **In the peripheral zones**, the demand for farmland encourages anarchic land settlement and cropping of steep slopes. Herdsmen are driven out, dealing a fatal blow to the large livestock-rearing sector. In less than five years, new farm settlements on the Bamboutos have left livestock nothing to graze but slopes that cannot be cropped (Fotsing 1989). The rangelands still available are overgrazed and managed cyclically using strategies based on seasonal transhumance.

AREAS EXPOSED TO A VARIETY OF EROSION RISKS

Rain is the main erosive agent threatening farmland in the Bamiléké area. Erosive rain falls on poorly covered soil at an intensity of 75-120 mm/h. Cloudbursts of 150 mm/h for 15 minutes are relatively frequent (Morin 1989). They are linked to the squall lines and fall in March-April, June and October on almost bare soil (the start of the cropping season and the time of hoeing and harvesting).

At the beginning of the rainy season, rainstorms beat down on the dry and sometimes powdery surface – which is poorly protected by burnt-off plant cover or totally bare after clearing or ridging. In the middle of the rainy season, the rain beats down on weeded, waterlogged plots. Even though runoff does not start until the soil is fully saturated, it can then cause severe flooding and even landslides.

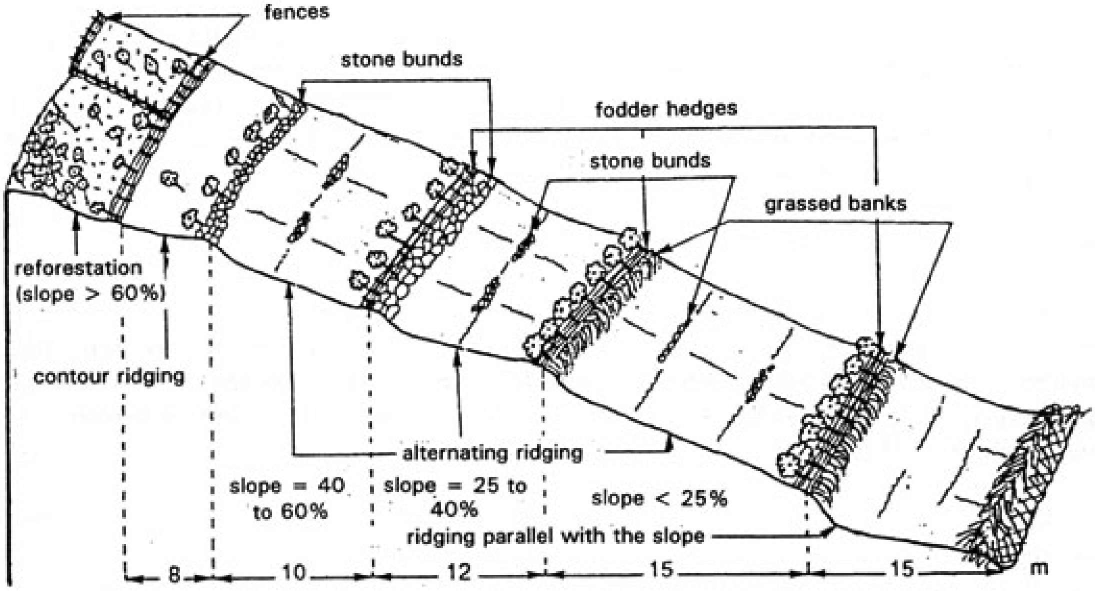
Runoff coefficients are low because of the high total porosity of the surface structures. Infiltration is 50-100 mm/h on soil of basaltic origin, and only 9-10 mm/h on granitic soil. The great depth of basaltic soils and the thick mantle of alterite they cover – sometimes over 3 m – absorbs almost all rainwater, thus impeding runoff. On granitic slopes the sandy-loam texture and shallowness of the soil allow formation of a slaking crust and increased runoff. Elsewhere, the shortness of slopes due to the undulating landscape reduces the speed of surface flow and thus its erosive capacity. As soon as it accumulates, runoff spreads out in the bottom lands, marshes or subsidence basins.

TYPES OF EROSION AND DEGRADATION OBSERVED

In the western highlands, erosion depends initially on the impact of rainsplash and the presence of soils that allow runoff. However, erosivity depends largely on farming techniques.

In areas of traditional intensive polyculture, there is little erosion, the only exception being dry mechanical erosion due to the use of ridging. Nevertheless, the land at the bottom of concave slopes, which has been longest in use, is showing signs of impoverishment – a clear indication of the low level of colluvial inputs and of the extent of erosion and local leaching. Current changes also encourage the onset of runoff and erosion. The area around dwellings and the lower sides of paths and tracks are prone to rill erosion, which increases near secondary dwellings and the outlets of spillways built by the Public Works Department on public roads.

FIGURE 69
Some erosion control measures to be implemented



Continuous cropping on the same plots leads to recourse to mineral fertilizers. Chemical fertilizers (N20-P10-K10, urea and N12-P6-K20), officially meant for coffee, are diverted to food and horticultural crops. Fertilization rates are high (250-300 kg/ha on horticultural plots in the Djutitsa foothills), but nitrogen excess and potassium deficiency are observed (154N 63P 54K for coffee, 147N 72P 72K for food crops, and 427N 218P 235K for market-garden crops) (Ducret and Grangeret 1986). On the gravelly hilltops, maize is deficient in nitrogen, potassium and phosphorus. This is attributed by farmers to exhaustion of these gravelly soils which “don’t hold fertilizers properly”.

On higher slopes where the natural vegetation is still in place, water runs off over the carpet of grass cover with no damage to the soil, even on steep slopes. On slopes with depleted vegetation, sheet erosion gradually loosens the clumps of stubble and their roots; this is then compounded by trampling by livestock, which compacts the soil and creates the conditions for concentrated runoff. Some sand and gravel may then be carried off (Morin 1989).

On recently occupied land, slipshod farming techniques are leading to soil degradation. In the Bamboutos, repeated eco-burning is destroying the structure of topsoil over trachytes which were never very cohesive. At Baleng, on 25% slopes tilled in ridges parallel with the slope, Olivry (1974) recorded 120 t/ha of degradation during three rainy season months. He attributes the high sediment load in runoff at Mbam throughout the rainy season to particles removed from food-crop plots in the Bamiléké country. Nevertheless, the figures are low compared with the 500 to 700 t/ha/yr recorded at Adiopodoumé under crops on sandy ferralitic soil on a 22% slope (Roose 1977a).

In conclusion, soil degradation in the Bamiléké area is inversely proportional to the intensification of cropping and the amount of plant cover at ground level, and does not depend on the slope. The situation therefore calls for a rethinking of current strategies for developing available land, taking account of the wisdom patiently accumulated by local farmers in their many years of experience.

SOME SUGGESTED IMPROVEMENTS

EROSION CONTROL MEASURES (Figure 69)

Restoration of the traditional bocage system: maintaining the legal barriers and improving forage, and planting forage hedges on cultivated plots located on sloping land. Forage hedges of *Leucaena*, *Callyandra callothyrsus* or forage hibiscus, cut every three months to provide livestock fodder and to manure and mulch cultivated plots, will not reduce the arable area by much. Reinforced horizontally with raffia ribs, they will reduce water speed, halt sediment transport and control the movements of livestock. They will be planted every 15 m on slopes of under 25% (every 10 m on steeper slopes). Spacing will also have to take account of the size of family farms and the existence of livestock paddocks and fences around dwellings. Grass strips will be planted on the lower side of these fences to maximize their effectiveness in curbing sediment transport. Reconversion to the bocage system will be easier if farmers are encouraged to rear sheep.

Orientation of ridges on slopes as a function of the slope:

· **on slopes of under 25%:**

- small contour ridges, preferably tied, on the hilltops on shallower soil, in order to facilitate infiltration and hinder formation of runoff; care will be taken to ensure that the ridges all end at the same point to ensure a special channel for runoff;

- tied ridges in rows of six to eight ridges every 5 m, half-way down the slope on plots multi-cropped with coffee and foodcrops; the rows will be separated by forage hedges; a furrow between each strip, regularly mulched and broken on the downhill side by a small line of stones, will channel runoff;

- large ridges perpendicular to the slope near thalwegs on deep soils with tubers under permanent cultivation; this layout will prevent gullying in heavy rainstorms, while permanent soil cover will curb erosion;

· **on slopes of over 25%:**

- small tied contour ridges from the summit down to the lower third of the slope; this accounts for the physical constraints of ridging and seems more effective than simple contour ridges in breaking the force of runoff and facilitating infiltration of rainwater;

- ridges in alternating rows every 5 m toward the foot of the slope; if the soil cover is relatively thin with abundant coarse elements, ridges should not follow the slope as the soil is almost bare during the period of heavy rainstorms.

Construction of small stone lines parallel with contour lines, half-way between the hedges and preferably across the runoff routes. These lines will curb the speed of runoff and thus reduce soil erosion. The stones used are those piled by farm women to clear the plots.

Building large stone lines on the uphill side of the hedges every 10 or 15 m, using the stones and boulders that litter agricultural land in the granitic zone. These lines will reinforce erosion control structures. By curbing mechanical erosion, they will also constitute the first step in forming gradual terraces.

Light mulching on cultivated plots: uses banana or raffia leaves or twigs cut from hedges, and is necessary on plots that are not under crops during the second cropping season. It cuts evaporation and conserves soil moisture, helping plants to withstand water stress at the beginning of the cropping season. Under the shade-giving coffee bushes, it will eliminate the need for the frequent tillage that cuts the trees' roots and accelerates dry mechanical erosion.

Reforestation with eucalypts combined with annual crops on slopes between 40 and 60%. An intercropping system based on semi-shifting rotation. For the first two years after the trees are planted, the whole plot is tilled and cropped. In the third to sixth years, fallow and cropping alternate each year on different parts of the reforested area. Thinning is started in the sixth year, to pave the way for gradual renewal of the plantation. Tree size is controlled by systematically removing surface roots that can harm crops. The trees then send down tap roots that helps to maintain the stability of the slopes. Their slowly decomposing leaves act as a mulch, protecting the soil from rainsplash and maintaining soil moisture, so that only light tillage is required at the start of the cropping cycle. Plots of potato, garlic or onion grow well between eucalypts planted 5 to 8 m apart in the Bamboutos reforestation area.

Systematic reforestation with eucalypts on slopes of over 60%, with a ban on any crops that require tillage. The trees must be spaced far enough apart (3 to 4 m) to allow the development of an under-storey to protect the soil from rainsplash. Such areas can then be used as rangeland when the trees have grown to over 2 m. If the slope lies over a slide bed-plane, coppiced eucalypts felled every 5 to 7 years will gradually dry out the underlying water and stabilize the slope. This tree is also a good source of firewood and timber, and can produce a good income (Fotsing 1992c).

RESTORING SOIL FERTILITY

Rational applications of mineral supplements and the sale of appropriate fertilizers will compensate for potassium and phosphorus deficiencies. Ploughing in P and K before sowing and dressings of N during the growth period will certainly be advantageous and less expensive. (The 20 – 10 – 10 for P_2O_5 and K_2O costs more than other products).

Improving the fallow by introducing pulses as a catch crop sown under the last crop after hoeing will hasten reconstitution of nutrients in plots being rested. If these plots are used as pasture for small ruminants they will benefit from the animal dung.

Improvement of animal husbandry methods. With small tethered livestock, this will mean shifting their stakes systematically so that the same areas are not overgrazed. With large livestock, it will mean instituting a semi-stabling system near campsites, and rotational grazing coupled with a short dry-season transhumance covering the entire range land area.

Building cisterns for better water management during the dry season. In areas with many buildings, these cisterns will collect water from roofs, watercourses and paths. This reserve of water will be used in brick-making, as a supplementary source of irrigation for vegetable gardens during the off-season – as is seen among some Bafou market-gardeners – and for stock watering. The latter will eliminate the need for herders to move their herds during the dry season, which encourages farmers to take over grazing land.

Integrated plant and animal husbandry in mountainous regions, strictly delimiting the sphere of influence of each. Dung from places where livestock is stabled will fertilize cultivated plots, while fencing a section of grazing land will foster forage regrowth. Livestock can also eat crop residues on harvested fields.

Construction of compost-manure-rubbish pits. This can become a widespread practice in populous areas, using the pits from which earth is taken for brick-making. Kitchen refuse, ash, coffee residues, brewing draff, waste from animal pens, banana stems, etc. will be piled up here and slowly decompose in the shade of the trees surrounding the houses. Refuse with a slow humification rate will be left behind, while a portion of the organic manure taken to the fields will promote the spread of market-gardening. In areas of extensive livestock production, the pits will be dug between grazing land and farm land, so that dung gathered on the range will be mixed with dried straw, constituting a major source of organic fertilizer. This technique will reduce the practice of dry-season burning, which exposes the soil to runoff and erosion.

These support measures will back up the suggested improvements, mainly the reorganization of the fertilizer market, as well as the whole supply and marketing system. This will allow generalized access to inputs and make it easier for farmers to sell their produce. Setting up “fertilizer banks” for each district and collaboration between farmers’ organizations and agricultural co-operatives are also fundamental (Fotsing 1992a, b). Lastly, a general restructuring of the land-tenure system is imperative if farmers are to have the security of tenure essential for any sustainable intervention.

CONCLUSIONS

Concerted initiatives by the authorities have met with very limited success in the face of the ever-present threat of erosion and soil degradation in the Bamiléké area. First and foremost, the farmers’ lack of enthusiasm for the proposed erosion control measures reveals the wide gap between these proposals and the farmers’ own approach to land use. The processes of soil degradation now underway are a reality that present techniques can no longer control. On the other hand, the relatively effective traditional techniques simply require improvement, for they are well integrated with the environment and take into account the central rôle of women in the agricultural production process. The suggestions have therefore been largely based on local know-how. If properly applied, they will preserve the agricultural potential of this region for a long time to come.

Chapter 11

Agroforestry, mineral fertilization and land husbandry in Rwanda

ATTAINING FOOD SELF-SUFFICIENCY IN A HEAVILY POPULATED TROPICAL MOUNTAIN REGION

THE SITUATION

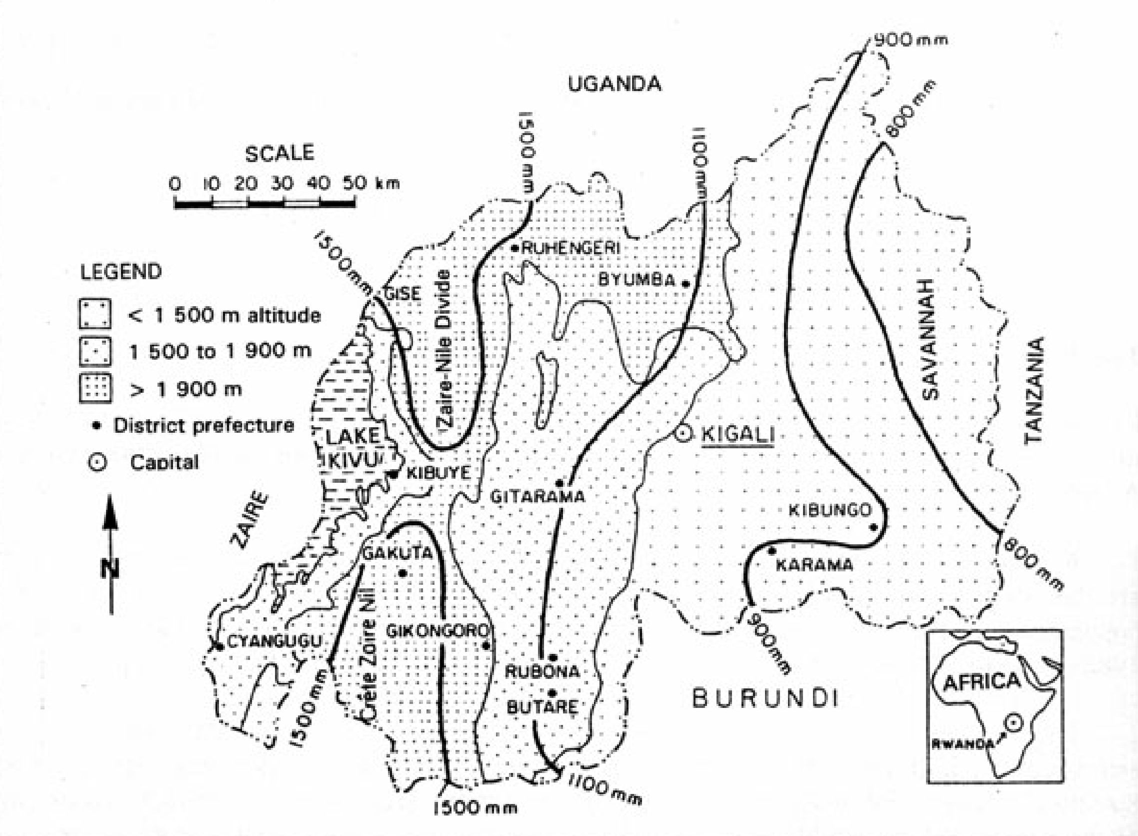
Rwanda is a small (26 000 km^2) mountainous (900 to 4 200 m altitude) land-locked country in Central Africa, more than 1 000 km from the Indian Ocean and 2 000 km from the Atlantic.

A country with a thousand hills, Rwanda has a very wide variety of landscapes. There are six major bioclimatic zones, divided according to geological bedrock, landform, population density, crops, and especially rainfall, which increases with altitude (Delepierre 1982; Gasana 1990) (see Figure 70).

The country has recently undergone massive demographic growth: its population was estimated at 1 million at the beginning of the century, 2.6 million at Independence in 1962, 8 million in 1992, and will exceed 10 million towards the year 2000. The growth rate is one of the highest in the world – 3.7%, meaning that the population doubles every 17 years. Economic growth can no longer keep up with population growth, and the farming population has fallen below the poverty threshold. As the country has virtually no more land reserves, the average size of holdings is shrinking dangerously; it is now under 0.8 ha, and more than 25% of families have to subsist on less than 0.4 ha.

Three communities inhabit this high, tropical landscape: artisans (5%), farmers (85%) and herders (10%). The farmers – the largest group – cultivate the slopes of mid-altitude hills, while the herders occupy the hilltops during the rainy season and the lowlands during the dry season. As a result of population pressure, agriculture rapidly took over all arable land, so that the large cattle herds were forced into the eastern savannahs or the highlands (the Zaire-Nile Divide and volcanoes). Moreover, 50% of farming households today have some sheep or goats, and 30% have one or two cows. When farms are only 0.4 ha it is no longer possible to expand animal husbandry and forage crops: fallow periods have almost disappeared, and grazing is limited to roadsides and private or communal thickets. The trend is inexorably toward keeping small animals (goats, pigs, chickens) more or less permanently penned. This

FIGURE 70
Agro-environmental zones of Rwanda showing altitude (< 1 500, < 1 900 and > 1 900 m) and rainfall (< 900, < 1 500 and > 1 500 mm) (cf. Delepierre 1982)



raises the problem of fertilizing land that was hitherto manured with cattle dung, for the reduced availability of dung means that it is no longer possible to maintain fertility on more than 30% of the land. More organic manure (from pens), more mineral supplements, and mulching will thus be needed.

The main problem for this agricultural country (more than 90% of the population earns its living from agriculture) with scant mineral or commercial resources is that of ensuring food and wood self-sufficiency for a very large population (from 150 to over 800 per km^2), without degrading this landscape of large elongated hills.

Since erosion risks vary greatly in Rwanda, the volcanic zone (one-third of the country), the areas surrounding Lake Kivu, and the Zaire-Nile Divide (where risks of landslides are greater, the steeper the slope, the more abundant the rainfall [up to 2 000 mm] and the more frequent the earthquakes) have been left aside, and the results confined to those obtained on the central uplands (in the Butaré region) and in the low-lying savannah zone of the east (Karama).

ANALYSIS OF LOCAL CONDITIONS

The two zones selected vary considerably in terms of erosion risks.

- **The low-lying plains** (900 to 1 500 m altitude), covered in shrub savannah, receive 800 to 1 000 mm/yr of rain over two rainy seasons. This area is less rugged (slopes of less than 15%), less well-watered, and less densely populated than the rest of the country as a result of malaria and various tropical ailments, and consequently less exposed to the risk of erosion. Most of the eastern part of this area is presently given over to extensive livestock production, even though the soil is often quite fertile. The ferralitic or ferruginous soils here are less acid and less desaturated than elsewhere, but water runs off more easily (a result of the formation of slaking crusts) and crops suffer each year from rainfall irregularity and stress. Managing surface water is probably the main problem for agricultural development in the area, while losses through erosion and drainage are moderate.

- **The central plateau** (1 500 to 2 000 m altitude) receives between 1 200 and 1 500 mm of rain, spread over ten months. Rainfall erosivity is significant (250 to 500 R_{USA} units), and the very dense farming population (250 to 800 per km^2) has to cultivate every piece of land, including slopes of over 40% on the sides of convex hills.

During the first season (September to December), the rain is fine and only one quarter as forceful as in West Africa. It falls on dry, well-drained, and manually well-tilled soil, and does not cause much damage. However, in the second season (February to June) there are several larger, heavy storms (60 to 100 mm/day). If they fall on moist soil, on steeply sloping slopes or soil fine-tilled for sowing, the water forms rills, which then scour the full depth of the tilled soil down the whole length of the plot. All this soil easily blocks the erosion control ditches, which overflow, so that the runoff accumulated in them then cuts gullies which will wreck erosion control measures all the way down to the foot of the hill.

The topsoil horizon is quickly scoured, not only by rill erosion but also by dry mechanical erosion following multiple tillage procedures: deep-ploughing the land twice (to dig in weeds) and hoeing twice in each cropping season causes 30 to 60 tonnes of earth to move down the slope as far as the next obstacle, so that banks rise by 15 to 30 cm per year.

At this rate, the soil cover on the hilltops is soon stripped, uncovering alterites and blocks of rock. Much less water is now absorbed and retained, which means that during periods of heavy rainfall, large amounts of water gush down from the degraded hilltops, gullying the slopes, changing the flow rate of rivers, increasing peak flows, attacking river banks, and washing away the gravel from river beds. The delicate balance in these mountains is disrupted by uncontrolled clearing, overgrazing, growing crops that provide little cover on very steep slopes, and the removal of stones that protect river beds for building.

Ferralitic soils are generally very desaturated, acidic, (frequent pH of 5 – 4), deficient in P and N, and poor in bases. They seem on the whole very permeable, except where they have been compacted (tracks, cattle trails, paths to dwellings) or pounded by rain. They retain little water (1 mm of available water per centimetre of soil) or nutrients (1 to 5 meq/100 g of fine soil), so that it is important to maintain an adequate level of organic matter. They are often rejuvenated by erosion, with a layer of rubble or ferruginous gravel at a depth of between 30 and 100 cm. Soil erodibility ranges from low to medium on schist, and Wischmeier's K factor is generally under 0.20 (Roose and Sarrailh 1989, Ndayizigiyé 1993).

TABLE 40

Erosion (t/ha/yr) and runoff (% of annual rainfall) on small plots (5 x 20 m) on steeply sloping (25-60%) ferralitic soils in Rwanda and Burundi

Plant cover	Treatment	E t/ha/yr	Runoff Kaar %
Bare soil	tilled parallel with the slope	300 to 550	10 to 40%
Manioc or potato, maize/bean or pea-sorghum, as companion crops	traditional hoe tillage	50 to 150 (300)	10 to 37%
Crops + idem + 200 trees/ha	litter 50 kg/tree/yr	30 to 50 (111)	5 to 7%
Idem + trees + hedges every 5 to 10 m	biomass 3 to 6 kg/m^2/yr	year 1: 7 to 16 year 4: 1 to 3	10 to 15% 1 to 3%
Idem + trees + hedges	$\pm$ covered ridges every 5 m	1 to 4	0.1 to 2%
Banana plantation	open, mulch removed (10 t/ha/yr)	20 to 60	5 to 10% (45)
	or complete, mulch spread out or in lines	1 to 5	0 to 2%
Coffee plantation or manioc	thick mulch (20 t/ha/yr)	0 to 1	0.1 to 10%
Pinus forest, pasture, old fallow	(5-15 t/yr of litter)	0 to 1	1 to 10%

( ) = maximum levels recorded

Except for the two planting periods the countryside is green, for annual rainfall is good -if irregularly distributed. Erosion risk would therefore be moderate if the cultivated slopes were not so steep (Berding 1992). Two country-wide surveys indicated that 50% of the cultivated land is on slopes exceeding 18%, 20% on slopes exceeding 40%, 5 to 6% on slopes exceeding 65% (the limit for terracing), and 1% on slopes exceeding 84%.

Erosion risks are aggravated locally by two phenomena.

- **Land tenure problems.** The concern for equality in inheritance means that each heir receives an equal share of each section of land, which means in turn splitting the original plot into as many vertical strips as there are heirs. The result is that on densely populated hills (those farmed for a long time) very long, narrow plots are put under crops at the same time, which seriously increases the risk that sheet erosion will scour the soil right to the bottom of the slope. Once such scouring starts, it happens again each year in the same spots, because it is difficult to prevent runoff from flowing toward the lowest points in a field. The land is quickly ruined. Land tenure laws should be changed.

- **Landslides.** If erosion control on a hill calls for digging total absorption ditches on slopes of over 40% or on shallow soils on a sliding alterite (schist, gneiss, micaceous rock or volcanic ash on granite domes), the slope is thrown out of balance. If a long series of storms waterlogs the soil cover (and especially if this is compounded by earthquakes), it can start sliding from one of these ditches, and continue down to the river, which can then be temporarily blocked by this mass of earth.

Experiments show how urgent it is to combine all available erosion control techniques in order to stabilize sloping land while also substantially increasing its productivity (see Table 40).

There are about 250 reliable measurements of annual erosion on plots of 100 m^2 (20 m in length) fairly similar to farmers' fields, on steep slopes (25 to 60%, except for the IRAZ banana plantations, where S = 8%), on ferralitic soils that have been somewhat rejuvenated or received colluvial deposits and are very desaturated and acid, but also very resistant to rainfall aggressiveness (K < 0.2 to 0.1). The results of these experiments indicate that:

- the risks of sheet and then rill erosion are very high on bare soil, varying from 300 to 550 t/ha/yr, depending much more on rainstorms than on slope; it would take only 5 to 10 years to remove the whole topsoil horizon (20 cm) at this rate;

- the risks of runoff (Kaar = 10 to 40%) can be serious on such steep slopes when they are poorly covered (as with degraded soil);

- traditional farming methods and intercropping do considerably lessen risks (C = 0.2 to 0.5), but not enough, since the tolerance threshold is no more than 1 to 12 t/ha/yr depending on soil depth;

- trees dotted among the crops do little to improve soil conservation;

- hedges of grass or bushes every 10 metres, plus large ridges covered with pulses or sweet potatoes every 5 metres, do constitute a valid preliminary solution;

- mulching (tested under banana, coffee or cassava) is a second solution which is immediately effective even on steep slopes;

- reforestation with pines (needle litter being very effective) or other species allowing an under-storey quickly reduces runoff and erosion to acceptable levels (Roose, Ndayizigiyé and Sekayange 1992).

Blind ditches and bench terraces cannot be studied effectively on these small plots (5 m wide). On land managed under erosion control projects, it has been seen that these methods can increase risks of gullying and landslides where the soil cover is thin or the slope too steep (> 40%).

Farming methods – not just erosion control structures – play the major rôle in stabilizing slopes.

In conclusion, these verdant landscapes can give an impression of stability to busy experts who are used to the gullied, bare land of semi-arid regions. In reality, however, the soil is very poor, very steep slopes of 60 to 100% are cultivated out of necessity as land is short, rain is excessive at some periods and scant at others, and the cover provided by crops on the most degraded land is too light to protect the soil from the various erosive processes in the Rwandan hills (see Figure 71).

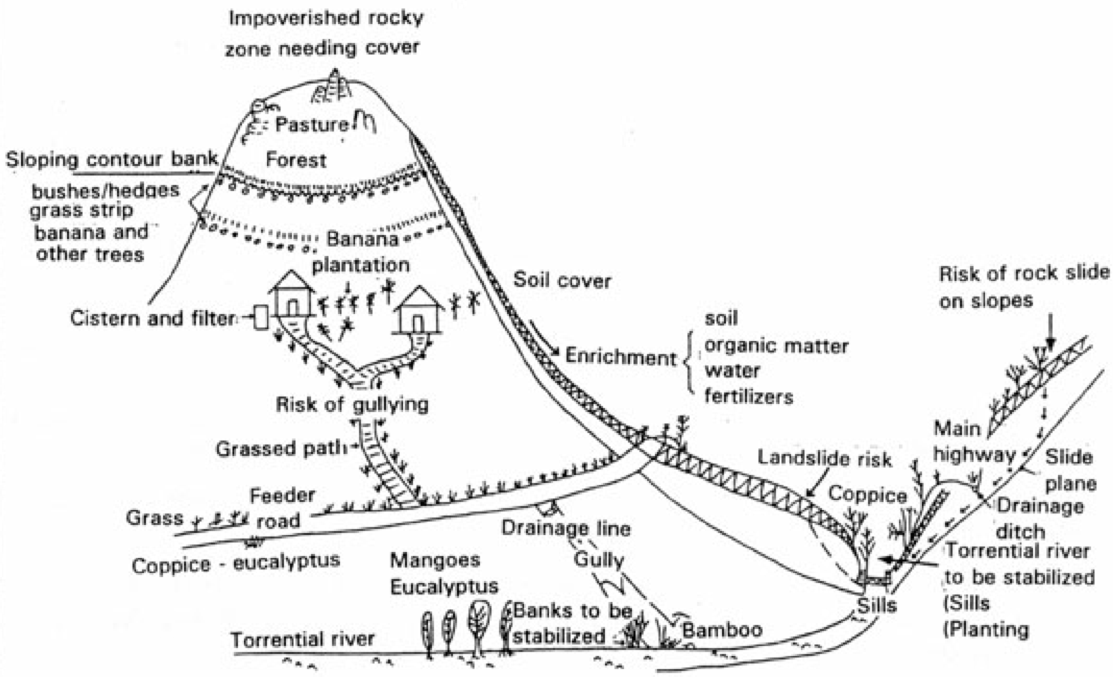
FIGURE 71
Six processes leading to rural environmental degradation (cf. Roose 1992a, b)
Quartzite/schist hill

1. Soil degradation: • organic matter ↘ • fertility ↘ infiltration ↘
2. Sheet and rill erosion
3. Dry mechanical erosion: creep

} scouring of topsoil; farmers' responsibility

4. Gullying (tracks)
5. Landslides
6. Shifting of torrent channels

} serious accidents downstream (mud flows, flooding); State responsibility



TRADITIONAL TECHNIQUES

The crops are planted in dispersed fashion around the habitat in direct relation to soil fertilization. When a young family sets up home on a levelled platform cut into the hill, it plants its banana plantation around it, and this will receive most of the available nutrients (domestic waste, crop residues, ash, peelings and latrine waste). Companion food crops are grown between the bananas: maize, beans, cush-cush, potato and herbs. A small field of maize intercropped with beans receives a little manure/compost, and broadcast-sown sorghum is grown in the second season.

The only plots not eroded are those that are mulched and under coffee trees: in order to avoid the penalties conscientiously imposed by Ministry of Agriculture field staff, coffee plots (100 to 200 m^2) are copiously mulched with cassava and sorghum stalks, various types of grass pulled up from the banks, and banana leaves. The remaining land (two-thirds) receives no manure or fertilizer, and inevitably degrades under such frugal crops as cassava and sweet potato.

Weeds are carefully pulled up, either – depending on need and season – to feed stabled animals, or to cover furrows and reduce erosion, or to be piled up in large heaps, covered with earth and immediately planted with sweet potato cuttings. In any case, vegetation is very quickly recycled.

Plots are sometimes scattered several kilometres away from dwellings (rented fields). Despite the many disadvantages (time spent travelling back and forth, difficulty in guarding and manuring plots), scattered fields do allow farmers to cope with climate-related risks (localized storms and hail, damage from animals and disease). Young technocrats dream of dwellings concentrated in villages and consolidation of landholdings so as to promote intensive, modern, mechanized farming. This is a serious mistake in a country with no alternative way to feed a very large rural population forced off the land (no industry, no international waterway, no trade). Furthermore, the land is too steep to risk the introduction of tractors (little likelihood of cost effectiveness, and risks of compaction), and an element that now enriches the land (domestic waste) would become a pollutant hard to control within a village.

Present farming techniques take a great deal of work, which is often performed by groups of neighbours using two rudimentary implements, the machete (sometimes curved like a sickle) and a long-handled hoe. Following a short fallow (from a few months to one or two years), the soil surface is cleared of infesting weeds and then deep-ploughed to turn in the weeds (30 cm and more). Stolons and other persistent roots are dried in heaps, and composted or burnt. A month later the plot is fine-tilled for drill sowing (maize) or broadcast sowing (second-season sorghum); an intercrop may be sown after the first hoeing to fill empty seed holes and cover the whole area.

All tillage is manual, using hoes. Animal traction is difficult on steep slopes and is never even considered, for there is no tradition of draught animals. There is no mechanization (far too expensive at such a distance from the sea), which means that there is little compaction of deep horizons, and drainage seems normal. Deep drainage would be needed only in the vicinity of springs.

Ridging or larger mounding is confined to tuber crops and digging in weeds. On the other hand, crops are usually grown on raised beds or large mounds in the valleys and marshlands in order to ensure good drainage.

Apart from spreading manure on fields near dwellings, soil fertility is maintained by intercropping, rotation, digging in weeds, and a short fallow. However, there is an erosion control technique traditionally used on steep slopes, especially for growing peas on schist and in the highlands in the north and on the Zaire-Nile Divide (Nyamulinda 1989). It consists of micro-step terraces 1 metre wide, cut into the slope, preserving the root systems of clumps of grass. This allows space for a double row of maize/beans or peas. The risers (0.5 to 1 m high) are kept firmly in place by the root networks. The main concern with these narrow terraces is to keep the cultivated beds within the topsoil horizon, for the wider the terrace the more the soil structure is disturbed and the more the sterile deeper horizons are exposed (Roose *et al.* 1992). The traditional technique is to turn half a bed on to the one below in the second year – thereby mechanically shifting the surface layer of soil right along the slope. Trials on erosion plots have shown that with an improved version of this method (placing beds strictly along the contour and using the grass from the risers) all erosion can be stopped and rainwater better managed, even on schist soils on 60% slopes.

Lastly, there is a local technique of managing runoff on tracks, which consists of digging a pit in the upper slope, in which runoff and its load of sediment are directed. When it is half-full of sediment, a clump of banana trees is planted in it, to benefit from the additional water and nutrients. When the first pit is almost full, another is dug lower down (= Rudumburi).

In conclusion, traditional methods allowed maintenance of the stability of the landscape and a modest production level. Now that the population has become too numerous to keep enough land under fallow, something has to be done to keep the soil in place, but also to bring about a rapid increase in soil productivity for both food and fuelwood crops).

SUGGESTIONS FOR MANAGING SURFACE WATER

ADAPTATION TO EACH CLIMATIC REGION

In semi-arid regions (especially the eastern savannah), placing land under cultivation brings a major increase in runoff and a reduction in evapotranspiration, and thus in the production of biomass. Runoff control measures (improvements in infiltration and localized storage) can therefore have a considerable impact on yields of crops that suffer as much from drought as from mineral deficiency. Farmers will quickly become interested in runoff management techniques.

In humid regions (R > 1 000 mm), clearing land and putting it under cultivation bring an increase in the risks of runoff, in peak flows of rivers, and therefore in the risk of erosion of banks. There is a consequent reduction in drainage, the leaching of fertilizers, and the dry season flow of springs and rivers. Runoff (and erosion) control will thus have relatively little effect on crop yields, unless there are periods of drought during vulnerable phases in the growth cycle. This is one reason why erosion control has had little impact on yields in the humid hills of Rwanda, the other causes being the chemical poverty and acidity of the soil.

In conclusion, if runoff is reduced by farming techniques and/or suitable erosion control structures, plant production must be intensified to avoid increased risk of nutrient leaching by drainage water and landslides on steep slopes: hence the attraction of intercropping, fertilization and agroforestry.

WATER MANAGEMENT STRUCTURES SUITABLE FOR RWANDA

Four approaches to surface water management can be identified, depending on climate and soil permeability, with corresponding erosion control structures and farming techniques (Roose, Ndayizingiyé and Sekayange 1992). Here only the most appropriate are described.

Cisterns of drinking water collecting 10 to 50 m^3 of clean water from roofs considerably alleviate the work of carrying water, improve hygiene, and allow for a few penned animals, the production of manure and a very intensive multi-storey garden around dwellings.

Cisterns or pools collecting runoff water (100 to 500 m^3) on tracks or rocky or overgrazed slopes allow livestock watering and supplementary irrigation of short-season vegetable and fruit crops (see Haiti).

Total absorption ditches encourage infiltration of runoff water on slopes of less than 20%, on deep, permeable soil. Unfortunately, they require a lot of work (200 to 350 days to dig, plus 20 to 50 days per year for upkeep), and hardly improve crop yields at all (which is why farmers abandon them). Their main attraction is in the gradual transformation of the landscape into very gently sloping terraces. Diversion ditches are unadvisable for mountainous regions, as gullying is bound to set in at their outlets.

Stop-wash lines or semi-pervious microdams (lines of grass, stones, hedges, grassed banks) do not stop runoff, but do slow down water, dissipate its energy, and spread it into sheets, thereby encouraging sedimentation. A bank quickly forms (20 to 30 cm/yr), with a gradual terrace which can then be transformed into two horizontal terraces, one enriched (reserved for intensive cropping), and the other poorer (frugal crops such as cassava and sweet potatoes), so that fertility must be gradually restored (see Figure 72). The demand for labour is more occasional (50 days to build, plus 10 days per year for upkeep), as are fertilizer requirements.

Horizontal or bench terraces allow all water (rain + runoff between terraces) to be absorbed, and make the most of manure inputs. Clearly, however, bench terracing requires a huge investment in terms of labour (500 to 1 000 days/ha to build) and inputs (10 t/ha of manure, 1 to 5 t/ha of lime, plus the fertilizer for each crop) before the natural fertility of the soil is restored. This method should be chosen only if there are both inputs and the markets and praticable roads to capitalize on surplus production. There must be no risk of landslides.

Micro-step terraces (cultivated width about 1 metre) on permanent grassed risers (maximum 50 to 100 cm) require much less work and stabilize steep slopes very well under manual intercropping, since the crop roots remain in the original topsoil.

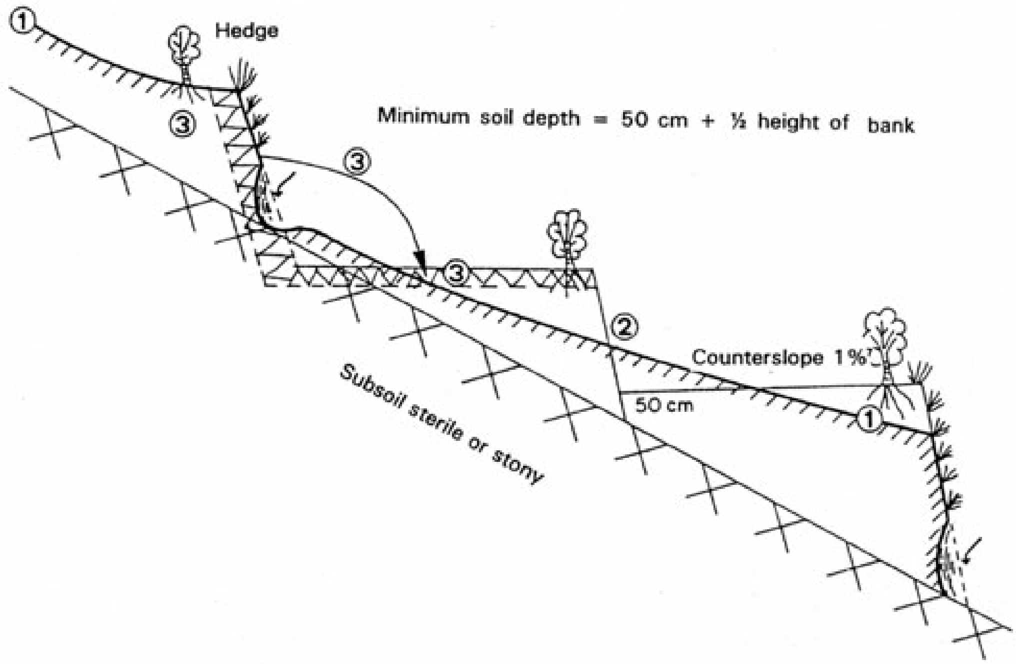
THE MOST SUITABLE TILLAGE TECHNIQUES

Tillage techniques that modify the state of the soil surface, roughness, plant cover, the activity of mesofauna and/or infiltration capacity are often very effective in reducing the volume of runoff and dissipating its energy.

Flat tillage with large clods is essential on soils that are too compacted. It temporarily increases infiltration, improves water storage and helps to dig in crop residues and combat weeds. Unfortunately, it inhibits earthworm activity, reduces soil cohesion, and increases erodibility by runoff water, especially if seeds are sown on a bed of very fine aggregates.

Mounding and ridging, parallel with the slope, gather together good topsoil so that large tubers can be grown, but these practices are dangerous on steep slopes since they concentrate runoff into trickles that can dig rills and gullies, and detach gravel and other stones that protect the soil from rainsplash.

FIGURE 72
Development of gradual terraces into horizontal terraces: a CIGAND project proposal



(1) At present the hills hold many gradual terraces which are too wide between banks which are too steep or even undermined at their base. After 5 to 7 years, the lower part of the terrace has filled out with fine soil, while the upper part is scoured and tends to become sterile: intervention is required.

(2) Fine the line in the terrace where sterile subsoil or rock appears at about 1.3 m (50 cm + ½ the height of the bank), plant a new line of grasses, and build a bank at a 40% slope, covered with grass + fodder legumes.

(3) To prevent the terrace above from becoming sterile after levelling work, the wall of the uphill bank can be knocked down one last time to correct its slope, and a good layer of topsoil spread on the terrace above.

Tied ridging perpendicular to the slope improves water storage under small rainstorms, but can lead to gullying or landslides under heavy storms. Only **large ridges (H = width _ 40 cm) permanently protected by creeping plants** (e.g. sweet potato or forage pulses) and at intervals of under 5 metres, can break the force of runoff on slopes. Combined with hedges, they can quickly stabilize steep slopes (20 to 60%).

SUGGESTIONS FOR MANAGING SOIL FERTILITY

BIOMASS MANAGEMENT

In Rwanda, most farmers are too poor to buy enough mineral fertilizer to boost the productivity of all their land. Traditionally their only means of maintaining or restoring soil productivity is the biomass produced on their fields and on fallow areas, roadsides, communal forests, etc. Application of SPR and SWC methods (ditches) does not increase biomass production, and also reduces the productive area. Land husbandry, on the other hand, attaches great importance to improving biomass production and to careful management of organic matter so as to restore the essential nutrients to the soil as quickly as possible.

In the tropical African rain forest 8 to 15 t/ha of litter are returned to the soil each year. Under savannah 2 to 8 t/ha of leaves are returned to the soil, unless they are destroyed by fire or livestock! After clearing (burning off natural vegetation and putting the land under crops), the amount of organic matter in the topsoil horizons falls by 40% in four to ten years, depending on how organic residues are managed – manure, compost, direct turning in, or mulching.

Under crops there is a fair amount of available biomass:

- maize and sorghum can leave 2 to 5 t/ha/6 months of residues, at present used for feeding stock or mulching the coffee plantation;
- soybeans, groundnuts and beans produce 0.5 to 2 t/ha of good-quality fodder;
- cassava and sweet potatoes provide 0.5 to 2 t/ha of biomass which can be used for feeding pigs or mulching the coffee;
- a banana plantation (3 x 5 m density) can produce 3.3 t/ha of stems and 2 to 6 t/ha of leaves which can be used as mulch or fodder;
- short fallow periods (a few months between two cropping cycles) and weeds provide 0.5 to 2 t/ha/yr of green matter.

AGROFORESTRY

This method can considerably boost biomass production on cultivated fields. Two hundred trees (*Grevillea robusta*, *Cedrella serrata*, *Polyscias fulva*, etc.) planted in or around fields can produce enough firewood for the whole family, plus 1 to 4 t/ha/yr of leaves and twigs very useful for mulching.

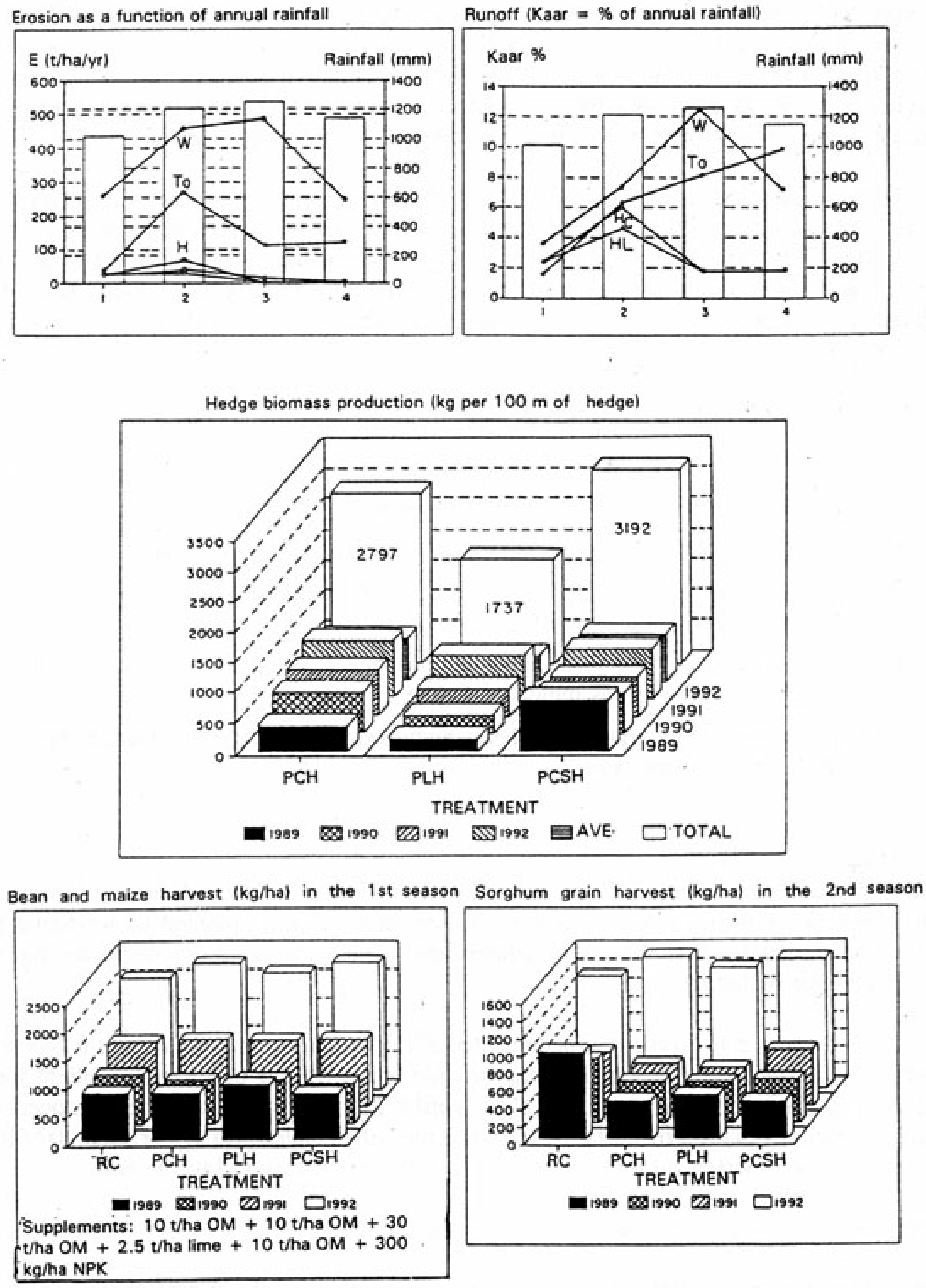
Planted every 5 to 10 metres, hedges of *Calliandra calothyrsus*, *Leucaena leucocephala* or *diversifolia*, or *Cassia spectabilis*, can provide 3 to 9 t/ha/yr of leaves (excellent fodder) and 2 to 7 t/ha/yr of firewood; in other words, more biomass may be produced on a cultivated field from crop residues, trees and hedges, than under primary or secondary forest. However, it is important to make sure that enough of it is restored to the soil.

BIOLOGICAL UPTAKE OF NUTRIENTS THROUGH AGROFORESTRY

If the soil is neither too acid nor too deficient in phosphorus, the shrubs chosen for hedges can fix nitrogen from the air. Depending on author and site (Balasubramanian and Sekayange (1992) in the eastern savannah, König (1992)

FIGURE 73

Effect of hedges of *Leucaena leucocephale* and *Calliandra calothyrsus* (1 m thick every 7 m) on average annual runoff (Kaar %), erosion (t/ha/yr), hedge biomass production (kg/100m/yr) and harvests of two cropping seasons at the ISAR station at Rubona in Rwanda on a 27% slope and on acid ferralitic soil (cf. Ndayizigiyé 1993)



W = Wischmeier's standard bare plot
CH = *Calliandra* hedge
P = production
LH = *Leucaena* hedge
RC = Regional control plot
CSH = *Calliandra* + *Setaria* hedge

TABLE 41

Requirements of NPK, lime and manure for each crop on the acid ferralitic soils of Rwanda (cf. Rutunga 1992)

Crops	N	P	K	Lime, manure, inoculant
Bean	34	25-30	34	depending on cryptogamic diseases
Soybean	20-40	40-50	30-50	+ inoculant + lime if pH < 5
Pea	34	34	34	+ inoculant + lime + manure
Groundnut	30	30	0	
Sorghum	60	60	17	at altitude + manure (+ lime)
Maize	78	42	42	
Wheat	88	42	42	
Irrigated rice	60	30	30	for two tonnes of paddy
	100	60	60	for six tonnes of paddy
Potato	50	100	200	+ lime + manure if at altitude
Manioc	100	50	100	
Horticultural crops	30-50	30-70	100-200	or 35 tonnes of manure

and Ndayizigiyé (1992) around Butaré on the central plateau), cutting the hedges three times can bring up to the soil surface: 75 to 130 kg/ha/yr of nitrogen, 2 to 20 kg of phosphorus, 20 to 60 kg of potassium, and similar amounts of calcium and magnesium, depending on the richness of the soil in these elements – an input of minerals close to that from 10 tonnes of farm manure. Apart from the litter provided by 200 trees per hectare, it is clear that agroforestry can make a considerable contribution to the organic and mineral balance of the soil in two ways: by significantly reducing nutrient loss through erosion and drainage, but also by extracting nitrogen from the air and through the uptake of nutrients carried by drainage beyond the reach of the roots of annual crops.

APPLICATIONS OF ORGANIC MATTER AND MINERAL SUPPLEMENTS

Figure 73 compares the effects of three types of hedge, always at intervals of 7 metres, on erosion (t/ha/yr), average annual runoff (Kaar %), biomass production from hedges, and cereal production.

Biomass. *Calliandra* hedges give twice as much biomass as *Leucaena* (4 to 8 t/ha/yr). Prunings spread on the ground three times a year cover 80% of the surface with *Calliandra* and 40% with *Leucaena*. However, after two weeks all the small leaves have gone, digested by soil microflora, leaving only the twigs – which children can collect as firewood. Perhaps other shrubs should be investigated for intercropping.

Runoff. Apart from the first month after planting, the soil is so well-covered that after two years runoff is negligible: 12% on bare soil, 8 to 10% under traditionally grown crops, 1 to 2.5% under crops with hedges every 7 metres. Runoff is serious only in the case of the long rainstorms of the second season under sorghum on a waterlogged soil. Maximum daily runoff reaches 68% on bare fallow, 20 to 35% under crops.

Soil loss. Sheet and rill erosion decreases from 450 t/ha/yr on bare fallow to 80 to 120 t/ha/yr under traditionally grown crops, and 1 to 2 t/ha/yr under crops two to three years after planting hedges. It should be noted that the crops received 10 t/ha/yr of farm manure (and even 90 t/ha in the third year), although even such a high input of manure was not enough to bring erosion down to acceptable levels. However, while erosion tends to increase from year to year under traditional methods, it decreases on plots protected by hedges proportionate to the slope of the land (from 27 to 15%).

Impact on crop production. In the first year harvests were much the same, indicating that the plots were similar at the outset. In the second year, despite 10 t/ha of manure, yields fell from 10 to 30%. In the third year, following an application of 30 t/ha of manure, yields climbed from 32 to 53 or 68% in the fields with hedges. It was only in the fourth year, when 2.5 t/ha of $CaCo_3$+, 10 tonnes of manure and N_{51}, P_{51}, K_{51} were applied that yields increased markedly from 500 to over 2 000 kg/ha of cereals and up to 2 318 kg/ha between the hedges, despite the space taken up by these hedges (15%). Second-season sorghum production remained poor (420 to 640 kg/ha) except after liming and supplementary mineral applications (up to 1 544 kg on the plots with hedges).

In this trial on acid ferralitic soil, it seems that even if erosion and runoff are brought under control, yields still continue to fall. Ten tonnes of manure plus six tonnes of pulse mulch were not capable of increasing yields of cereals and beans, because the plants, the soil, the animals and the organic manure are deficient in the same elements (especially P and N). However, yields tripled and the erosion control measures paid off after the pH was corrected (2.5 t/ha/3 yrs of lime was enough to eliminate aluminium toxicity), and supplementary minerals applied (60 units of NPK were enough for the cereals).

So far it seems that farmers are becoming steadily more interested in hedges, but more as sources of dry-season fodder and boundary markers than as erosion control measures. They have not fully grasped all that is involved in the hedge system, particularly the need to cut back roots and branches to limit competition with crops.

RESTORING SOIL FERTILITY

Outside the volcanic zones, desaturated ferralitic soils are very acid, often exhibit aluminium toxicity, and have excellent drainage, which means that there is a high risk that fertilizer will be leached out in drainage water, especially if runoff is suppressed without intensifying cropping. In such circumstances, farmers will reject soil conservation as leading to no increased return for their work. It is vital that soil conservation, water storage and fertility restoration be introduced simultaneously if there is to be any significant improvement in yields.

The following six rules must be followed if soil fertility is to be restored in one or two years:

- control of runoff and erosion;
- deep subsoiling in order to reorganize rooting;
- stabilization of macroporosity by digging in organic matter (or lime) and by a crop with a vigorous rooting system;
- correction of the pH (pH 5);
- revitalization of the soil through applications of manure or compost (3 to 10 t/ha/2 yrs);
- correction of the main soil deficiencies, or at least provision of the essential crop nutrients.

MAINTENANCE MANURING

As was seen in the Rubona trial (Figure 73), once erosion has been brought under control and the physical, biological and chemical fertility of the soil restored to an acceptable level, plants still have to be fed (localized manuring) as and when needed (staggered doses), depending on crop production goals (N = 40 to 160 kg/ha/yr + P = 30 to 100 kg/ha/yr + K = 20 to 100 kg/ha/yr) and the risk of periodic leaching. In practice, organic residues have to be better managed and the mineral supplements vital to the crops added, as ferralitic soil can store very few nutrients and little water.

Rutunga (1992) has noted that on Rwanda's poor land, liming (2 to 5 t/ha) should be done every three years, and organic manure applied every three crop cycles. On soil of average richness, liming makes little or no difference, but mineral and organic manuring does. As for rich volcanic soil, weak doses of NPK have so far produced only slight improvements in yields.

CONCLUSIONS ON LAND HUSBANDRY IN RWANDA (Plate 32)

In the heavily populated tropical mountains of Central Africa, the risks of erosion (300 to 700 t/ha/yr) and degradation of soil fertility increase with slope and population density (150 to 800 per km^2) (Figure 74).

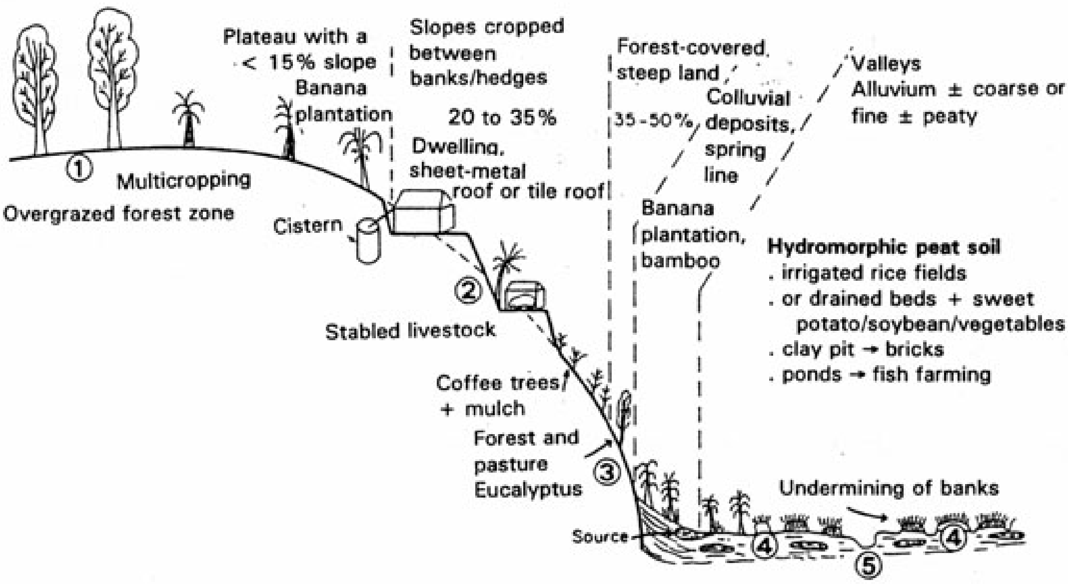
Some production systems can keep erosion at an acceptable level: mulching under coffee, banana or cassava, large contour ridges with permanent plant cover, green manure covering the soil surface, reforestation with species that provide good litter. Radical or gradual terracing (1 000 and 100 days' labour respectively) and other erosion control structures are less effective than biological systems (grassed banks, hedges, etc.) and require more upkeep and space.

Agroforestry (e.g. 200 trees per hectare plus hedges every 5 to 10 m) can control erosion (1 to 3 t/ha/yr), produce fodder and mulch (4 to 10 t/ha/yr) and take up nutrients from deep in the soil (N 20 to 100, P 10 to 20, K 2 to 40, Ca + Mg 20 to 40, etc.), with a reasonable amount of work (10 to 30 days per year). Animal husbandry can enhance the benefit of this biomass, since dung is one of the keys to fertilizing ferralitic soil, which is like a sieve.

However, despite applications of 10 t/ha/yr of dried corral-dung and 4 to 8 t/ha of pulse mulch, land productivity has remained very low (400 to 800 kg of beans, maize and sorghum, 3 to 8 t/ha of cassava). If the challenge of doubling production before the population doubles (17 years) is to be met, it is vital to propose a technological package comprising management of both water and soil: cisterns, hedges, organic fertilization (mulching, green manure and improved farm manure) with a mineral supplement (40 to 100 kg/ha/yr of NPK, and 2 to 5 t/ha/3 yrs of lime). SWC is not enough.

It may be noted that the densest populations in the world live in "multi-storey gardens" where the positive interaction between animal husbandry, crops and trees is carried to the furthest extreme. In Africa, much remains to be done before achieving the intensity of production found in the gardens of Asia.

FIGURE 74
Erosion risk and suggested improvements for the granito-gneissic hills of Rwanda



Ferralitic acid soil

- permeable
- heavy leaching
- P-N-K-Ca-Mg deficiency
- good resistance to erosion

(1) Rainsplash and rills → scouring of topsoil
(2) Rainsplash, rills → gullies, compaction of tracks
(3) Undermining of banks by river, gullies and mass sliding
(4) Deposits with very irregular texture: gravel-sand, clay-peat - drainage necessary
(5) Torrential river with very varied flows and solid loads

Problems

- How to feed a very dense population living on very poor soil
- How to evacuate excess water from very steep cultivated slopes
- How to improve management of bottom lands

Attempted improvements

1. Drain bottom lands, introduce streambed cultivation: very difficult when only part of the basin is being treated.
2. Slopes: stabilize ground with hedges every 10 m and 200 trees/ha.
   → production of fodder, firewood, mulch;
   → stabilize the ground against sliding (roots), runoff/mulch;
   → trees bring organic matter and nutrients to the surface;
   → grassed banks, and hedges.
3. Absolutely necessary on these poor, acid soils: biomass management + mineral applications:
   → manure/compost pits + lime and P_2O5 + ash to raise the pH to > 5;
   → staggered spot application of a mineral supplement for plants.
4. Transform banks into fodder belts stabilized by legume hedges + grasses and tillage detritus (roots, twigs, stones).
5. Improvement of tracks: generalized grassing, and drainage to cisterns or sedimentation pits planted with bananas.
6. Need to organize the marketing of agricultural products (tracks, etc.) and inputs.

Chapter 12

A new approach to erosion control in Haiti

An example of a calcareous-basalt transect in the hills of southern Haiti

The situation

A special context

Since the 1950s, Haiti has been experiencing accelerated degradation of its rural land and natural resources. Although agriculture is undergoing a particularly difficult crisis, it still constitutes one of the dynamic forces of the country's economy.

Malnutrition in the countryside, the decline in exports (50% in the last 10 years), a major rural exodus and the inability of families to save are thrusting Haitian farmers into a cycle of decapitalization that will be hard to break, for the very low farm income (falling from $450 to $250 in 1992) no longer allows most of them to renew either their livestock or their implements. Furthermore, the rising population has aggravated pressure on land, resulting in increasingly frequent cropping and reduced fallowing of the same land, leading in turn to overgrazing and hastening soil degradation.

This is seen not only in lower fertility, but also in accelerated soil loss, since the components of the physical environment are naturally fragile: 60% of cultivated land is on very steep mountain slopes (20 to 80%), with frequently violent rainfall conducive to runoff. The outcome of all these factors is lower returns on labour, in the face of which charcoal production seems a good alternative to improving farming income. This has led to uncontrolled deforestation, accelerating the deterioration of the natural resources that underpin agriculture.

The consequent decapitalization, accompanied by a loss of social cohesion, forces farmers into a survival mentality, making it hard to approach land management as a group effort (control of livestock grazing and of woodcutting), although this is a *sine qua non* of successful development or erosion control efforts.

The failure of so-called "modern" erosion control strategies

From the 1960s until 1990, national authorities were advised by international bodies and donors that the answer to the crisis of the rural sector lay in solving natural resource conservation problems. The special situation in Haiti encouraged implementation of a large number of schemes and projects based on a "modern" strategy of rural development, thus turning this country into a kind of erosion control laboratory.

Unfortunately, this approach to improvement and development nearly always led to closing off large areas to livestock, or else to soil and water conservation schemes (SWC) that turned erosion control into an isolated experience. Such projects achieved only mixed and questionable results, and often ended in failure.

The strategy adopted concentrated on developing a unified area, usually a watershed, emphasizing the physical coherence of the various processes. It gave priority to infrastructure installations (roads, feeder roads, gully control, contour channels, dry stone walls, radical terraces) with most of the work being done with the help of the local populace in exchange for some remuneration (in money or kind). And it was meant to have an almost immediate effect on the conservation of natural resources.

Failure sprang basically from the fact that "general interest" was the paramount factor, legitimizing infrastructure development and making soil conservation (SWC) the prime objective – although Haitian farmers had a very different view, and saw such projects simply as ways of ensuring an immediate income, even though the proposed conservation techniques failed to offer short-term improvements in yields and income.

Furthermore, there is no direct relationship between these techniques and the set of constraints that farmers have to face. This gap between proposals and constraints arises from a deep ignorance of the farmers' economic perspective, of how farming systems work in general, and of land tenure issues in particular.

The latter entail an inheritance system that encourages fragmentation and joint ownership, aggravating land insecurity and the danger of food insecurity as farm plots shrink in size.

The installation of erosion control structures means sacrificing some of the already limited arable land, with no possibility of improved yields for many years to come. The extra work required for their upkeep is work that only the farmers themselves can assure. Furthermore, these techniques neither reduce degradation on the land between the structures nor improve productivity. They are not very effective, and sometimes increase such risks as overflow, gullying and landslides by upsetting ecological balance on the slope. To avoid these constraints, erosion control structures are often built on land marginalized by farmers.

Similarly, research work focuses more on selecting species and on the depth or inclination of terraces than on ways of integrating trees or mechanical structures into traditional farming systems.

Project organization needs revision, and a change from the approach whereby the population is used as a labour pool without any real participation. Project monitoring and evaluation are also needed.

There is thus a complete divergence between the objectives of a project that prioritizes the capital development approach and the objectives of the people involved (who are rarely consulted). The situation is now such that it is no longer enough either to protect or to conserve the soil. The population is growing rapidly, and production must be increased without degrading the environment.

A new participatory approach: the Salagnac/Aquin Projects and PRATIC

Another approach, based on rural development, has been worked out since 1985, aiming mainly at solving the people's immediate problems (food security, improved yields, better returns for work) through better land use using techniques, suited to the Haitian context, that safeguard the environment and land resources. Soil and water conservation, from being an end in itself, becomes a means of establishing stable production systems.

This approach, now known as land husbandry, seeks to improve infiltration on fields so as to increase biomass production (and hence yields) by providing better soil cover and re-establishing the balance of organic and mineral matter in the soil. It attempts to reduce the impact of erosion and sediment transport by modifying production systems, while ensuring that farmers take responsibility for their own environment.

It was adopted by two French aid projects, Salagnac-Aquin (1978-92) and PRATIC (1988-92), concerning the Petite River transect Nippes-Salagnac-Aquin (Figure 75), with activities[1] aimed at encouraging intensification and diversification of farm production while stabilizing slopes: new cash crops, increased foodcrop yields on land with the best potential. The goal was to relieve the most vulnerable land from cropping pressure (frequent tillage and overgrazing) and transform it into a forest- and fruit-tree farming area, improving animal husbandry conditions, etc. It was based on the following principles:

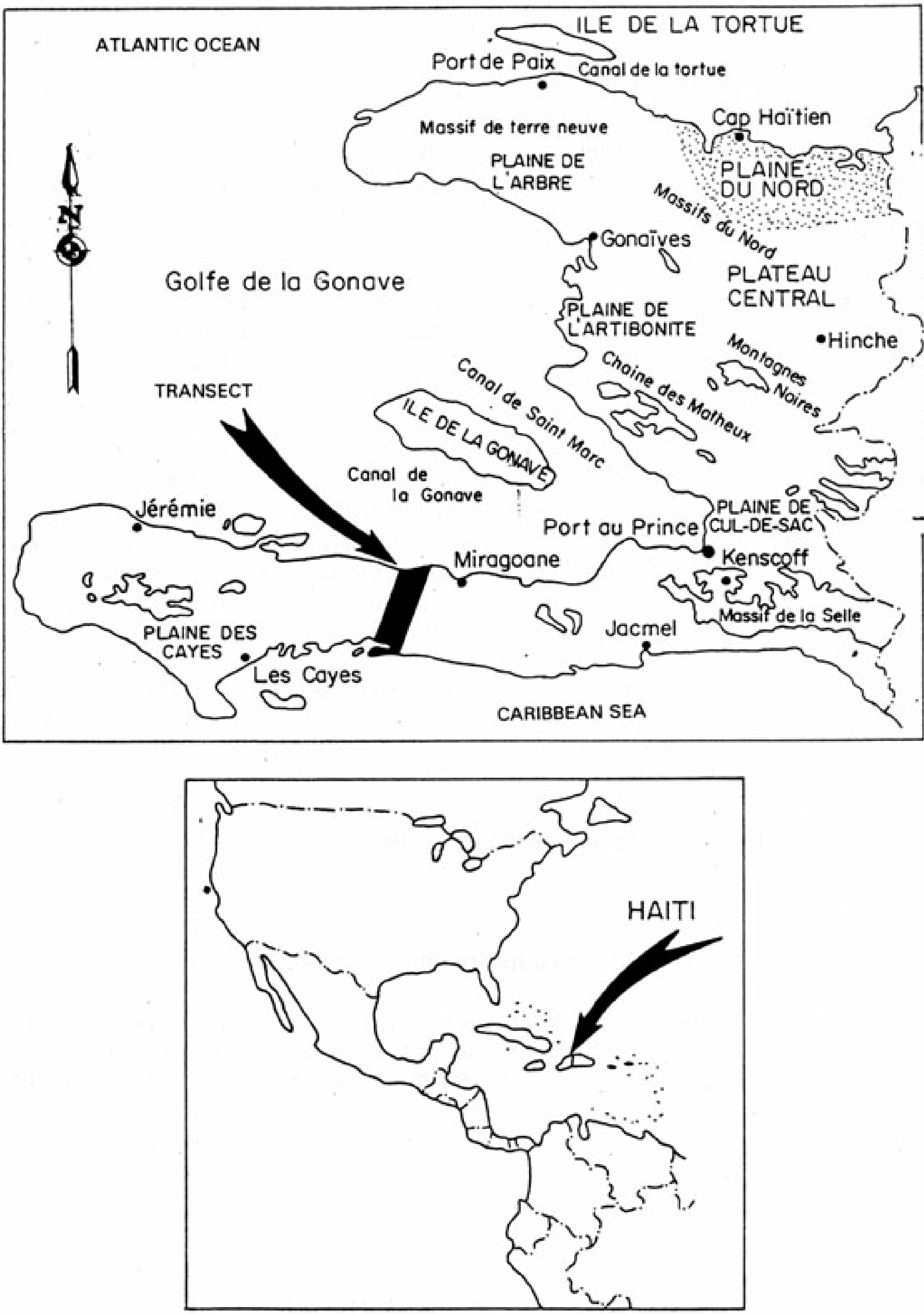
- **Farmer participation right from the project design stage.** This is a decisive factor for protection activities and vital to project success, as the farmers are the only people who can guarantee upkeep of erosion control structures at the plot level and/or on the slope as a whole.

- **Reinforcing traditional methods of soil and water conservation.** Haitian farmers have themselves adopted traditional survival strategies to control erosion and boost soil fertility.

- **Selecting zones that have retained maximum** agricultural production potential.

- **Intervening on individual plots and slopes**, and then, whenever possible, at the watershed level. Erosion control thus focusses first on the plot, then on the farm, and finally on the whole area. Piecemeal treatment of individual plots is no alternative to treatment of a watershed, for they require different strategies (the rural development and capital development approaches), which should in fact be complementary.

FIGURE 75
Map of Haiti



- **Combining soil conservation activities with convergent activities** that allow enhanced production systems (intensification and diversification of cropping, improved animal husbandry, creation of savings and credit).

- **Setting up a system of contractual relations** with precise definition of the conditions of intervention, and of farmer-project relationships, with clarification of the activities that are the strict responsibility of each farmer (improvements on individual plots), those that are the responsibility of the rural community (roads, feeder roads, communal cisterns, gully control), and finally the commitments of the project.

- **Allowing for planning, monitoring and evaluation** (measuring the effects). This type of programme will require much time (8 to 10 years) before it has any noticeable effect on production systems or can modify practices while ensuring that farmers take responsibility for management of their environment. It has three necessary phases:

- **1st phase: analysis of local conditions** in order to discover the potential and limitations of the physical environment, including the processes of soil degradation (where, when and how they arise), but also the farmers' traditional methods of farming their land and managing water and fertility. This analysis will foster dialogue with the communities and help build trust.

- **2nd phase: on-site trials** in order to establish technical terms of reference (comparing traditional techniques with the proposed techniques).

- **3rd phase: evaluation of the results by both communities and experts**, prior to planning intervention on whole hillslopes and watersheds.

ANALYSIS OF LOCAL CONDITIONS

A VARIETY OF NATURAL ENVIRONMENTS

This variety springs from the interaction of several factors, the most important of which are the nature of the soils, the bioclimate and the topography.

Four major agro-environmental units (Figure 76) have been identified, with various sub-units. These distinctions are fundamental to any understanding of the choices made by farmers regarding crop distribution and land use on each plot. They are as follows:

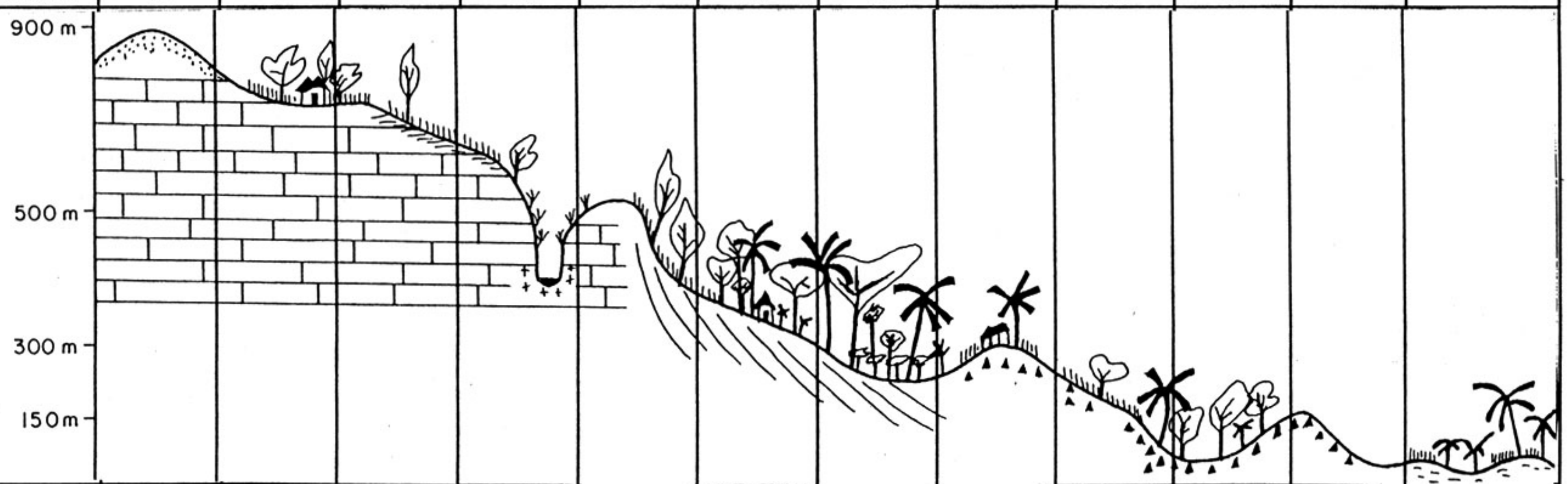
Unit 1: high bluffs and calcareous uplands. Between 500 and 900 m in altitude, they have ferralitic soil on the higher reaches, and calcimagnesic soil lower down. They are stony, and organic fertility is poor. Rainfall is frequent and sometimes heavy (60 to 88 mm/h). Winds can be violent and constitute an additional crop constraint. The basic crop combination is maize-beans-sweet potato, with the occasional addition of cabbage and yam. This is the most deforested zone on the transect except for areas that are densely populated thanks to the presence of gardens, always owned outright, around the home: the *devant porte kaye* garden, also known as the *lakou*.

Unit 2: marly-calcareous hillslopes and bottom lands. This is an area where springs emerge, and where the soils are more favourable to permanent crops (vertisols, brown calcareous soils). Rainfall is heavy enough to

FIGURE 76
Agro-environmental cross-section of the transect

SOUTH KM 0 — KM 11 NORTH

UNITS	1				2			3				4
SUB-UNITS	13	11	12	14	21	22	23	33	32	31	34	



	13	11	12	14	21	22	23	33	32	31	34	4
agro-environmental zones	high bluffs and calcareous uplands				marly calcareous slopes			andesitic/basaltic bluffss				Aquin alluvial plain
bioclimates rainfall length of dry season	1800 to 2200 mm 2 to 3 months				1500 to 1800 mm 3 months			1200 to 1500 mm 3 to 5 months				600 to 900 mm 6 to 8 months
slopes	25-40%	< 5%	10-25%	35-70%	40-60%	15-40%	10-20%	5-10%	10-30%	5-15%	20-45%	< 5%
soil types	rendzinas	deep ferralitic soil	shallow ferralitic soil	calci-magnesium soils, lithosols	scree on silty-clay soils	brown calcareous soils	vertisols	calcic melanitic soil	fersialitic soils	vertisols	eroded fersialitic soils	vertisols
erosion processes	sheet and groove	degradation	sheet and groove	grooves and rills	absent	sheet, groove and rill	absent or mass movement if drainage line	sheet and rill	sheet, groove and rill	undermining of banks	mechanical and gullying	sheet and especially gullying
erodibility	+ +	0	+	+ + +	0	+ + +	+	+ + +	+ + + +	+	+ + +	+ + + +
fertility	+	+ + +	+ +	+	+ +	+ +	+ + + +	+	+ + +	+ + + +	+	+ + +
cropping system	long fallow and July pea	potato, maize, bean, cassava and yam	potato, maize, cabbage and bean	maize and bean	maize, sorghum, Congo pea	maize, coffee, Congo pea, bean and tubers	banana, coffee, tubers	maize, Congo pea, sorghum, cassava	sorghum, Congo pea, maize	banana, tubers	groundnut	sorghum, cowpea, Congo pea, grape, maize
afforestation	0	+ + +	+	+	+ +	+ + +	+ + + +	+	+	+ + +	0	+ +

allow two cropping seasons, mainly yam, maize, sorghum and black beans. Banana, coffee and malanga (*Xanthosoma* spp.) are also found in the cooler spots (gullies, bottoms). Forest cover is extensive, with a preponderance of breadfruit (*Artocarpus incisa* non-*semifera* variety).

Unit 3: andesitic or basaltic bluffs. This unit is less well-watered (1 200 mm/yr) and below 300 m in altitude. A fairly marked dry season makes only one cropping season possible: sorghum, groundnut, Congo pea, and sometimes maize. The soils of volcanic origin are very well-suited to agriculture; however, they are often found on slopes, exposing them to strong sheet erosion from diffuse runoff or groove and rill erosion.

Unit 4: the Aquin plain. This lies between sea level and 300 m. The climate is dry tropical, with a mean annual rainfall of 600-1 000 mm with considerable yearly variation and a dry season of six to eight months. The soils are vertisols, with little infiltration on gentle slopes (3 to 10%). Cropping systems concentrate on various combinations: maize, cowpea, sorghum, Congo pea, vigna. Gullying is frequent at points where rainwater concentrates (roads and paths).

A VARIETY OF PRODUCTION SYSTEMS

Several factors account for this diversity:

- unequal pressure on landowning;
- complex types of land tenure, the four major types being (in decreasing order of security): land ownership with formally divided inherited land, informally divided inherited land or jointly owned inherited land; to which should be added types of land use: owner-operated (the most common), tenancy ($60 to $120/ha/yr), and share-cropping (one-third to one-half share handed to the owner), the system in use among the poorest;
- the available human resources, whether sold or bought;
- the availability of livestock resources.

These internal factors give rise to three major farming systems, corresponding to a variety of socio-economic levels:

- **Low:** farmers owning very little land (less than 1 ha), tending to share-crop, with very meagre capital resources and reduced livestock resources, and who very often have to sell their labour to augment their income. For some this is simply the way they start off in farming, but for others it is a permanent condition, the main cause being land rentals that obviate savings.
- **Medium:** there is enough arable land (1 to 3 ha) to feed the whole family, making the head of the household less dependent on rich farmers and the market, but also less integrated with the latter. Accumulation is based on farm production, and can be slowed down by the growth of the family. Farming swings between the two extremes, keeping a dynamic balance.

- **High:** arable land (more than 3 ha) allows production in excess of family needs, and there is enough livestock to function as productive savings. The accumulation processes usually start with a large inheritance and/or a second activity (carpentry, bricklaying, etc.). These farms draw on a significant labour pool, and quickly increase their capital.

These differences in farming systems explain the different ways in which natural resources are managed, and the different degrees of their degradation, and also why strategies for maintaining fertility will be different. For example, the density of livestock per hectare on farms with little land will tend to lead to compaction of soil, then runoff and finally erosion; selling one's labour or working on land with insecure tenure does not encourage a maximum investment of labour or inspire people to protect the cultivated area. Jointly owned land shows advanced degradation: severe compaction, outcrops of mother-rock, no trees, very poor fertility.

A variety of degradation processes

The range of factors mentioned above (agro-environmental conditions and farming systems) also explains the variety in processes of soil-cover degradation, which happens in three stages:

- constant, rapid mineralization of organic matter, not compensated for after clearing (little or no organic matter dug in) and hastened by (selective) erosion;

- gradual slipping of surface layers through repeated tilling of soil under foodcrops that are not long in the ground (on slopes the soil is always tilled downhill);

- onset of runoff and gullying following compaction of the soil by tethered livestock and on paths, especially following reduction in the water storage capacity of soil scoured by dry mechanical (man-made) erosion; in areas with calcareous substrata the saturation point is reached after 70 to 80 mm of rainfall on deep ferralitic soil and less than 30 mm on worn-out land or rendzinas; and rainstorms of more than 60 to 80 mm/h occur three to six times every year, plus hurricanes every four to ten years, with more than 400 mm of rain in five days.

Sheet erosion seems insignificant in Unit 1: true slaking crusts are rarely seen, but there are frequent aggregate discharges, as well as disintegration of mounds and compaction of the soil surface. Clayey, well-structured, chalky and pebbly soils are very resistant: rainsplash dislodges aggregates.

Linear erosion is seen everywhere in the form of grooves (channels of several centimetres) (Unit 1) and rills (tens of centimetres), quickly developing into active gullies (metres) (Units 2, 3, 4) if nothing is done to stop it. Land where there are outcrops of mother-rock ("worn-out land"), tracks and paths, overgrazed fallows and vertisols on basalt are the source of dangerous runoff on steep slopes. Impermeable brown soils on basalt give copious runoff (Pi = 2 to 5 mm with moisture).

Mass movement takes the form of creep and dry mechanical erosion due to tilling on steep slopes, and through headward cutting starting from the network of gullies on convex slopes (especially Unit 3).

Erosion of banks is very widespread in the plains, where rivers carrying excess sediment loads (Unit 4) frequently alter channel.

Generally speaking, erosion is more significant on basaltic or andesitic than calcareous soil, although economic effects vary according to the nature of the subsoil. Thus, on a basaltic or andesitic substratum there is a high rate of weathering of mother-rock and pedogenesis is quite fast, so that there are fairly good possibilities of restoring fertility following degradation. However pedogenesis is much slower on calcareous substratum, and once the soil capital has been depleted there is much less possibility.

Farmers' traditional strategies and their limitations

In these very varied conditions, farmers choose, combine and apportion plant species by area and season. Cropping patterns are thus the outcome of reasoned choices and indicate how far farmers have adapted to local conditions. For all that, there is not necessarily a proper balance, and there are certain worrying developments that could end in failure.

Combating degradation: a farmer's way of managing fertility

The three Haitian gardens: improving fertility or increasing soil degradation by transferring crop residues?

Fertility in the three gardens involves livestock-based transfers.

Each farm in Unit 1 comprises at least the following three gardens:

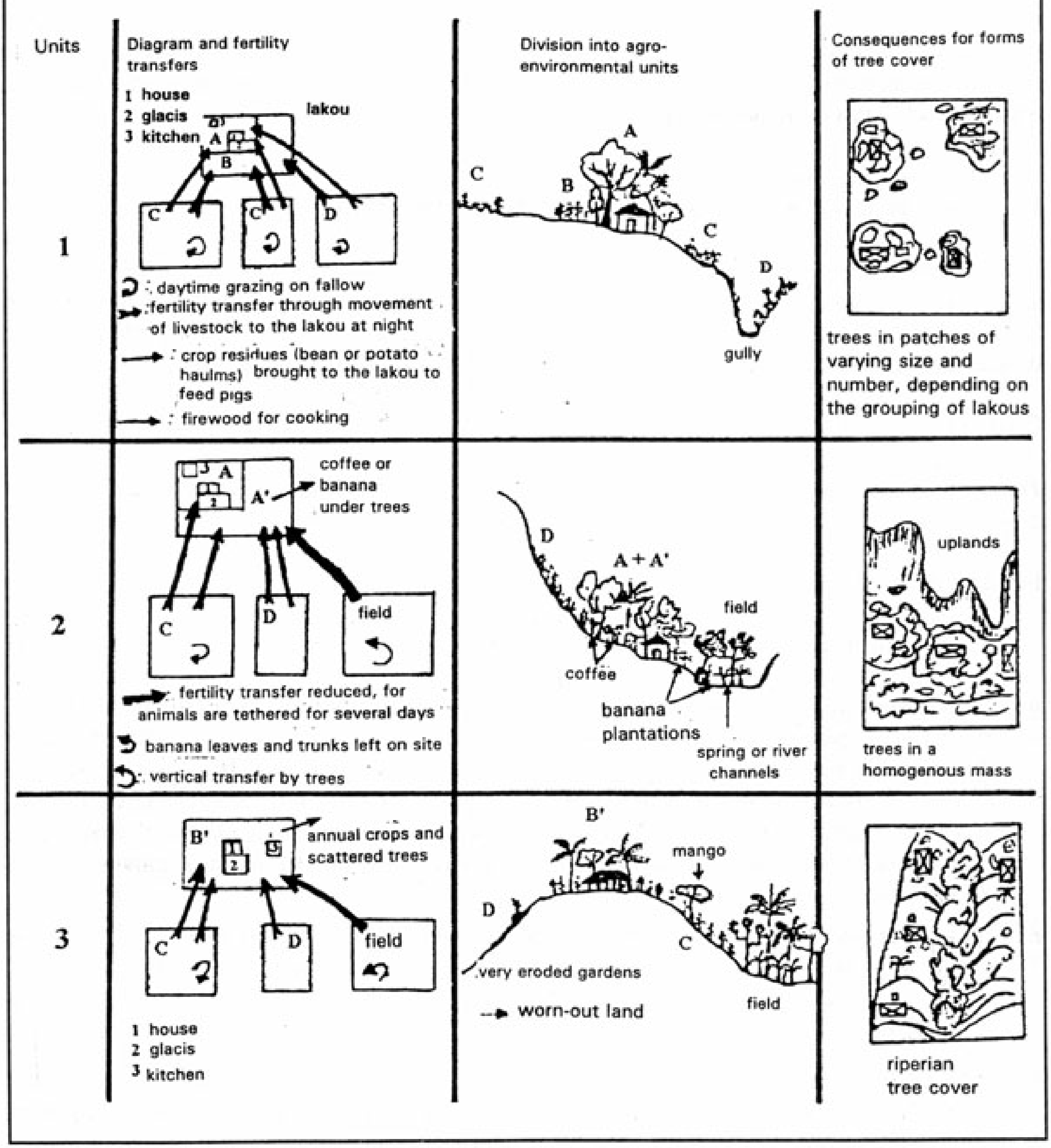
- **The *devant porte kaye* garden (A)**, also called *lakou* (500 to 1 000 m^2): this is an area of dense vegetation surrounding the house, and is always owned by the householder. Many perennial or annual species are grown in combination here, forming several storeys: avocado (*Persea americana*), chadequier (*Citrus maxima*), banana, coffee, malanga (*Xanthosoma campestris*), taro (*Colocacia esculenta*), yam (*Discorea* sp.), chayote or christophene (*Sechia edulis*), pumpkin (*Cucurbita moschata*), chives (*Allium fostulosum*).

- **The *pré-kaye* garden (B)** (1 000 to 5 000 m^2): this treeless area is bounded by a shrub hedge to mark off the property and protect crops from wind and animals. Beans, maize, yams, sweet potato (*Ipomea batata*) and cassava (*Manihot utilissima*) are grown here in combination.

- **The *loin kaye* garden (C)**, often with a total area of over 5 000 m^2: this garden is found in areas with very few trees and far from dwellings. It may be rented, share-cropped or jointly owned. Fertility is low and soil is degraded. Farmers intercrop beans and sweet potato for six months, after which the plot is left as grassland. If the garden is extremely degraded and situated on a steep slope (D), it is left fallow for long periods (more than three years) as goat pasture (racks zone).

Farms in Unit 2 differ in various ways from those in Unit 1. The considerable tree cover in these zones makes it hard to distinguish between A and B gardens, so that both could be lumped together as a single A garden. However, there is a new type of garden here that the farmers call a "field" and is comprised basically of banana

FIGURE 77
Types of garden, fertility transferral and tree cover (cf. Guarrigue 1990)



(sometimes combined with malanga) under tree cover. These gardens are not always found near dwellings, and their location depends on the availability of water and the coolness of the soil, i.e., in the bottom lands or near spring lines.

In Unit 3 there is still the garden near the house, in a space protected and bounded by a continuous hedge, situated on dry bluffs, although it tends to become poorer at lower altitudes, sometimes whittled down to a few trees scattered around the house (coconut, mango); in short, gardens A and B tend to become a single, lightly wooded, B-type garden. There are also perennial bottomland gardens, heavily wooded and very fertile, which can be classified as A gardens growing in wetter areas.

This garden structure disappears in Unit 4.

Arguably, the distribution of the different types of garden is mainly determined in Unit 1 by the distance of plots from dwellings, and in Units 2 and 3 by soil type (lowlands = alluvial and colluvial deposits) and humidity.

It is important to note that farmers transfer crop residues from one plot to another in order to manage reserves of organic matter (Figure 77). However, while fertility increases in certain gardens (usually the freehold ones) near the dwellings, this is at the expense of other plots (usually share-cropped or rented) further away, where fertility drops because crop residues are regularly used on plots with more secure tenure. Farmers have little interest in fertilizing these more distant plots when they do not know if they will be able to use them the following year. The land tenure factor is pivotal to soil degradation.

The use of fallows

Fallows used to be common in Haiti, but are tending to disappear. Fallow periods can last from three months to two years depending on the type of garden and the land available to the farmer.

In Unit 1, the poorer land furthest from the home is left fallow for one or two years after a cropping cycle of one or two years. On the most fertile land closest to the home, the fallow lasts only two to six months – the time needed to fertilize the plot by keeping animals on it who are fed fodder. In the first case, the land is “rested.” The second is in fact a fertilization technique.

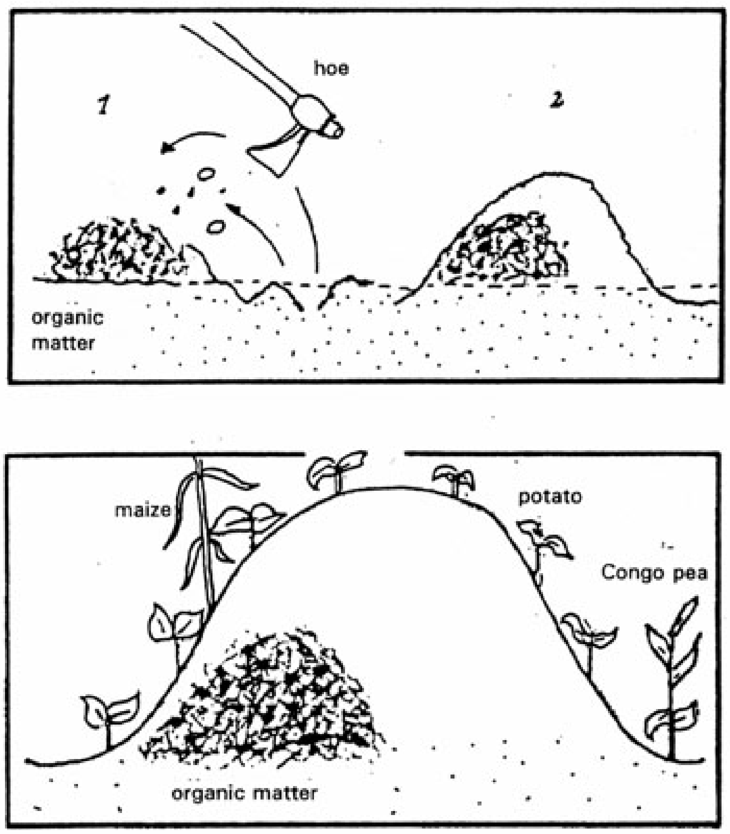
In Unit 3, intercropping (maize, sorghum, Congo pea) fill the plot throughout most of the year (April to January) and then preparation of the soil starts with the first rains (March/April). Fallows are infrequent and only at long intervals. Soil fertility depends solely on the effectiveness of intercropping, for there is no mineral fertilization. The farmer will always give economic reasons (no seed, insufficient labour available, etc.) for not cultivating a plot, rather than reasons connected with preserving fertility.

Conclusions. When fallow periods are long (one to two years), livestock is left tethered without fodder, initially to eat harvest residues on the spot (maize or sorghum stubble, or potato haulms), and then to graze. This gives an on-site recycling of organic matter from animal dung which, being unfermented, loses much nitrogen in the sun. This technique often leads to compaction of the soil on steep slopes, encouraging runoff.

Concentrating organic matter within mounds

This practice is followed on all types of garden (Figure 78). After a fallow period, and one month before sowing and planting, weeds are hoed, dried and piled up. They are then covered with earth from the surface horizon (15 cm), which is the richest in organic matter, to form mounds about 1 metre in diameter. This procedure assists root growth by improving drainage and aëration, but, more importantly, it allows a concentration of organic matter within the

FIGURE 78
Preparing a compost mound (cf. GRET/FAMV 1991)



mound. As the most demanding plant, maize is sown in the most favourable location, while Congo pea – less demanding because of its deep, powerful root system – is sown in the least favourable location.

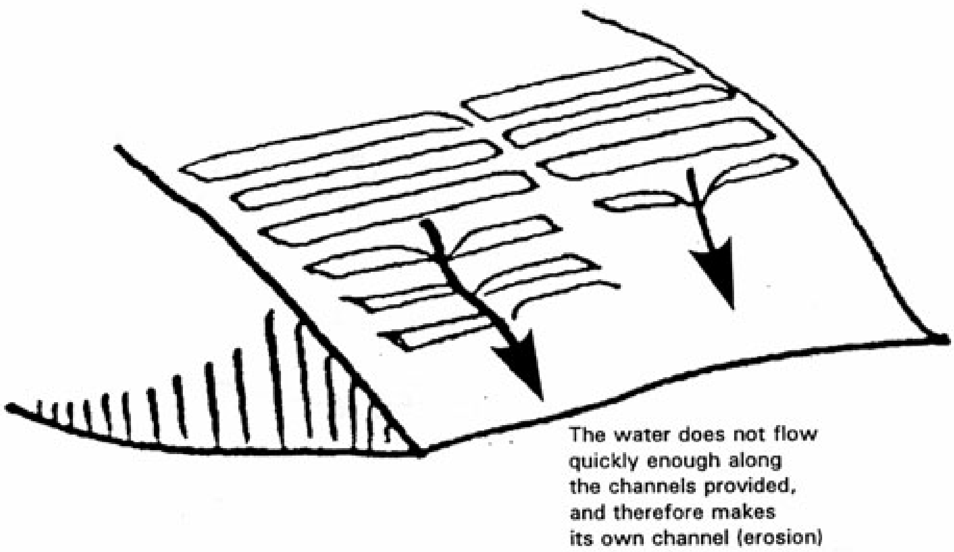
Burning

This practice is common in Units 3 and 4 where the residual plant material is very woody – sorghum stubble, Congo pea or cassava stalks – and is burnt when there is enough of it, since it would decompose too slowly otherwise. Although such burning allows rapid preparation of the ground and also releases a large number of mineral elements, making them available quickly at the start of the growing season, there are some drawbacks: it encourages runoff and scouring on steep slopes, and does not allow enhanced water retention or enrichment with organic matter by digging in. If the slopes have good organic matter content, there is less degradation, but sheet erosion is still significant.

Combating Sheet Erosion

Sheet erosion occurs in Units 2 and 3 on slopes, and in Unit 1 on degraded soil on steep slopes.

FIGURE 79
Effect of overly long ridges (cf. Smolikowski 1989)



The farmers use traditional control measures, but these are limited in effect – although they do have the advantage of being integrated into the farming system and could therefore be improved.

- **Horizontal ridges** (Figure 79) on a slope are not enough to stem erosion. They have only a limited effect on runoff, and rarely follow contour lines. And when they are too long, water collects at certain points, the ridges give way, and linear erosion starts with heavy rainstorms.

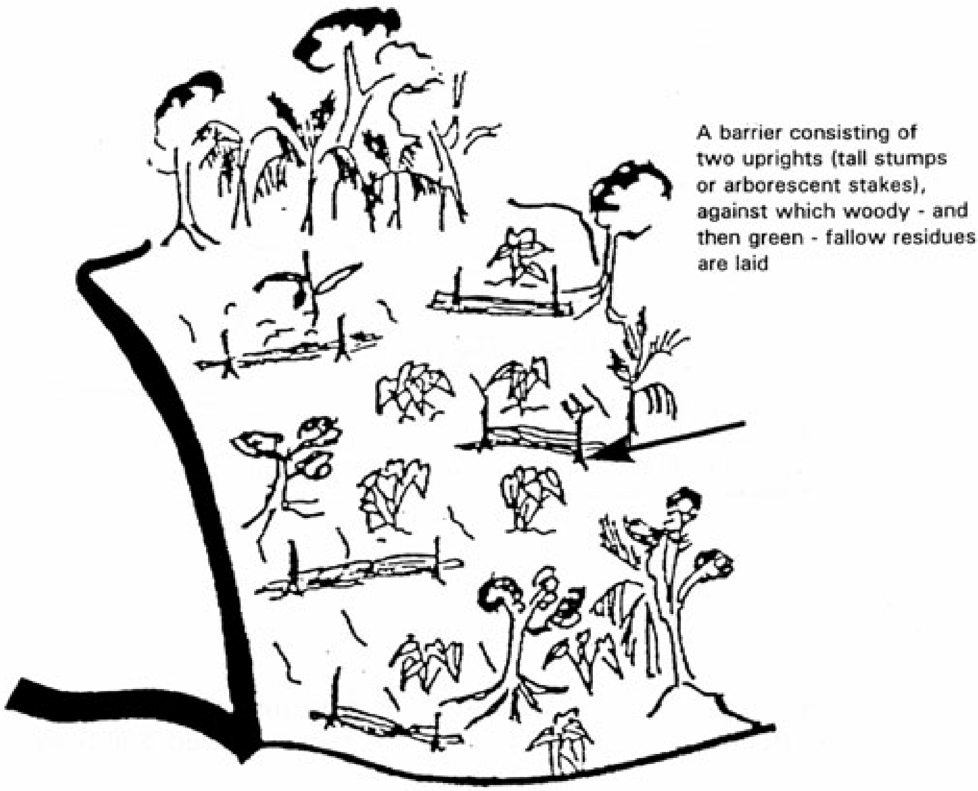
- **Straw barriers** are widely used, but to little effect. These small barriers (Figure 80) are made by sticking two wooden posts into the ground, then laying other woody residues between them, interwoven with green fallow residue after clearing. These structures are not permanent and can have no cumulative effect over the years. Moreover, they are only roughly horizontal, and are too permeable.

- **Hedges** of various species could have some degree of effectiveness. Unfortunately, they are found only on plots near dwellings (A- and B-type gardens), i.e., on gentle slopes on freehold land. Furthermore, they are planted chiefly as enclosures and not along the contour lines, with the main purpose of protecting against theft and preventing animals from straying. The species used are not attractive to livestock and produce little biomass. Here too, such investments are made on land with the most secure tenure.

COMBATING LINEAR EROSION

Farmers also use wattle barriers to prevent rills or grooves, but this is less common, since these forms of erosion appear mostly in Units 3 and 4 where vegetation is sparser.

FIGURE 80
System of straw barriers (cf. Smolikowski 1989)



For small and medium gullies, farmers build small sills of plant material or stones, but this not-very-common practice requires care and upkeep, since the structures are often fragile and can be swept away in heavy rain.

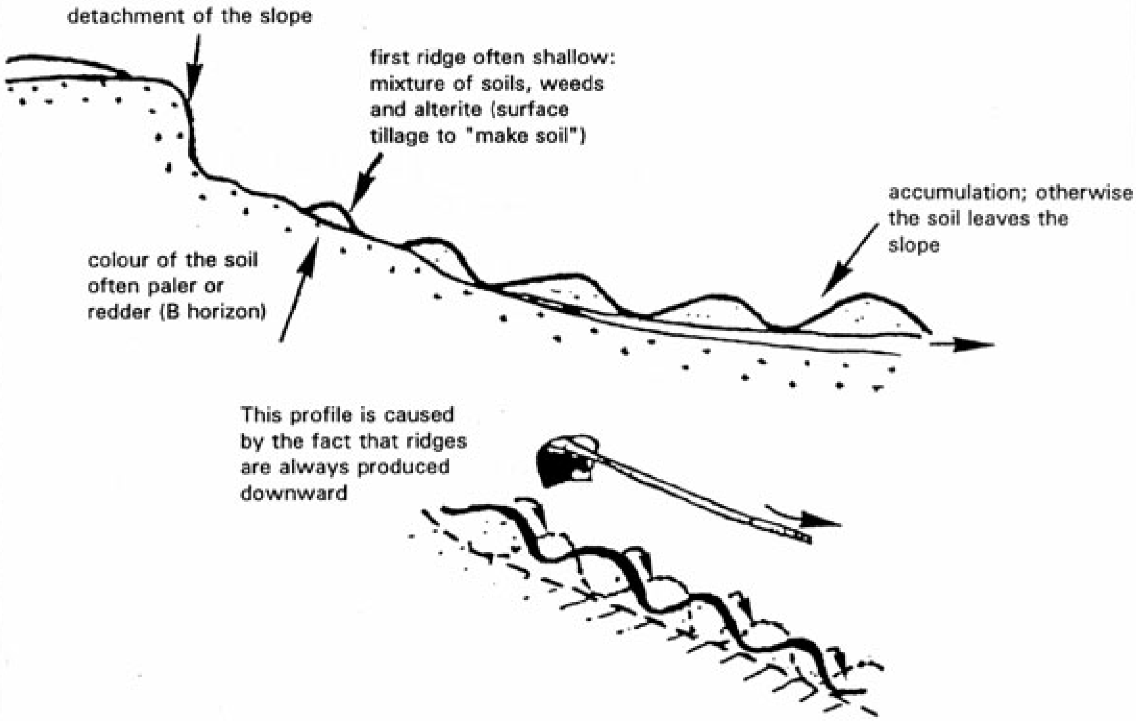
Combating mass movement

There is no traditional technique for combating this form of erosion. Moreover, such phenomena are often hastened by the way that farmers till slopes: each year they work from top to bottom as they prepare mounds or ridges, so that a portion of the soil is moved downhill (Figure 81). This amounts to a gradual sliding of the surface layer material.

One way of managing biomass: wooded gardens

The existence of a tree strata in the various gardens and their distribution in the different environmental units has already been mentioned (Figure 77). Despite what people say, trees always play an important rôle in Haitian farming. This rôle may expand or contract according to circumstances, but management of trees is closely tied to the

FIGURE 81
Man-made erosion: tilling the soil on a slope (cf. Smolikowski 1989)



production factors of the farming system concerned (land tenure, income level, method of stock rearing, form of inheritance,[2] etc.).

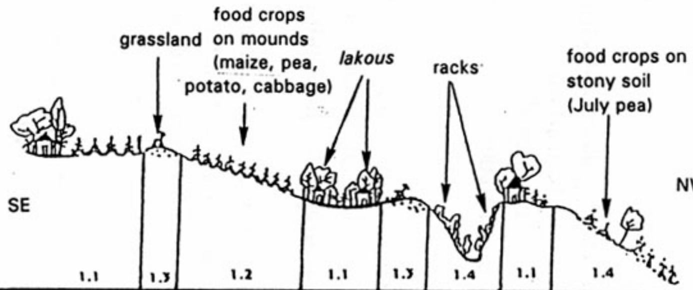
Haitian farmers are aware of the environmental rôle of wooded spaces (better infiltration of rainwater, biomass production, reduction in the effects of rainsplash and in mass movement). However, outside factors (pressure on land and low incomes that tend to favour the sale of charcoal) and other implicit farming constraints often make it hard for them to preserve this heritage.

Moreover, the traditional tethered system of animal husbandry precludes planted trees. The role of livestock in savings and in income-producing gives animals priority over trees. Growing trees or shrubs requires a major change in methods of animal husbandry.

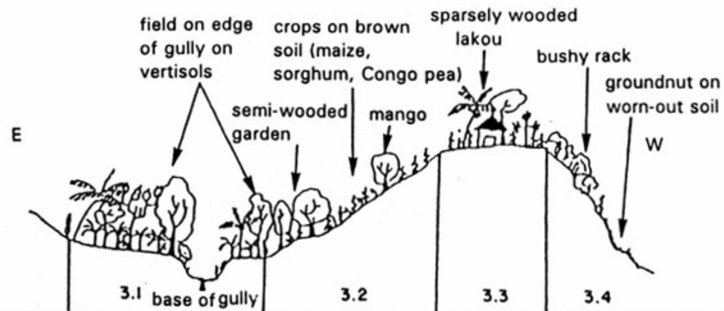
All these traditional erosion control techniques confirm that Haitian farmers are the shapers of the agrarian landscape. However, despite their remarkable adaptability, the whole approach to production and the dynamics of

FIGURE 82

Types of erosion control and main actions in the agro-environmental sub-units of the transect



General limiting factors	Intervention (watershed level)	Intervention (plot level): sun-units	limiting factors due to physical environment	intervention
• isolated area/no market/no vehicle roads • heavy runoff on rendzina, track and path • no watering point for household, seed-bed and livestock requirements	• concrete feeder road • recovery of runoff water (track, sloping ground, paths) • water storage in individual and collective cisterns	1.1	• soil degradation through mineralization of organic matter • low chemical fertility • violent winds	• development of fodder and fruit crops • mineral fertilization on cabbages • enclosure/windbreaks
• little diversification and intensification of crops • few inputs, no access to credit • considerable wandering of livestock because of scant fodder potential • often violent winds	• extension of market-garden techniques • people's savings and credit bank and input shop • hedges	1.2 1.3	• steeper slopes • sheet or mechanical erosion • selective erosion leading to scouring • compaction leading to heavier runoff • reduction in organic matter • violent winds	• enclosure/windbreaks • contour plant buffer strips to form gradual terraces • staggered roforestation _ forage grass • development of market-garden crops: use of stored water, mineral fertilizer and powdered corral dung • semi-stabled livestock raising
• many landless peasant farmers	• construction sites provide work for the neediest	1.4	• very degraded soil • very steep slopes • significant runoff, and groove and rill erosion	• no-grazing area: reforestation with staggered trees and dorage grass • sills and cisterns in fully bottoms for intensification



General limiting factors	Intervention (watershed level)	Intervention at plot level: sub-units	limiting factors in terms of the physical environment	intervention
• little plant diversitification • tree production limited by small number of commercially viable varieties	• grafting young and mature mango trees • introduction of new varieties of mango and avocado to satisfy the export market	3.1	• undermining of banks or minor shifts in bottom lands	no action in gullies or bottom lands
• very meagre fodder potential, frequent scarcity • animals left to wander • isolated area: no vehicle roads	cf. plot interventions • concrete feeder road (planned) with recovery of runoff water	3.2 3.3 3.4	• poor to zero infiltration and poor to very poor reserve • heavy runoff, leading to scouring, then formation of rills or grooves • heavy tillage causes dry mechanical erosion • no plant cover	• contour plant buffer strips, using fodder species, and grass strips combined with fruit or forest species, and introduction of a straw mulch: formation of gradual terraces and agroforestry • plots fenced off to prevent livestock from wandering at will

• seriously isolated • many springs barely working • fruit-tree potential insufficiently exploited	• laying out concrete feeder road • springs • grafting of fruit trees to satisfy the export market	2	no intervention carried out on individual plots	
• track barely passable • access to household water very laborious • little fodder potential	• track upkeep • drilling wells	4	• poor infiltration, leading to copious runoff, hence heavy gullying • no plant cover	• tillage trials on gentle slopes • treatment of gullies by building dams made from filled sacks, reinforced with plant hedges, followed by a garden: cassava, banana, tobacco • introduction of legumes

rural Haitian society admittedly lead to breaking points which could compromise the sustainability of certain systems. The main causes include the following:

- a very restrictive agrarian space, exposed to all types of erosion;

- land tenure problems that hamper co-ordinated control structures on a plot or slope and also encourage erosion;

- abrupt changes in techniques as a result of economic breakdowns (the coffee market) forcing farmers to introduce new crops or at least grow them on a new, more intensive scale, and so hasten the process of degradation (clearing and weeded crops);

- intensification prevents renewal of stock of organic matter and replacement is insufficient; tillage also accelerates sliding of the soil cover, so that in a few years (six to eight) "mixed" land can turn into "worn-out" land.

Conclusions. The farmers' traditional techniques for managing water and soil fertility – and also their tillage techniques – must be reinforced, in order to improve management of surface water, increase organic (then mineral) inputs, and improve plant cover by encouraging the use of enclosures.

Control measures [Plates 20 and 21]

In recent years, the Salagnac project has implemented a number of important activities (a marketing network, a store of inputs managed by a farmers' association, a people's savings and credit bank, individual and communal cisterns). The situation was ripe for an environmental management investment project (PRATIC) based on this approach.

So far as intensification of plant production is concerned, there are three spheres that now offer a promising future for the densely populated mountainous areas:

- the market garden and food crop combination: market-garden crops are the top rotation crops and pay for the applications of mineral fertilizer that often allow a doubling of foodcrop yields;

- fruit tree farming: a sizeable and growing market in the United States;

- dairy farming.

The solutions envisaged addressed production and farm issues at the watershed and individual plot levels alike. Technical proposals were tested for each of the agro-environmental units (Figure 82) for:

- management of surface water;
- management of fertility and biomass;
- management of livestock;
- development of agroforestry;
- support activities to backstop these proposals.

SUGGESTIONS FOR IMPROVED MANAGEMENT OF SURFACE WATER

Harvesting runoff: diverting potentially dangerous water and putting it to good use

Such water is harvested especially in Units 1 and 2, allowing:

- **protection of areas with good agricultural potential** (A and B gardens, soils with good potential) against runoff; 3 km of paved track (US$12/m) have been built downhill of land with strong runoff (rendzinas) and uphill of ferralitic soils, allowing recovery of this water; the feeder road serves as a water harvesting area, and is protected by low walls and reinforced by channels acting as outlets into torrential gullies;

- **increased availability of water**, completely absent in Unit 1, for domestic needs, supplementary irrigation for establishing individual small pre-season market gardening nurseries, and watering semi-penned livestock; farm labour also becomes more plentiful by releasing household members from the time-consuming task of fetching water (2 to 3 hrs/day).

Collective cisterns in the fields (50 to 150 m^3) store water from tracks, paths or eroded slopes, as do individual tanks (8 to 12 m^3) from the roofs of houses. About 20 field cisterns (US$40/$m^3$) and 550 individual tanks (US$35/$m^3$) have been built.

Stone sills (Unit 1) have also been built to help trap sediment load and water in small gullies, with a view to creating islands of fertility, quickly capitalized on by farmers.

All these infrastructures have also allowed:

- **access to previously hard-to-reach areas**: the feeder road facilitates transport of farm produce to markets and will eventually reduce the use of pack animals to carry the produce; this would allow a partial reduction in overgrazing;

- **an immediate and visible improvement in income by creating employment** for the most poverty-stricken (wages for work on structures considered “communal”: track, cisterns, low protection walls, and sills).

The choice of structures and their location was made after a study of each sub-basin, and with the participation of the farmers. The study defined areas with heavy runoff, areas with good agricultural potential to be protected, locations for structures to divert excess water into torrential gullies, and the route to be taken by the track. The planning sometimes incorporated elements of production systems – building cisterns near areas where market gardening is well-developed.

Maximum infiltration and dispersion of runoff energy

Several techniques allowing better infiltration – **farming techniques such as mulching** and **hedge-planting**, i.e., contour planting of permanent vegetation – have been used on many farm plots, mostly in Units 1 and 3. All these act as buffer strips, halting sediment transport during tillage (mass movement caused by tilling from top to bottom of the slope) or heavy rain (sheet erosion), and should therefore lead in the medium term to the development of **gradual terraces**. This process requires simple but specific and regular upkeep. It makes use of the traditional techniques of wattle and hedged enclosures, and allows runoff to be slowed when the hedge is reinforced with its own residue (woody offcuts when gathering forage or firewood, or when pruning) and harvest residues (twigs, branches and straw) which are laid against this permanent vegetation. However, vegetation must be reinforced in fragile zones, and new filters of plant residue added when the old ones are destroyed or covered with soil, to prevent breaches.

Planting hedges is one of the techniques most widely extended by the project. It is clearly more beneficial on basaltic soil (Unit 3), for the material weathers very fast, and there are excellent possibilities of restoring soil fertility on degraded soils.

The potential is slight for calcareous soil (Unit 1), and the technique is attractive only for plots that still have good potential.

Few live hedges have been planted in Unit 2 areas, which still have good tree cover and were not considered a priority.

On the Aquin plain (Unit 4), hedging techniques have been used to treat gully bottoms. Weirs made of vegetation are built on alluvial deposits (deeper soil, rich in organic matter and with good moisture content) carried down by torrential, rain-caused erosion and trapped by small sills made of sacks of soil. This technique allows cultivation of such financially viable crops as banana, pineapple and coconut.

Suggestions for improved management of soil fertility and biomass

If the productivity of land and labour is to be increased, a vital first step is improved management of water, but also of nutrients and organic matter.

The nutrient turnover cycle should therefore be improved by reconsidering the use of the available biomass, which should be considerably boosted by material from the newly planted hedges.

The project began to extend the **practice of surface mulching** with a mixture of *Leucaena* or *Gliricidia sepium* residues and maize or sorghum stubble on the sloping ground of Units 1 and 3. This cover will probably be able to solve 80% of runoff and erosion problems on basaltic soil, and will considerably improve the balance of organic matter in calcareous soil, which is often very deficient. The technique has already been very successful on market-garden plots spread with mineral and organic fertilizer in the form of spot applications of powdered corral dung. The straw-dung combination produces “real manure,” which is more effective in fixing the nitrogen in excreta.

Suggestions for improved management of livestock

Animals – apart from cattle – are a form of savings that gives a quick return. However, there are considerable difficulties involved in their management in Haiti:

- left free, livestock prevent or destroy any biological control measure;
- tethered animals compact the soil, overgraze it and foster runoff.

TABLE 42

Selection of species on the basis of agro-environmental factors and types of structure

sub-units	vegetation fences		contour hedges			planting in rows or scattered
	formed of trees	formed of bushes	formed of trees	formed of bushes	leafy vegetation	
1.1	. *Grevillea robusta* . *Cedrela odorata* (cedar) . *Morus alba* (mulberry)	. *Hibiscus rosasinensis* (Chinese/Tropical hibiscus) . *Erythrina indica* (pine nut) . *Comocladia domingensis* (*pagnol* wood)	. *Citrus maxima* (chadequier) . *Citrus sinensis* (orange) . *Cedrela odorata*	. *Leucaena diversifolia* . *Gliricidia sepium* . *Hibiscus rosasinensis*	. *Panicum maximum* (Guinea grass) . *Pennisetum purpureum* (elephant grass)	nil
1.2	. *Grevillea robusta* . *Pinus occidentalis* (pine wood) . *Ocotea leucoxylon* (sand laurel)	. *Erythrina indica* . *Giliberta arboreca* (negress wood) . *Comocladia domingenis* . *Bursera simaruba* (gum tree)	idem 1.1 + . *Grevillea robusta*	. *Leucaena diversifolia* . *Hibiscus rosasinensis*	. *Pennisetum purpureum* . *Tripsacum laxum* (Guatemala grass)	nil
1.3	. *Pinus occidentalis* . *Casuarina equis.* (filao)	idem 1.2 + *Leucaena diversifolia*	. *Pinus occidentalis* . *Casuarina equiset.* (horsetail tree)	idem 1.2	. *Pennisetum purpureum*	. *Pinus occident.* . *Casuarina equis.*
1.4	idem 1.3	idem 1.3	. *Persea americana* (avocado)	nil	nil	idem 1.3
2	NO INTERVENTION					
3.1	nil					. *Persea americana* . *Manguifera ind.*
3.2	. *Swietenia mahogany* (cashew) . *Macrocatalpa longissma* (oak) . *Lisyloma latisiliqua* (tavernon) . *Pithecellobium saman*	. *Gliricidia sepium* . *Leucaena leucocephala* . *Jatropha curcas* (oil tree)	. *Persea americana* . *Manguifera indica* . *Citrus aurantifolia* (lime) . *Annonna reticulata* (cherimoya/custard-apple/sweetsop)	. *Gliricidia sepium* . *Hibiscus rosasinensis*	. *Pennisetum purpureum*	nil
3.3 et 3.4	. *Haematoxylon campechianum* (logwood) . *Lisyloma latisilique*	. *Jatropha curcas* . *Gliricidia sepium*	. *Anacardium occidentalis* . *Citrus aurantif* . *Annona reticulata*	. *Gliricidia sepium* . *Leucaena leucocephalla*	nil	nil
4	**Stabilization of gullies⟶**		. *Annona reticulata* . *Manguifera indica* . *Tamarindus indica*	nil	. *Musa* sp. . *Pennisetum purpureum* . Ananas	nil

However, the direction of the Salagnac/Aquin project, which is concerned with dairy production, has been towards semi-stabling, with livestock being kept in stables during the night, then being either tethered during the day or led to watering sites. This livestock management method could be developed thanks to increased fodder production (hedges), an increased number of watering points (tanks), but also more fencing to prevent animals from straying.

The importance of agroforestry in the suggested techniques

Agroforestry techniques developed under the project meet a variety of needs:

- improving infiltration by slowing flow rate;
- increasing production of biomass (about 3 to 5 t/ha/yr where the distance between risers is about 10 m) to improve fertility organically, spreading the residues from shrub legume cuttings on the ground; this biomass will restore nutrients quickly but steadily, and is also useful for feeding livestock (cut grass and legumes), firewood and, in the longer term, fruit and timber production;
- reducing erosion problems in synergy with the above measures and halting various processes of sediment transport;
- improving protection from wind and straying animals.

The main aim is not to reforest all the degraded areas but rather to:

- **cover 40 to 60% slopes by replanting trees in well-spaced stands** on very degraded land, and in more scattered formation on cultivated plots, in order to check the movement of the soil cover; fruit species have been planted (150/ha) on Units 1, 2 (calcareous-marly) and on Unit 3 in 0.5 m^3 pits with a good dose of organic matter;
- **partition the countryside with multipurpose risers** and surrounding plots with wind-break hedges of forest or fodder species, while promoting the development of gradual terraces; planting hedges to protect against straying livestock, to act as wind-breaks, and to stabilize the risers (along the route of a road or path), and also to mark off property and encourage intensification (market-garden crops, fruit trees); large cuttings are used to form partitions which are then reinforced with forest trees.

Various species have been used (Table 42) for such partitions, chosen on the basis of production factors (tenure, distance, arable land), farmers' needs (fodder, wood, fruit, etc.), but also the physical potential of the plot, according to the sub-units described above. These species are carefully distributed over the area in question:

- forage grass on the risers as they are built to hold them in place and act as a second filter;
- hedges of legumes grown as bushes (2 to 3 prunings a year) on the upper side of the risers every 25 cm;

- forest or fruit trees below the risers (or above, if the soil is very moist), 5 to 8 metres apart depending on the space between risers.

SUPPORT MEASURES

These indispensable measures encompass:

- **Introduction of more profitable crops –** market-garden production. This diversification of crops in Units 1 and 2 is the "transmission belt" between control measures, increased soil fertility and increased productivity and production with the corollary of increased income. The constant expansion in cash crops means that the farmers now hope to protect and therefore better manage their land. Development measures require various kinds of support measures – as for cabbage-growing. Cabbage requires a significant investment by the farmer (seed, fertilizer, organic matter, water, treatment products), and although cabbage is often planted in C or D gardens, the farmers would now like to improve these gardens by adding wind-breaks and fences, and planting grass to benefit from fertilizer inputs and existing tanks and fruit trees, thus ensuring protection and a better return on their investment. For the first time, fertility is being transferred *to* C and D gardens.

- **Measures concerning livestock.** The emphasis today is on increasing milk production, which entails action to improve nutrition, management, and genetic factors.

- **Diversification of fruit production.** A number of double-grafting programmes (grafting on adult trees over 5 years old) have been implemented right across the whole transect in order to introduce improved varieties (oranges, mandarins and grapefruit for the American market) or off-season varieties (mangos, avocados) for the national market.

- **Better land tenure.** The proposed control measures represent a significant outlay in labour and sometimes money. When farmers have good land tenure security, they are much more interested in improvements that do not offer an immediate return. Otherwise the real owner may very well want to recover a plot that has been rented out or share-cropped, or perhaps increase the rent. Most control measures have been confined to owner-operated plots – which restricts interventions aimed at a whole hillslope or sub-watershed.

  Similarly, the introduction of intensification techniques (the use of mineral and organic fertilizers) will be difficult if the plot is share-cropped or in short-term tenancy, even if returns may be immediate, for such an investment can work to the advantage of the owner, who can then take back his/her land the next year. It has been seen that the most degraded plots are those where land tenure security is weakest, and that fertility is constantly being transferred from these plots to others.

  Trials of long-term leases (8 to 10 years) were started when the contract between the project, the owner and the tenant was signed (the situation is more complicated for share-croppers), thereby giving greater tenure security and entitling the tenant to benefit from what his/her investments produce.

- **On-site trials.** These are very important, and must serve as demonstrations. They have consisted in:

- introduction of the technique of tied ridging to replace potato mounds on steeply sloping ferralitic soil (sub-units 12); this trial could not be continued;

- trials on different horizontal biological structures with different plant materials (*Gliricidia sepium*, *Calliandra*);

- more exacting studies on the relation between erosion risks and runoff under different cropping systems, and on the effect of contour hedges and hedge management on total water, fertility, erosion, and biomass production; political events prevented the implementation of these trials.

[1] These activities were abruptly broken off following the suspension of aid after the September 1992 coup.

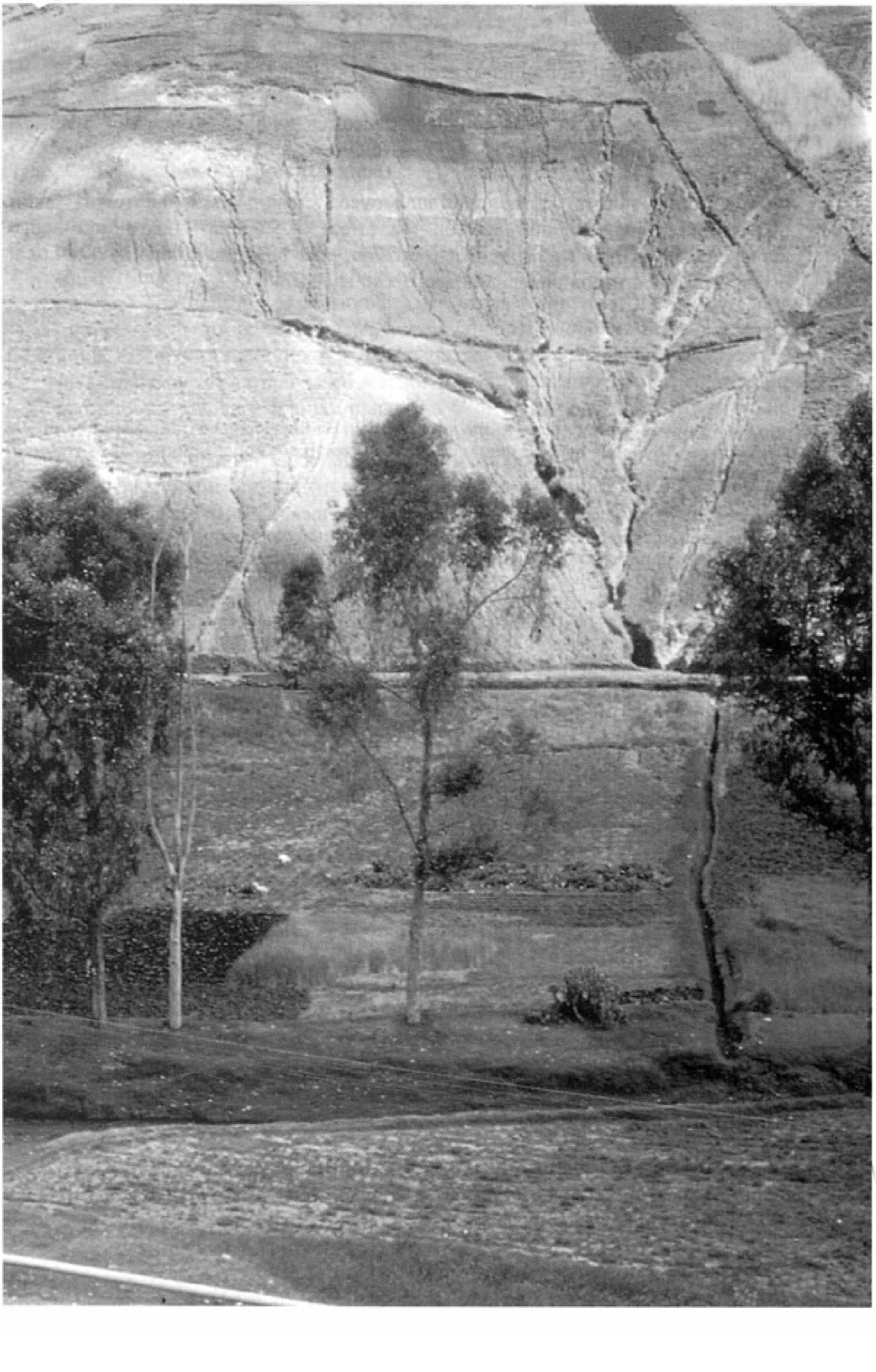
[2] Usually, when a farming couple dies, the *pré-kaye* garden will be kept and divided into a number of A-type gardens, or destroyed (trees felled, crops divided) and abandoned. Since the number of heirs makes it impossible to share out the inheritance equitably, the land becomes jointly owned.

CONCLUSIONS

There have been many projects to develop the rural sector in Haiti which have often disrupted the physical environment by implementing poorly integrated erosion control structures which were, moreover, seldom properly maintained.

Land husbandry offers new hope in terms of interventions in the rural sector. Its methods show that there is no contradiction between development of agricultural production (intensification and diversification of plant and animal production) and protection and conservation of the environment (fertility, soil and water) which is the true basis of such production. This strategy must be identified with the human landscape. Its success depends on understanding how farming systems operate, and on knowing the physical environment and more particularly the potential of the soil.

Erosion problems vary enormously because of the great variety in physical, social and economic contexts. However, peasant farmers continue to use management techniques that cause the least imbalance in the environment. It is vital that these be taken as a starting point and improved, if integrated solutions are to be found. This approach will ensure that the farmers adopt and maintain the various measures and structures, intensifying production and protecting the environment.



Chapter 13

Agricultural erosion in the Ecuadorian Andes

A NATURAL AND HISTORICAL PHENOMENON

THE SITUATION

Although Ecuador is a small country (270 000 km^2) in terms of the South-American continent, it contains a remarkable mosaic of landscapes. This variety, which encompasses the juxtaposition of cold, temperate and hot ecosystems within a short space, is a result of the huge mountain barrier of the Andes, locally called the *Sierra*. This range, running from north to south through the centre of the country, is bordered on the west by the Pacific coast and on the east by the Amazonian foothills. Wedged between two low plains, the Sierra is hence a classic mountain environment with striking variations in altitude.

Human activity, traditionally agricultural, has had to adapt to this high mountain environment. Early on, during the two thousand years preceding the Spanish conquest, the Sierra was the centre of a flourishing agriculture, for the population, which never exceeded 200 000, was able to develop an approach that was in harmony with the environment. These long-ago societies spontaneously practised crop diversification and land use involving different ecological zones, and developed an irrigation system with channels following the contour of a tight network of terraces. Over the centuries, the troubled history of the Spanish conquest and more recently the social effects of population pressure have forced an imbalance in the relationship between human beings and environment. At present the agricultural frontier is expanding upwards and is coming up against the constraints imposed by mountains (those of climate and slope). This is the context that has seen the development of the *minifundio* area – which, in the very difficult conditions of foodcrop plots of less than 1 hectare, is now facing acute erosion problems.

SOIL EROSION: DIAGNOSIS AND SOURCE

A NATURAL PHENOMENON: A MOUNTAIN ENVIRONMENT

The Sierra is an enormous mountain barrier, 100 to 120 kilometres wide, made up of two parallel ranges (the *Cordilleras*) with a depression between them formed by a succession of fault basins. The main landforms are as follows:

TABLE 43
Agrarian structure in Ecuador 1954-1985: number of holdings and area occupied (expressed as percentages)

Size in ha	1954		1974		1985	
	Number	Area	Number	Area	Number	Area
0-20	90	17	85	19	83	20
20-100	8	18	12	34	15	44
> 100	2	64	2	48	1	35

- **In the intra-Andean zone** there are two distinct tiers within watersheds. Below 2 400 m the terrain is relatively flat (0 to 20% slope) with scattered shrubby xerophytic plant cover. The people live in small villages and grow irrigated crops: sugar cane, fruit trees and vegetables. Evidence of erosion can be seen everywhere – not only in the irrigated areas where there is insufficient control over water, but also in the areas poorly protected by the shrubby plant cover. However, most of the Sierra landscapes lie on the second tier between 2 400 and 3 200 m, which has the following features:
    - a tight network of ravines and *cañones* – evidence of active headward erosion -where slopes are over 70%; there is very little agriculture, and only shallow soils;
    - flat runon areas (less than 10% slope) where the large cattle ranches (*haciendas*) are found; the landforms between these areas and the ravines are much less regular (25 to 50% slopes), with a pronounced shrinking of small maize plots in the face of long-standing and very active erosion;
    - either pediment-terraces or débris cones, rising up to the mountainous zone; on slopes of less than 25% animal husbandry flourishes on large- or medium-sized farms (*haciendas* with hundreds of hectares, or *fincas* with tens of hectares); higher up, between 3 000 and 3 200 m, are the first escarpments, where the first wave of *minifundios* has been established, a development that has led to increased erosion.
- **On the ranges or *cordilleras***, the Andean highlands start at 3 200 m (De Noni and Viennot 1985), and it is here that *minifundios* have spread extensively in the last ten years. Potato, onion, broad bean, barley, quinoa, lupin, etc. are grown as high as 3 800 m, where extensive sheep and goat-rearing takes over – and sometimes llamas, which can go as high as 4 400 m. The ever-increasing inroads of agriculture in this environment is reflected in active degradation.
- **Lastly, on the outer slopes**, gradients are even steeper (over 70%). Erosion is localized and depends on soil instability, which increases as the natural vegetation and pastures are steadily replaced by tropical crops.

The Andes thus constitute an environment very prone to erosion (through the action of rain and humans), since there is a relationship between slope, speed of flow, volume of runoff and intensity of erosion.

AN HISTORICAL PHENOMENON: *MINIFUNDIOS* AND *HACIENDAS*

The Sierra is the region of the country with the greatest population pressure on land. As a general rule, heavy population densities, varying from 50 to over 200 per km^2 (Ambato region) (Delaunay 1989), characterize the *minifundios*. The distribution of farm units (number and area), based on Ministry of Agriculture censuses, is given in Table 43.

For all years, *minifundios* (0 to 20 ha) account for more than 80% of the farm units, but occupy only 20% of the arable land and are located mostly in places where it is hard to get a good return. The good flat land in the watershed is managed by the *haciendas* for extensive cattle ranching. This paradoxical situation is the outcome of an historical process with three key phases (De Noni 1986):

- the historical consequences of the Spanish conquest were dramatic, leading to a general decline in population (through war, disease, etc.); in practice, the indigenous people were treated as slave labour and were herded together on to huge estates, which then quickly developed into the large farms better known as *haciendas*;

- since the beginning of this century, Ecuador has seen a remarkable expansion in population, particularly in the rural sector; in 1586, the population of the whole country was about 150 000; between 1780 and 1886, it doubled from 500 000 to 1 000 000; and between 1886 (Estrada 1977) and 1989 it increased tenfold, reaching 10 500 000;

- in the face of the widespread discontent of a rapidly growing population, on 11 July 1964 the military government then in power passed an agrarian reform law with the aim of abolishing the virtual condition of servitude (*huasipungo*) to which the numerous labourers on the *haciendas* had been reduced since the conquest; the large landholders were to surrender their privileges and give up a part of their land; this is how the *minifundio* agrarian system developed, with the units being run by small peasant farmers who were now free landowners; in reality, however, the *haciendas* kept the best land for themselves, yielding only inhospitable land to the agrarian reform.

HAZARDS: THE IMPACT OF EROSION ON THE AGRICULTURAL ENVIRONMENT

The combination of a mountainous landscape and heavy population pressure on the land is the cause of the chronic erosion found in the Andes. Along the whole length of the Andean depression, the frontiers of colonization have been pushed further and further back in the space of a few years, with a proportionate increase in the forms of erosion and in the amount of abandoned land.

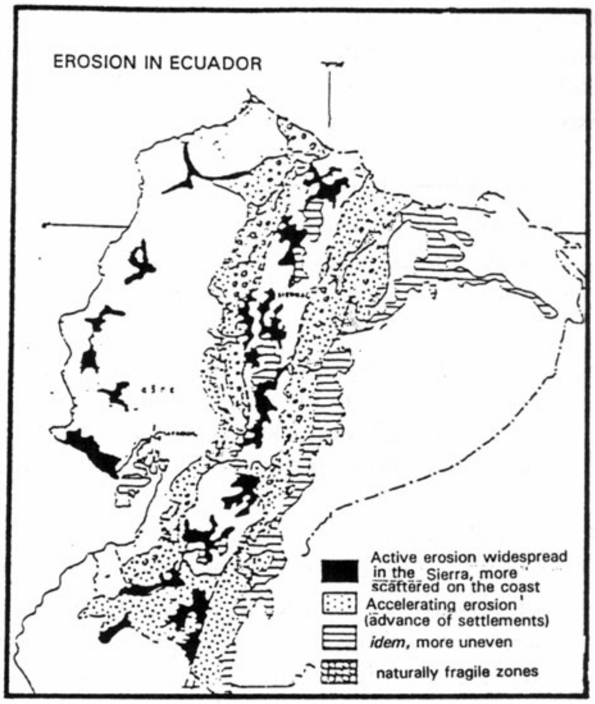
EXTENT OF AGRICULTURAL EROSION

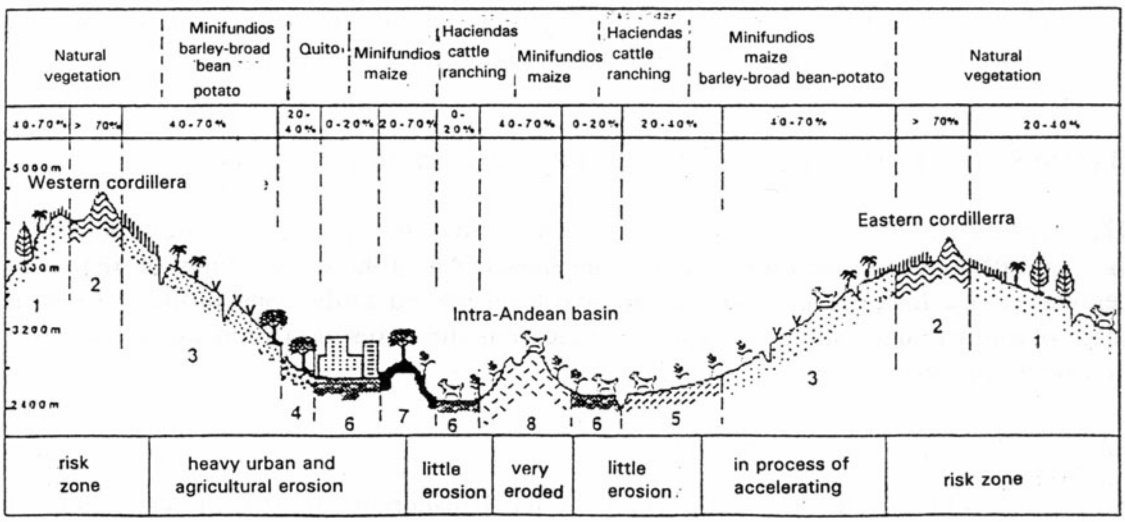
According to the results of a joint survey by the Ecuadorian Ministry of Agriculture and Animal Husbandry and ORSTOM on the main processes of erosion in Ecuador (Almeida, De Noni *et al.* 1984, De Noni and Viennot 1987), 50% of the country’s area (70% of it in the Andes, and 30% in the coastal and Amazonian regions) is affected by processes of degradation. In the Andes, the most degraded region, there are two distinct zones:

- the intra-Andean basin (1 500 to 3 000 m) where very little arable soil is left; in the northern and central sections of the basin there is a formation of hardened volcanic ash, locally called *cangahua*, remarkable for its extent and its depth, and sterile for agricultural use; this formation appears when soil and volcanic ash have been scoured by erosion;

FIGURE 83
Soil erosion and conservation in Ecuador (DNA-ORSTOM project)

ECUADOR:
- 270 000 km² > 10.10^6 inh.
- 3 NATURAL REGIONS
1. Coast
2. Sierra
3. Amazonia





MAIN UNITS IN TERMS OF LANDFORMS AND SOIL

Landforms	Caldera, neck	Gullied slopes, cones 1 3 4	Pediment-terrace 5	Horst, graben 6 7	Extinct volcano 8
Soils	cryandept orthent	dystrandept hydrandept	arguistoll hapludoll	haplustoll/ *cangahua*	*cangahua* durustoll
OM %	9 to 12	6 to 15	5	3 to 4	< 1
pH	5.5	5 to 6	> 7	> 7	7 to 8.5
CEC meq/100 g	2 to 10	15 to 40	20 to 80	20 to 50	20 to 30
T/S %	10 to 80	2 to 50	80 to 100	100	100
Granulometry	SL	L	AL	AL	LSA
Remarks	coarse elements	H% 50 to 250%	smectite		hardened CO_3Ca

TABLE 44
Soil loss on 50 m² plots (1981-84 and 1982)

Year	ALANGASI		ILALO	
	Mollisols and *cangahua*		Mollisols and *cangahua*	*Cangahua*
	Various treatments (maize, pasture) t/ha	Degraded pasture t/ha	Maize t/ha	Fallow t/ha
1981-84	62	314	631	71
1982	58	204	421	58

- the highlands and outer slopes of the two ranges (3 200 to 4 000 m) where active erosion develops as the agricultural frontier advances – as it has continuously over the last twenty years. Although soil cover is still present throughout these regions, it is showing alarming signs of degradation in some places.

PREDOMINANCE OF WATER EROSION

During the nine-month Sierra cropping cycle from September to May, water erosion is very active (wind erosion is not considered here, since it is more localized and has little effect on crops), mainly in the following forms (De Noni and Trujillo 1989):

- diffuse and concentrated runoff is the most widespread form, whatever the geological origin of the soil – pyroclastic formations in the northern and a large part of the central Sierra, and volcanic-sedimentary material in Loja province in the south; land affected by this process has shallow soil with truncated horizons, and is scored by erosion in U or V shapes according to how cohesive and granular the soil is; these linear forms quickly develop into badlands;

- runoff combined with small mass movements (15 to 20% slopes), a process seen in soils with a discontinuous texture, where a clayey soil of volcanic origin, rich in montmorillonite, lies over a hard *cangahua*-type formation; the processes work together, shaping the soil surface into eroded precipices as high as 3 or 5 metres; this happens in the northern and central parts of the Sierra (Carchi, Pichincha and Chimborazo provinces);

- mass movement is confined to the Cumbe area, south of the Cuenca basin, where the whole landscape has a moutonné appearance; erosion takes the form of creep, with humps and hollows developing in hilly landscapes with clayey non-volcanic soil.

HIGHLY ACTIVE RUNOFF PROCESSES

Other studies by the DNA-ORSTOM project on 50 m^2 cultivated runoff plots (10 x 5 m) also show the extent of runoff caused by human activity. Table 44 groups together soil loss for the period 1981-1984, as recorded on two plots in the Quito basin – at Alangasi on a 28% slope and at Ilalo on a 33% slope (De Noni, Nouvelot and Trujillo 1984 and 1986). The year 1982, during which most of the erosion occurred, is shown in a separate column.

TABLE 45
Annual soil loss and rainfall on 100 m ^{2} plots

		Year 86-87			Year 87-88		
		Total annual rainfall mm	Control plot with crop	Bare tilled fallow	Total annual rainfall mm	Control plot with crop	Bare tilled fallow
TUMBACO	Erosion t/ha/yr Runoff coeff. %	478	3.02 3.7	12.9 6.6	457	42.18 4.4	82.82 15.5
CANGAHUA	Erosion t/ha/yr Runoff coeff. %	366	3.8 1.6	56 5.9	308	6.89 1.9	83.6 11.1
MOJANDA	Erosion t/ha/yr Runoff coeff. %	588	1.15 0.9	5.9 2	547	0.52 1	96.94 8.4
RIOBAMBA	Erosion t/ha/yr Runoff coeff. %	537	1.44 0.9	56.9 23.3	532	52.2 15.5	198.7 21.3

TABLE 46
Development of agricultural production in the Sierra 1970-85 (in tonnes)

CROPS	1970	1975	1980	1985
Barley	79 087	62 801	24 350	26 723
Maize	167 990	90 247	45 266	35 421
Wheat	8 1000	64 647	31 113	18 464
Potato	541 794	499 371	323 222	423 186

Since 1986 the project has expanded its scope, establishing larger runoff plots (20 x 5 m = 100 m^2) located throughout an area stretching 800 km along the Sierra, from Pichincha province in the north, to Loja province in the south. There are two types of plot: a bare, tilled plot, in accordance with Wischmeier's prescription (Wischmeier and Smith 1978, Roose 1968) and a control plot using local crops and practices. The bare Wischmeier plot is not only a fundamental scientific reference plot, but in the present case also reflects the real features of the farm year – fallow poor in leafy vegetation and soil bare at the time of sowing barley. For the period 1986-88, the results are given in Table 45.

The following are the main lessons to be drawn from the results:

- Events of spectacular erosion on cultivated soil: for example, on the 50 m^2 plots monocropped with maize, erosion exceeded 600 t/ha.

- Irregular erosion from one year to another: at Alangasi and Ilalo soil losses in 1981, 1983 and 1984 were low compared with 1982, when most of the erosion occurred. The results also vary considerably from one year to another on the individual station; for example, in 1987-88 16 times more soil loss than in 1986-87 was recorded at Mojanda, and 7 times more at Tumbaco on the Wischmeier plots, and 32 times more at Tumbaco on the control plot.

- The absence of a regular erosion season during the year (most of the erosion is the result of the five most erosive rainstorms, out of a total of some forty erosive rainstorms per year per station): the amounts of rain in the individual rainfalls are not the only explanation of soil losses. In calculating correlation coefficients for the years 1986-87 and 1987-88, it appears that the best correlations with the weight of eroded soil are recorded with IM15 or IM30, although the maximum intensities in the Sierra are only low to average: 15 to 45 mm/h. The “R” values on the erosivity index are therefore only moderate, rarely exceeding 100: 60 at Cangahua, 90 at Tumbaco, and 100 to 110 at Mojanda and Riobamba. However, all these figures are also subject to annual variations, and can be considerably higher and extremely erosive. On the Ilalo plot (50 m^2), erosion was over 400 t/ha/yr in 1982; an IM15 of 90 mm/h was responsible for 270 t/ha/day of lost soil, and another of 70 mm/h for 120 t/ha/day.

ABSENCE OF CONSERVATION METHODS AND FOOD DEFICIT

The history of land use clearly brings out two distinct types of farmer: rich landowners on the *haciendas*, and marginalized peasant farmers on the *minifundios*. The latter are forced by sheer necessity to produce more in order to survive: driven into a marginal environment, they have been obliged to push the environment beyond its limits, with the result that all along the Sierra today there is a striking absence of erosion control practices suited to the environment (De Noni, Viennot and Trujillo 1986). For example, on the densely cultivated highlands of Chimborazo and Cotopaxi provinces, there are some perfunctory soil conservation structures consisting of hedges and small ditches. The latter are very shallow (20 to 40 cm) and steeply sloping (20 to 25%) in comparison with a conventional ditch, so that they cannot channel excessive water, and rapidly become gullies. Similarly, hedges, usually composed of *sigses* (*Gybernium*), are placed randomly in relation to the main slope. Moreover, these structures, set on the edges of plots, are only rarely combined with contour tilling.

There is also systematic destruction or abandonment of early agricultural structures inherited from pre-Columbian societies. These remains (Gondard 1983), mostly bench terraces, are made with risers built of stone or blocks of hardened ash. At Pimampiro in Imbabura province, the risers are deliberately knocked down to make room for large plots mechanically tilled in the direction of the slope. Similarly, near Zhud in Cañar province in a recently settled area with medium-sized holdings, wide concave terraces dating from the Cañari civilization are appearing from beneath the shrubby vegetation (*chaparral*) during clearing. At Punin and Flores, as well as Colta and Chunchi, all in Chimborazo province, at an altitude between 3 200 and 3 600 m, and on steep slopes (40 to 60%), there are real terraces separated by risers several metres high. Here again, the intermediate risers have been abandoned or destroyed, leaving only those that lie along property boundaries, so that they now border excessively wide and sloping “pseudo-terraces”, which are totally unsuited to local conditions.

Certainly in order to survive, but also in the hope of entering the market economy, the small farmers have oriented the *minifundios* toward the crops that provide the basic local foodstuffs – cereals (maize, wheat and barley) and tubers (potatoes). However, natural limitations have prevented the development of profitable farming, so that the situation of the *minifundios* is now very precarious: in some regions self-subsistence is barely assured, while surplus production is rare and depends on a year of exceptional yields. Ministry of Agriculture data on levels of farm production over the past 15 years clearly illustrate this crisis situation (Table 46).

TABLE 47
Conservation methods tested on improved 1 000 m² plots

Stations	Slope %	Crops		Conservation methods	SOil losses t/ha/yr		Annual runoff coefficient %	
		86-87	87-88		86-87	87-88	86-87	87-88
TUMBACO	20	maize	maize	grass strips with three forage species	1.08	0.42	1.5	0.8
CANGAHUA	20	maize	maize	*cangahua* walls	0.45	0.33	0.1	0.5
MOJANDA	40	barley/potato/beans		sod walls and large quinoa-covered ridges	0.38	0.19	0.3	0.1
RIOBAMBA	20	potato/beans/barley		grass strips with mixed cropping (barley, beans)	0.43	7.6	0.3	6.2

It can be seen that there was a huge and generalized fall in yields of all these crops between 1970 and 1980, particularly for maize and wheat, which form the traditional staple diet of the rural population.

SUGGESTED IMPROVEMENTS [Plate 22]

Given their physical isolation in the highlands, *minifundio* farmers mainly need more on-the-spot technical assistance. Various forms of State intervention need to be increased: the organization of practical training in mountain farming, instruction in the use of fertilizers, selected seed, and of course conservation techniques, etc. Relations between *minifundio* farmers, technicians and agricultural scientists must be increased without delay, while combining research and development activities.

The programme of international co-operation between the National Agricultural Directorate (DNA) of the Ecuadorian Ministry of Agriculture and ORSTOM was designed in this context. It is a relatively pioneering project for the country, and indeed for the whole Andean region (De Noni and Viennot 1987, 1989), which has set up research stations on the farmers' land which are jointly managed with the farmers themselves. The stations have large runoff plots of 1 000 m^2 (50 x 20 m) for study of the effects of erosion on land under crops when improved with some simple conservation structures. The stations were set up in 1986 at the same time as the previously mentioned 100 m^2 plots (see Table 46) in order to allow comparison of the effects of erosion under traditional farming methods (100 m^2 plots) and under improved methods (1 000 m^2 plots). While the plots were being laid out, a socio-agricultural field survey was carried out to determine the various farming systems used in the research area, with particular emphasis on identifying conservation methods. In the absence of traditional practices, it was decided to test the effectiveness of simple semi-pervious contour structures in combating runoff energy, with the structures gradually developing into pseudo-terraces (Roose 1971; 1986; 1987a, b). An effort was made to keep as close to farmers as possible, using materials commonly used in the region, generally to fence off plots. The three main types of structure were thus as follows: low walls made of clods of earth or blocks of hardened volcanic ash (*cangahua*), or, more simply, grass strips, either grazed or cropped (quinoa or lupin). The methods tested over the period 1986-88 gave the results seen in Table 47.

These data demonstrate that simple conservation systems within the reach of the local farming community – contour ridging combined with grass strips or low earth walls – can noticeably reduce erosion. On all the improved plots, whatever the station, earth loss is minimal and erosion tolerable – usually less than 8 t/ha/yr and often close to 1 t/ha/yr. Yields are also better; for example, at Mojanda the potato harvest was 4.3 t/ha on the control plot and 7.6 t/ha on the improved plot.

At Riobamba, for the period from 20 September to 12 November 1987 (the sowing date), three erosive downpours resulted in a soil loss of 33.8 t/ha on the traditional plot where seedbeds had been prepared, while erosion on the improved plot was only 1.1 t/ha for the same period and the same tillage. And at Tumbaco, rainfall on 19 October 1987 alone, in the middle of the fallow period and one month prior to sowing (on 18 November), caused a soil loss of 34 t/ha, while the improved plot lost only 140 kg over the same period.

Although encouraging, these preliminary data show that not all the problems have been overcome, and that before launching awareness and extension programmes it is essential to carry out observations under both experimental and on-site conditions. This remark is based on the example provided by the changing size and shape of the grass-clod walls on the Mojanda station. Initially they were about 30 cm high, made up of two layers of earth clods. Then, although erosion on the plot was insignificant (0.2 to 0.3 t/ha/yr), in the course of the cropping year the farmer moves considerable amounts of soil from the top to the bottom of the plot with the broad blade of his mattock (*asadon*). Digging or hoeing always starts at the foot of a wall, creating a hollow at the base, and the soil is then drawn towards the bottom of the plot until another wall comes in the way. These simultaneous processes of hollowing out in front of walls and filling up behind them meant that the walls had to be heightened several times, rising from 30 to 130 cm during the 20 months of observations, while the initially straight slope steadily developed into terraces. It is estimated that almost 40 tonnes of soil per 100 linear metres accumulates behind the walls in this way each year.

CONCLUSIONS

As one of the major mountain barriers in the world, the Andes constitute an environment that is naturally prone to erosion. Erosion has also been exacerbated in Ecuador over at least the past two decades by the impact of the *minifundio*, with a troubled history that has led to small farmers being sidelined onto inhospitable land. Thanks to work carried out jointly with the local small farmers, the DNA-ORSTOM project has blazed a new trail, carrying out trials that demonstrate that erosion control is not an impossible challenge, despite natural limitations and the weight of history. Using simple structures suited to local conditions and accepted by the local people, this approach should lead to conservation of soil fertility, guarantee better harvests, and effect an all-round improvement in farmers' living standards within a single generation.

Chapter 14

The Mediterranean Montane Region of Algeria

AGRICULTURAL INTENSIFICATION... WITHOUT DEGRADATION

THE SITUATION

Although the northern region of Algeria is by far the most productive, it is a very fragile area of young mountains, with soft rocks such as argillite, marl and schist alternating with hard rocks such as limestone and sandstone. The semi-arid Mediterranean climate brings fine, gentle, but saturating rain during the cool winter, and dangerous thundery rainstorms during the torrid summer months.

The soils (regesols, grey vertisols, brown calcareous soils, and red fersiallitic soils) often have a slaked surface, and are gravelly, poor in organic matter, and deficient in phosphorus and nitrogen.

Following various waves of colonization (Roman, Turkish and French) and recent population pressure (51 inhabitants per km^2 in the mountains), there are now frequent signs of overgrazing (six sheep per hectare) on completely bare mountains. Sheet and rill erosion, gullying and mass movement, displacement of wadi channels and degradation of riverbanks, destruction of roads and accelerated silting-up of reservoirs over the past 15 to 20 years are all signs of advanced and general degradation in this area.

In view of these serious erosion problems, between 1940 and 1970 foresters and rural engineering experts developed a strategy entailing capital investment in rural development (SPR), comprising:

- reforestation of high valleys and mountain tops;
- control of torrents and gullies;
- terracing of cultivated land: in 30 years Algerian terraces were built on more than 300 000 hectares (at a cost of between US$ 1 000 and 2 000/ha).

The main objective was a reduction in the siltation of dams, since suitable sites for reservoirs are limited.

However, by 1977 the failure of SPR in the rural environment was clear: the farmers rejected the terracing system which deprived them of 10 to 20% of their arable land and offered almost no improvement in soil productivity; wood production was still too low; and the siltation rate was still rising! Terracing projects were halted for economic reasons (the second oil crisis) (Heusch 1986). Forestry experts carried on with their work of reforestation and torrent control (RML), but apart from some land improvement projects (subsoiling on brown soil with calcareous crusts), little more was done to stabilize the land farmed by small farmers (Roose 1987a, b).

The first measurements of erosion on runoff plots (Kouidri, Arabi and Roose 1989) confirmed the view that sheet erosion on slopes accounted for only a minor part (0.2 to 1 t/ha/yr) of the sediment load in wadis (Heusch 1970, Demmak 1982). This may explain why the reduction in the siltation rate of reservoirs was still so high even when the slopes had been well reforested or terraced. The wadis are the focal point of the various phenomena, for gullying and wholesale crumbling of slopes sheared away by wandering wadis are the primary source of the sediment carried by rivers during the heaviest flood flows.

Nevertheless, sheet erosion from slopes can be very high – up to 80% of the heaviest rainstorms falling on slaking or sealing crusts or on soil compacted by overgrazing, roads, cattle trails, and fallows left as common grazing land. And it is this runoff from bare slopes that creates gullies, swells very dangerous peak flows, undermines riverbanks, and leads to heavy sedimentation in reservoirs.

In view of the present-day difficulties and slowing down of industry, the Algerian government is promoting a return to the land, with the intensification of mountain farming. However, it hopes that this can be done without hastening montane degradation and siltation of the reservoirs that are so indispensable for irrigation and the constantly expanding towns.

Before farmers can take an interest in maintaining their land and the quality of surface water, it would seem vital to address their immediate concerns – those of increasing their income and security while improving the management of water and nutrients on productive land. The first thing to be done is not to stabilize gullied land, but rather to analyse and improve production systems and the water and mineral balance of the best land. Restoring forests and treating gullied slopes is still the main concern of the forestry department.

This new approach has given rise since 1985 to a “land husbandry aid programme” concerned with research and training, and involving the participation of a dozen research scientists from INRF and ORSTOM. The programme covers three sub-programmes:

- two surveys of the effectiveness of SPR, first by the forestry department in order to discover the most effective interventions, and then by a multidisciplinary research team in order to make a scientific analysis of the reasons for successes and failures;
- the treatment of small catchment areas (20 to 300 ha) near Médéa, Mascara and Tlemcen;
- evaluation of the volume of runoff and erosion with the help of a rainfall simulator and a network of runoff plots and gullies.

Here only the main data from the INRF station at Ouzera (Arabi and Roose 1989) are reported, although similar data have been gathered near Tlemcen (Mazour 1992).

DIAGNOSIS: TRIAL CONDITIONS

Fifteen runoff plots (22.2 x 4.5 m) were prepared on farmers' fields around the Ouzera research station, 90 km south of Algiers.

The landscape consists of a series of calcareous uplands (900 to 1 200 m in altitude), with steep slopes (12 to 40%) and deep valleys where wadis flow intermittently.

Soil types depend on lithology and topographical position (Pouget 1974, Aubert 1987), and are as follows:

- pale yellow lithosols on grey calcareous colluvial deposits, rich in $CaCo_3$, but poor in organic matter;
- darkish grey vertisols on marl, well-structured, 2% organic matter, saturated with calcium, pH 7 to 8, very resistant to rainsplash, but prone to gullying and mass movement;
- red fersiallitic soils on soft limestone, poor in organic matter, fragile and lacking stability on the surface;
- brown calcareous soils on colluvial deposits, 2 to 3% organic matter, a shallow profile, but well-structured on the surface.

In this mountainous region (Blidéen Atlas), the forest cover decreased from 18 to 13% between 1982 and 1991, while vineyards and orchards increased from 2 to 7% and 8 to 14% respectively – a typical effect of population growth and the development of mountain farming. Tillage practices are confined to ploughing twice to control weeds, then a cover crop to dig in fertilizers (N33, P45, K90) and slightly reduce the size of clods.

The average annual rainfall over the past 40 years is 680 mm at Médéa, although between 1986 and 1990, rainfall at Ouzera station (7 km away) varied between 408 and 566 mm, and the rainfall aggressivity factor (Wischmeier's R_{USA}) was about 46.

The aim of these trials was to compare potential runoff and erosion risks on a bare tilled plot (international control) with those under four production systems (a vineyard, an orchard, an agropastoral system and a sylvopastoral system) on four typical soils in a semi-arid Mediterranean zone with mild winters.

The improvements to the regional control plot consist of rough but carefully oriented tillage, the use of herbicides and pesticides, improved seed, balanced fertilization, a fodder fallow of legumes, and intercropping in rotation under the orchard. The recorded parameters are rainfall (amount, intensity, erosivity), runoff (Kaar, the average annual coefficient, and max KR %, the maximum coefficient for a heavy rainstorm as a percentage of rainfall), erosion (fine suspended matter and coarse sediment), production of biomass and fruit, net income and the soil surface parameters (closed, open and covered surface, surface humidity).

Hazards

Rainfall was 100 to 250 mm less than the average. Only one set of major rainstorms was recorded, totalling 130 mm in three days, and falling in the summer on dry soil.

TABLE 48

Runoff (% of rainfall), erosion (t/ha/yr), yields (t/ha) and net revenue (in dinars [28 DA = $US 1]) for 15 erosion plots at the INRF station at Ouzera, Algeria (cf. Arabi and Roose 1992)

	Average runoff Kaar %	Maximum runoff Max KR %	Erosion t/ha/yr Med. Max O	Harvest t/ha/yr	Net revenue Da/ha/yr 28Da = 1 US$
Agropastoral system, vertisol, 12% slope					
1 - International control fallow, untilled	18.2	7 to 86	2.7 (6)	0	0
2 - Improved: rotation wheat/ intensive legumes	0.6	1 to 8	0.11 (0.2)	4.8 grain 3.1 straw 5 bean	36 200
3 - Improved with alfalfa pasture	0.6	0 to 9	0.05 (0.3)	6.5 grain 2.2 straw	35 800
4 - Local control: extensive wheat and grassland	2.1	7 to 16	0.19 (0.3)	0.7 grain 0.2 straw	2 500
Sylvopastoral system, brown calcareous soil, slope 40%					
5 - Internat. control, bare soil	11.3	34	1.8 (2.7)	-	-
6 - Pine forest, rich in litter	0.5	1 to 3	0.02 (0.04)	-	-
7 - Overgrazed mattoral	12.0	3 to 25	1.7 (2.1)	-	-
8 - *diss* pasture + litter	0.8	2 to 7	0.03 (0.04)	-	-
Apricot orchard, red fersiallitic soil, slope 35%					
9 - Internat. control, bare soil	15.5	25 to 50	9 (20)	-	-
10 - Improved = apricot + wheat/legume rotation, fertilizer + strips	0.6	0 to 9	0.09 (0.2)	0.8 fruit 6.0 bean 2.0 straw	42 200
11 - Local control: apricot 8x8 m	3.1	11 to 12	0.66 (1.3)	0.7 fruit*	10 000*
Grapevines on 30% slope, brown calcareous gravelly soil					
12 - International controls, bare soil	9.5	16 to 36	1.53 (2.3)	-	-
13 - Local control = 30-year grapevine + 2 tillages	1.5	3 to 8	0.11 (0.2)	2.8 grape	34 300
14 - Improved = grapevine + implements + herbicides	4.3	8 to 26	0.13 (0.2)	3.0 grape	35 100
15 - Improved = grapevine + wheat/legume rotation, 2 tillages + fertilizer	0.2	0 to 3	0.004 (0.1)	4.0 grape 3.4 bean 1.5 straw	65 400

Med. = median; Max. = maximum in 1990

* The apricot harvest was very poor because of an attack by insects.

Rainfall is much less forceful than in West Africa. The annual average rainfall ratio is about 0.1 at the Médéa station, 0.5 in Côte d’Ivoire and 0.25 in the mountains of Cameroon, Rwanda and Burundi.

Average annual **runoff** (Kaar %) (Table 48) is modest (0.5 to 4% of rainfall), and the maximum during a rainstorm is 8 to 36% (40% in exceptional cases). On the bare control fallow, annual runoff was still modest (10 to 18%) compared with levels in a tropical environment (25 to 40% in Côte d’Ivoire). However, if the bare soil is packed down or waterlogged during the winter, runoff can exceed 50 to 80% on marl and red fersiallitic soil.

With similar soil conditions, slopes and tillage techniques, it was noted that plant cover – especially with improved techniques – effectively reduced erosion risks.

As many other writers have noted, tillage improved infiltration. For example, under the grapevines on the plot where tillage was replaced by herbicides in order to control weeds, runoff increased significantly because the surface horizon was compacted, but at the same time erosion decreased because the soil was more cohesive. In the case of an exceptionally heavy rainstorm, the water storage capacity of the soil would soon be exhausted, and runoff could increase to such an extent on the tilled plot that it would carry away the tilled – and therefore less cohesive – horizon, at least on the steepest slopes. This is frequent in the fields.

Under natural vegetation (scrubland developing into grassland or forest), very considerable litter cover (more than 80% of the surface covered) meant that although runoff was frequent on soil compacted by overgrazing it was never dangerous (max KR 7%). However, it has often been observed in Algeria that drainage lines and gullies arise on overgrazed rangeland (especially on tracks worn by livestock) or even in some forest plantations degraded by grazing.

Runoff generally begins after 20 mm of rain on dry ground, and after 3 mm on compacted or moist ground. The precise point at which rain gives rise to runoff clearly depends on the specific features of each rainstorm (intensity, but also capacity to saturate the soil), but first and foremost on the condition of the soil surface (humidity of the top 10 cm, presence of fissures, worm holes, slaking crusts, litter, pebbles and large clods). The most copious runoff occurs only when all the conditions are optimal – usually between November and March – or during an exceptional summer storm (every five years).

Sheet erosion was a very modest 0.1 to 2 t/ha/yr on cultivated fields and 1.5 to 18 t/ha/yr on bare fallow despite steep slopes (12 to 40%), for rainfall is fairly gentle ($R_{USA} < 50$) and the soils are very resistant (K = 0.01 to 0.01), rich in calcium-saturated clay, and often stony.

Even if erosion were to reach 19 t/ha/yr (1.27 mm of soil), it would take two and a half centuries to remove 20 cm of topsoil. It has been proved in trials that sheet erosion selectively removes organic matter, clayey and loamy colloids and nutrients, while rill erosion removes soil unselectively. Thus, when rill erosion sets in, it usually removes the topsoil, especially on steep slopes. If sheet erosion appears not to be the most powerful process on slopes, rill erosion and especially creep caused by farm implements appear to be the forms most active in transforming mountain landscapes.

For example, at Ouzera on an orchard planted 30 years ago, 30 cm of soil is now missing between the tree trunks. Even if recorded sheet erosion is as much as 1.5 t/ha/yr (0.1 mm), in 30 years 3 cm of soil would have been lost, while 27 cm must have been moved by dry mechanical erosion during the twice-yearly deep criss-cross tillage with a crawler tractor. Tillage therefore hastens the transformation of mountain slopes, contributing to the formation of banks on the edges of fields.

Soil erodibility was seen to be very low, even after three years of untilled fallow (K = 0.01 to 0.02). However, sheet and rill erosion are increasing each year.

Erosion was high on red fersiallitic soils (10 to 19 t/ha/yr), average on grey vertisols (2 to 3 t/ha/yr) and minimal on brown calcareous soils (1.5 to 2 t/ha/yr). It seems that gravel offers very effective protection.

TABLE 49
Effect of soil trype and slope (%) on runoff (%) and erosion (t/ha/yr) on bare fallow (cf. Arabi and Roose 1992)

	Covering of gravel (%)	Slope (%)	Kaar %	Max KR %	Erosion t/ha/yr
Brown calcareous soil (SPK 8)	16	40	11	34	1.8
Brown calcareous colluvial soil (VK 15)	20	35	10	36	1.5
Red fersiallitic soil (ARK 9)	0	30	16	50	9.0
Grey vertisol (APK 1)	4	12	18	86	2.7

TABLE 50
Effect of improved farming practices on runoff (average and maximum as % of rainfall), erosion (t/ha/yr) and net income ($US 1 = 28 dinars)

Situation		Kaar %	Max KR %	Erosion t/ha/yr	Net income DA/ha
Agropastoral:	traditional	2.1	16	0.189	2 504
	improved	0.6	8	0.054	35 810
	degraded	12.0	25	1.740	?
Sylvopastoral on brown soil:	reforested	0.5	3	0.034	?
	grassed	0.8	7	0.020	?
Orchard on red fersiallitic soil	traditional	3.1	12	0.656	10 000
	improved	0.6	9	0.088	42 187
Vineyard on brown colluvial soil	traditional	1.5	8.3	0.144	34 333
	improved	0.2	2.7	0.009	65 364

It is difficult to comment on the likelihood of runoff for different soils, since the slopes vary as much as the soil types. However, it does seem clear that average annual runoff and maximum daily runoff decrease as the gradient increases, at least on bare fallow (Table 49) – an astonishing conclusion that was previously reached by Heusch in Morocco (1970) and Roose in Côte d'Ivoire (1973).

This result throws doubt on the validity of the equations of Ramser, Saccardy and others, for whom the space between terraces should decrease as the gradient increases. Heusch has already shown in Morocco that the position of a field in the toposequence can be more important than the gradient of the slope itself.

SUGGESTED IMPROVEMENTS: INFLUENCE OF THE FARMING SYSTEM [Plate 23]

Better plant cover (high crop density, fertilizers, rotations with pulses, a winter crop between fruit trees and grapevines) steadily but undramatically reduced runoff and field erosion (Table 50).

More important, however, is the very marked improvement in crop yields and farmers' income (see Table 48). The traditional cereal crop can bring in 2 500 dinars/ha/yr, while the improved, intensive cereal/legume rotation brings in 35 800, and up to 42 000 or 65 000 dinars when this rotation is introduced between rows of grapevines or fruit trees.

These results show that it is possible both to intensify mountain farming and to reduce the risk of degradation of the rural environment.

The yields recorded on the traditionally worked runoff plots (100 m^2) were as poor as those on nearby farmers' fields (700 kg/ha/yr of winter wheat, 2 800 kg of grapes, 800 kg of apricots, these latter being diseased). On the neighbouring erosion plots treated with improved techniques, yields reached 4 800 to 6 500 kg/ha/yr of winter wheat, 4 000 kg of grapes, plus 3 400 kg of dried beans.

Furthermore, straw, pulsecrop leaves and other crop residues also increased significantly (from 0.2 to 2 or 3 t/ha/yr) so that livestock production and the availability of manure or organic residues can in the long run improve soil fertility and resistance to erosion.

Yield improvements are unlikely to be as spectacular on large areas as on the small erosion plots (100 m^2), but the first step has been taken: that of showing that farming can be intensified while steadily improving the rural environment.

That this is a viable investment is shown by the following. After subtracting the extra costs of improved seed, fertilizers, pesticides, herbicides, the work of soil preparation and harvesting, farmers are still left with a much higher net income than that from traditional crops.

1) extensive grazing in wooded areas can bring in 500 DA/ha[1]
2) traditional winter wheat 2 500 DA/ha
3) grapevines or traditional apricot orchards 10-17 000 DA/ha
4) improved rotation: wheat x fodder pulse 28-33 000 DA/ha
5) combination of this rotation with grapes and apricots 42-65 000 DA/ha

This would indicate that returns can be multiplied tenfold for cereals and threefold for grapes if an intensive system is adopted. If the traditional wheat-grassland rotation is replaced by intensified orchards, returns are multiplied twentyfold. This is one of the benefits of mountains with a mild, moist climate, for farming cannot always be intensified if the soil is too shallow and rainfall is less than 400 mm.

With such evidence in hand, it is possible to interest farmers in changing and improving their practices so as to increase conservation of water and soil fertility. Indeed, after three years of trials, the hill farmers copied the project methods and achieved better yields than the project itself in 1991, a year when rainfall was well distributed.

[1] 5 Algerian dinars (DA) = 1 FF $US 0.2 at 1992 exchange rates.

CONCLUSIONS

There has not yet been time to put into practice the full range of land husbandry measures for the improvement of a village-based area or small watershed. It takes time both to modify farmers' practices and to assemble the wherewithal for field demonstrations showing that land productivity can be improved, small farmers' incomes can be increased, and risks of degradation of the landscape can be reduced in mid-altitude Mediterranean mountain areas.

Chapter 15

Pays de Caux: a temperate, field-crop region in north-western France

PROTECTING THE DRAINAGE SYSTEM AND IMPROVING INFILTRATION

THE SITUATION

Runoff, soil erosion and flooding have become more frequent and more serious in the Pays de Caux region in the past 20 years (Auzet 1990; Papy and Boiffin 1988) – as they have in a large part of north-western France.

A very real desire for soil and water conservation has been growing for some years now. At first action was confined to combating catastrophic floods, but in recent years, local authorities in the Seine Maritime department have spent US$ 4 million on check dams. Efforts are now being made to implement comprehensive, long-term programmes for whole watersheds (regional operation set up in 1985 with the Board of Agriculture).

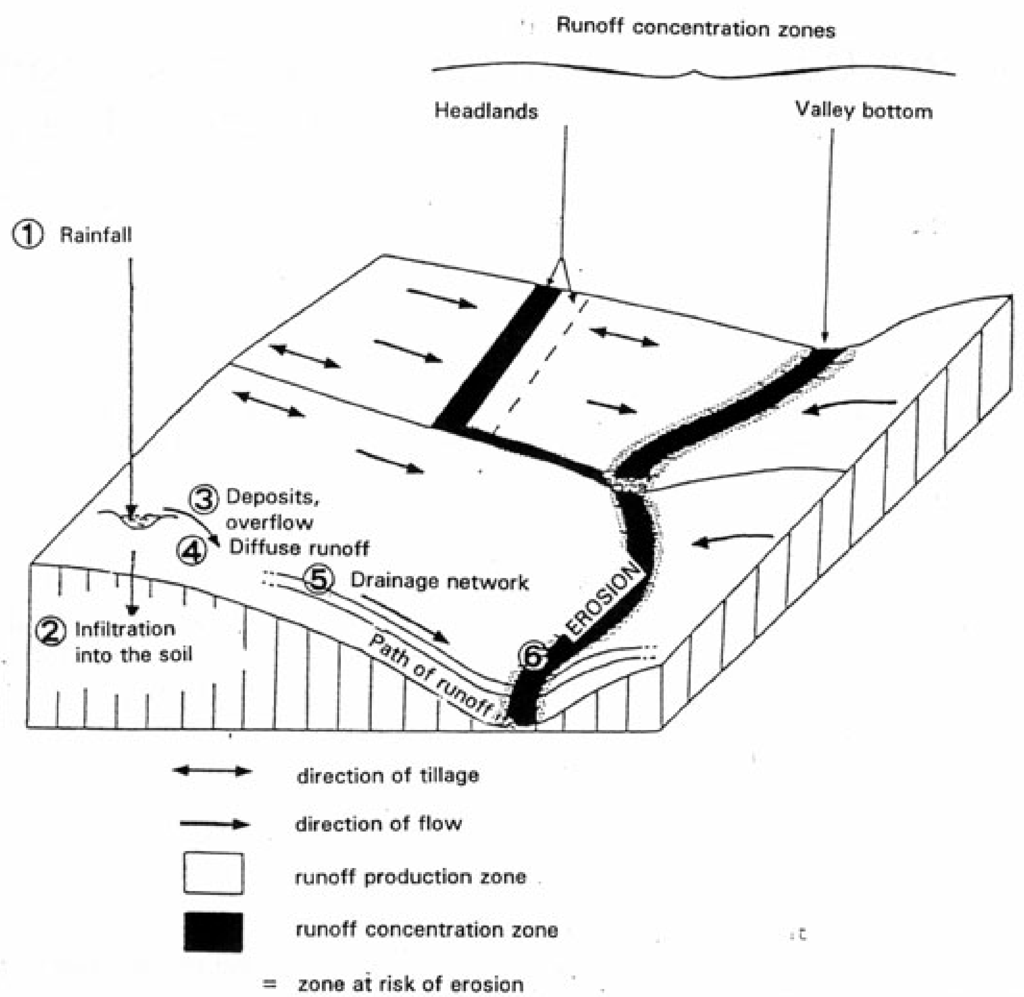
These programmes have two components:

- an agricultural component, to reduce soil erosion and runoff on slopes by increasing the roughness and infiltration capacity of the soil surface, with interventions by the individual farmer;
- a water-management component, for collective schemes to control the inevitable flows, and hence curb erosion and flooding in the valleys.

In the agricultural sphere, various techniques perfectly integrated with existing production systems have been developed in successive stages:

- precise definition of the type of erosion, and the factors on which intervention is possible (Boiffin, Papy and Eimberck 1988);
- investigation of the actual amounts involved in erosion phenomena (internal SRAE reports 1989, 1990, 1991) (Daix 1991, Ouvry 1992);
- analysis of production systems and points where manoeuvre is possible (in financial and technical terms) and the time available on farms (Papy and Boiffin 1988, Poujade 1989);

FIGURE 84
The dynamics of the erosion process in Haute-Normandie (cf. Boiffin, Papy and Peyre 1986)



- research into and propagation of agricultural solutions that are suited to the specific production systems, in order to increase accumulation and infiltration while preserving the potential and profitability of plots as well as facility of tillage;

- solutions are at first implemented individually so that each farmer can see that there *is* room for manoeuvre for him, and so that the rural community can then take collective control of the whole agricultural catchment area.

LOCAL CONDITIONS

The Pays de Caux area lies along the coast in the Seine-Maritime department. It is a chalky undulated upland area, with gentle slopes (1 to 5% on tilled land) throughout. It has no drainage system because of the underlying karst, and also because of a very tight network of dry valleys. Intensive multicropping is practised in these uplands.

The soil cover is fairly homogeneous. Brown, slightly leached soils have formed on the wind-blown holocene silt that covers the uplands. The amount of clay in the tilled horizon varies between 10 and 15%, and the organic matter in the tilled silt is close on 1.6%.

The climate is oceanic in type with gentle rainfall averaging 900 mm annually, spread evenly throughout the year. The heaviest day's rainfall in a 10-year period is only 48 mm.

HAZARDS: THE EROSION PROCESS AND ITS NEGATIVE EFFECTS

The erosion process is typical of that from concentrated runoff as described by Ouvry (1982,), Boiffin, Papy and Eimberck (1988), Boiffin, Papy and Peyre (1986) and Auzet (1990). Erosion phenomena are linear and generally confined to the thalweg axis, although they can also appear on the headlands (ends of fields) or on any lines of concentration between plots. Occasionally, erosion takes the form of shoestrings or parallel rills on slopes steeper than 4%. Damage often occurs in winter even though rainfall intensity is under 5 mm/h, and sometimes during summer storms. Soil losses are always confined to the thalweg, but vary greatly, ranging between 0 and 500 m^3/km^2 per year (Ouvry 1992).

On the basis of erosion type, Boiffin, Papy and Peyre (1986) divide the catchment area into two distinct zones (Figure 84):

- the sides and head of the catchment area, which produce runoff;
- the thalweg and other lines of concentration where the flow cuts into the soil.

The runoff in this region of very gentle rainfall depends mainly on factors related to the state of the soil surface, notably its roughness, and the speed of formation and extent of slaking crusts.

In winter, after the last tillage, 30 to 40 cumulative centimetres of rainfall of any intensity are enough to form the first thin slaked surfaces and sedimentation crusts. The roughness of the seedbeds allows a maximum surface retention of 3 to 6 mm and a minimum of 1 mm to zero, depending on the type of crop, the preceding crop, soil moisture when tilled, the type of implements used to prepare the seedbed, the number of farm machinery passes, and the type of tractor equipment (Boiffin, Papy and Eimberck 1988).

SOLUTIONS AND MEASURES ADOPTED

There are two consequences of the process of concentrated erosion:

- different solutions must be found and advised for slopes and thalwegs (unlike the case of regions where rainsplash is the most telling factor), and farmers must learn to treat these distinct sectors of a single plot in different ways;

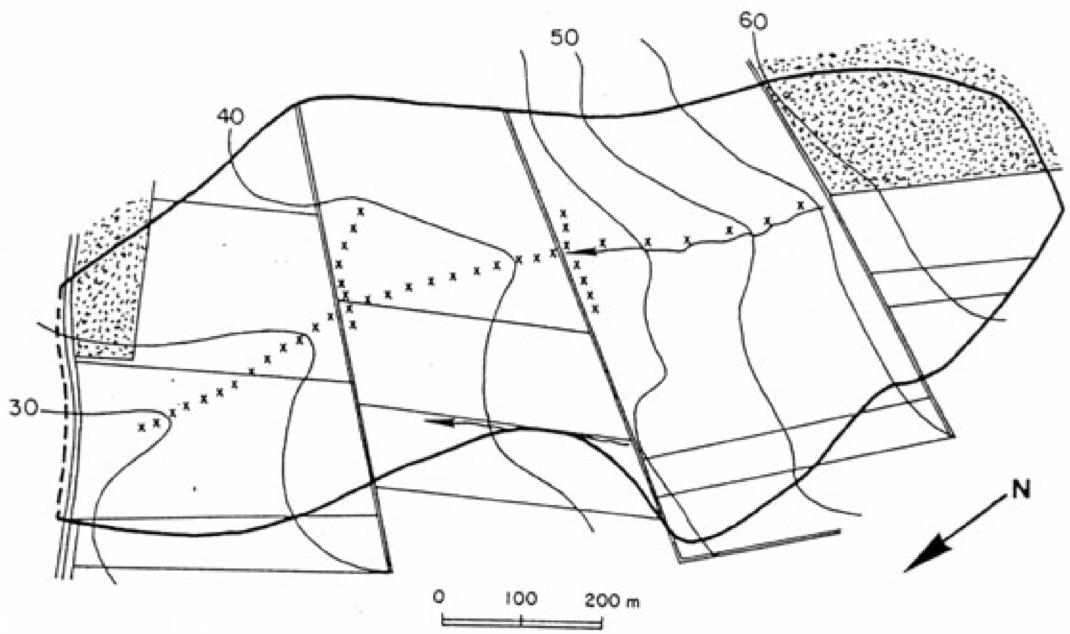
- farmers' motivation varies, depending on whether their plots are located upstream in the watershed or in a small valley where erosion is more of a threat.

FIGURE 85
Detailed survey and erosion dynamics of a catchment area in Bourg-Dun, France

LINEAR EROSION

Erosion recorded during the winter of 1988-89 (Ludwig)
Maximum erosion recorded at different dates between 1985 and 1988

CROPS IN ROTATION ON PLOTS: winter wheat, sugar beet, pea, potato, vegetables, maize for silage



The example of a watershed at Bourg-Dun given in Figure 85 covers 60 hectares, five of which were still under grassland in 1991. Consolidation dates from 1957, when the boundaries were fixed, with parallel plots lying in the direction of the slope. The production systems on the four farms consist of intensive multicropping.

Starting in 1978, erosion began to appear regularly on different sectors along the thalweg line, as Figure 84 shows. Ludwig, Boiffin and Masclet (1992) estimated the volume of the rills to be 100.8 m^3 during the winter of 1988-89.

By 1986, some of the farmers wanted to control soil erosion. When the rills and gullies started preventing them from moving harvesting equipment as they wished, the problem was serious enough to spur them into action. Loss of time for all the tillage work and loss of area in terms of non-harvestable zones and others where weeds could not be controlled were much more important issues for the farmers than the actual grooves caused by erosion – and in any case the area lost by cutting along the thalweg is very minor (between 0.1% and 1% of the land under cultivation).

MEASURES TAKEN

As a first phase, a relationship of mutual trust was established with these farmers, based on a thorough knowledge of agricultural constraints, farming systems and farm finances.

In a second phase, the farmers tested very simple agricultural solutions on their own plots – solutions that cost nothing and were usually based on observation and commonsense, so that they gradually realized that runoff and erosion are not inevitable, but can be curbed. The most delicate operation is that of distinguishing the different zones within a plot, and then selecting the right solutions for each. After this, collective action is needed to control and manage water over the entire watershed.

FARMING PRACTICES

All the solutions aim primarily at roughening the soil surface and ensuring good macroporosity, and secondly at slowing the formation of slaking crusts, then breaking them (Ouvry 1987).

For example, all wheel-marks must be eliminated, since they can cover between 5 and 33% of the soil surface for beet and maize, depending on the type and make of seed-drill and secondary implements (such as wheel-mark obliterators). For crops, the condition of the surface is determined at planting-time. A cloddy seedbed is prepared without crushing or rolling the soil surface, depending on the previous crop, residues and soil moisture. Highly articulated implements are not recommended: better a cultivator with rigid or vibrating tines which can prepare the soil in one operation, or sometimes two (Ouvry 1989).

For widely-spaced crops, it is recommended that fine tillage be confined to the seeding strip, i.e., one-third of the area, leaving the space between rows very cloddy. Use of a mechanical weeder or hoeing between the rows so as to break the slaking crust is also recommended for these crops. The choice of tine, either a blade-like jointer (not recommended) or a hoe-type shape (recommended) is very important, in view of its effect on the risk of summer erosion.

There is more room for manoeuvre over intercropping. Without going into detail, the solutions depend on the following points:

- the surface should be cloddy and rough for maximum surface retention by the last tillage;
- tillage should be perpendicular or diagonal to the slope; it may even be partial if there are strong climatic or time constraints;
- a mulch of crushed straw should be used;
- a green manure (or intermediate crop) can also be planted, so long as it is dense enough and grows quickly enough to protect the soil fast and maintain an infiltration rate of 10 mm/h; there must also be good control over its effects on subsequent crops.

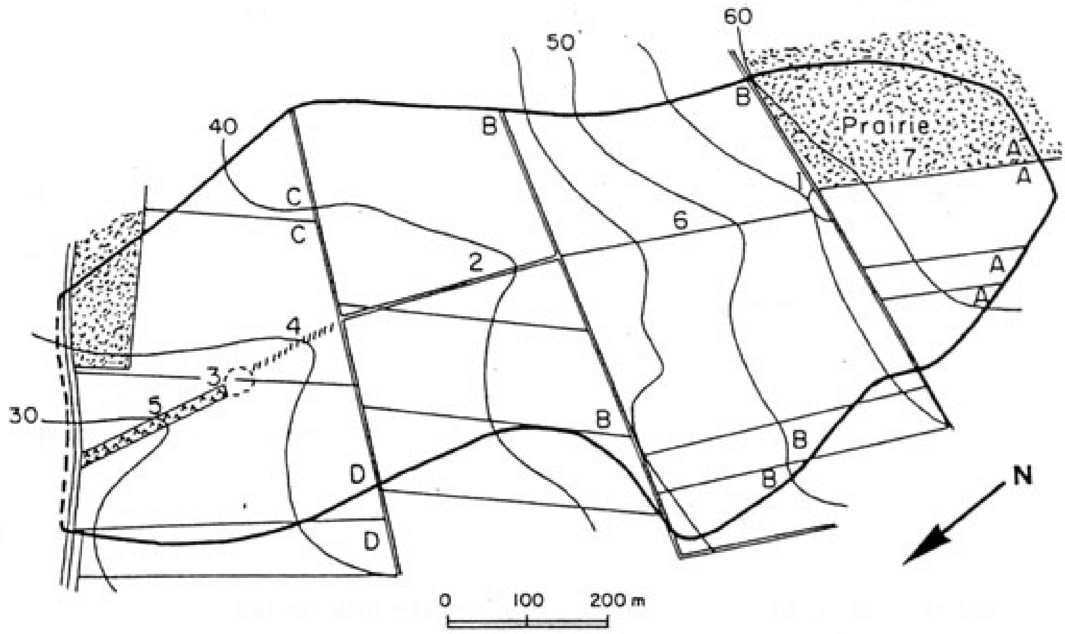
DRAINAGE

The aim is to install runoff harvesting structures, alternating with storage structures, in order to control flow (Boiffin, Papy and Eimberck 1988, Ouvry 1987, 1992). In this watershed the farmers have gradually set up the various components of such a system, as shown in Figure 86 (Ouvry 1987).

FIGURE 86
Reorganized drainage of the Bourg-Dun catchment area

HYDRAULIC ASPECTS OF THE ACTION TAKEN

4 farmers concerned A - B - C - D
1 - Pond 1987
2 - Drainage ditch 1988
3 - Pond 1990 abandoned due to sedimentation caused by erosion on sector 4 in 1990 and 1991
4 - Strip recompacted 1992
5 - Strip grassed 1992
6 - Boundary of the plot 1992
7 - Rangeland turned over in 1991



Some erosion control structures are permanent, while some, such as compacted strips, are temporary and have to be redone after each tillage. The strips have the attraction of being very simple, but are suited to very specific conditions, being limited, for example, to mild rainfall. However, they demonstrate three points to the farmers:

- something *can* be done;
- the two operational sectors must be treated differently;
- if this is not sufficient, a more radical solution will have to be devised, using ditches to divide the plot, or grass strips.

DIFFICULTIES ENCOUNTERED

All this work required considerable time. Furthermore, one of the farmers was not motivated, since his plots were located uphill and suffered no damage. This means that if measures to limit runoff are to be applied throughout a given area, they have to be an integral part of the agricultural advice given by all the experts and field staff.

If the expert advice is not followed, there may be various reasons:

- lack of time;
- humid climate;
- lack of suitable equipment;
- cost of green manure;
- side effects of green manure.

The search for solutions must therefore take account of these limitations.

COST

The cost of all these control measures comes under two headings:

- the average annual cost of one person totally engaged in regional mobilization for erosion control would amount to US$ 90 000;

- the cost of the solutions: the solutions sought always have the lowest cost possible, generally nil, apart from time; full advantage is taken of existing farm machinery and structures.

The only direct cost is that of green manure, which varies between US$ 20 and 60/ha.

The cost of drainage solutions varies widely:

- compacted strip = 0;
- ploughed furrow on the edge of the plot along the thalweg axis = 0;
- grass strip: grassing = US$ 0.6/m^2 (seed), and terracing under contract = US$ 6/m^2;
- ditch (section # 1 m^2) = US$ 7/m^2;
- pond 100 to 500 m^3 = US$ 8/m^3.

All the larger dams come under the responsibility of the local communities in association with the farmers:

- a flood meadow (pasture located at the bottom of the valley and barred by a compacted bank at least 1 m high), which could hold 1 000 to 10 000 m^3, would cost between US$ 6 and 12 per m^2 stored;

- a classic basin dam costing between US$ 20 and 40/m^3, or a cost per hectare of the catchment area of between US$ 300 and 3 000.

CONCLUSIONS

In view of the importance of the condition of the surface of cultivated plots in determining runoff and erosion risks, the farmers’ rôle is clearly critical. This surface condition depends on how the soil is used, the cropping system, tillage, and the choice of implements.

Preventive and remedial treatment of these phenomena will therefore be carried out with the farmers or not at all.

This long-term undertaking will be done by agricultural experts, working to show farmers how to integrate erosion and runoff control measures into their overall approach.

Moreover, preventive measures, dictated by the type of erosion, must be implemented simultaneously. This entails planning and establishing a drainage system at the time of consolidation of holdings, a step now being carried out jointly by the farmers and the members of the communal consolidation commissions.

Plots may also be aligned diagonally to the slope to take full advantage of any possible spreading, for saving 1 or 2 mm of runoff through surface roughness represents 30 to 50% of the total flow.

As a last resort, when runoff cannot be totally avoided, dams will have to be built to protect the village, in addition to the agricultural and drainage measures implemented at various points in the watershed.

Such structures are certainly of interest to all parties: soil erosion will be restricted on the farm; siltation of dams will be reduced; pollution will be reduced in regularly scoured catchments and rivers; and floods will also be less serious and less frequent in the rural towns.

Measures such as these, which will bear fruit in the long term, must be carried out within the framework of a comprehensive rural development policy decided by elected provincial and regional representatives.

PROSPECTS AND ORIENTATIONS

LAND HUSBANDRY: A NEW PHILOSOPHY

Runoff and erosion control has proven more complex than anticipated. On the one hand, there are many processes of soil degradation, and there is a long way to go before the technology is tailored to the range of environments found in the world: remedies are too often applied with no knowledge of their effectiveness against erosion, their feasibility or their economic viability in a given time and place. Moreover, many sociological and economic factors have not yet been properly grasped: land tenure problems and investment security, farmers' goals and priorities, the availability of land, inputs and labour, and opportunities to get more benefit from farm produce and improve living standards, health, etc.

Simply conserving soil cannot satisfy most farmers because it brings no immediate return for the extra work required. Most land is already so poor and degraded that even if losses through erosion are curbed, the productivity of both land and labour is still mediocre. However, the population doubles every 15 to 30 years, which implies the challenge of doubling production in ten years in order to catch up with the geometric progression in population. Soil conservation is not enough: fertility has to be restored in order to allow a satisfactory and early return on the labour invested. Land husbandry tries to bring about a decided increase in yields, while stabilizing the environment.

In pursuit of this aim, land husbandry improves the management of water, organic matter and nutrients in order to create intensification points for production and for development of the rural environment through animal husbandry (manure being one of the keys to productivity on tropical soils incapable of storing much water or nutrients), agroforestry and off-season crops. Land husbandry aims primarily at a signficant increase in yields (or, better, in net income), and this requires stabilization of the environment. Erosion control is no longer the rallying call for public opinion, but simply one necessary component of a technological package.

The belief was that soil nutrients could be mobilized through various biological means – manure, compost, mulch, hedges, green manure. Many recent examples from tropical countries have shown that on acid ferralitic soils agroforestry (and particularly cropping between hedges) can halt erosion even on steep slopes (25 to 60%) and curb the degradation of cultivated land. However, like green manuring, this "simultaneous cultivation and fallow" immobilizes 10 to 20% of the land simply in order to maintain a very modest level of production, not enough to keep pace with population pressure. If this vicious circle is to be broken, soil fertility must first be restored – which is not possible without massive applications of manure (3 to 10 t/ha), lime (1 to 5 t/ha) and mineral fertilizers that can be directly taken up by crops.

The densest rural populations in the world live in multi-storey gardens where positive interaction between livestock, crops and trees is pursued to the furthest extreme. In Africa there is still a great deal to be done in order to intensify animal husbandry and manage trees so as to minimize competition with traditional crops.

LAND HUSBANDRY: A STRATEGY FOR ACTION

This work has collated research on the dynamics of erosion and the erosion control methods developed over the past forty years, especially in French-speaking Africa, and has led to the formulation of new research approaches and orientations for rural development.

NEW RESEARCH APPROACHES

- Study of traditional strategies for managing water, soil and soil fertility: the way they work, the causes of their decline, and the possibilities of improving them;
- study of the feasibility, acceptability, effectiveness and economic viability of erosion control methods;
- study of the costs of erosion and of erosion control at the individual plot and watershed levels;
- regional adaptation of methods of managing water, nutrients and biomass;
- refining methods of dissipating runoff energy on slopes;
- the social and economic aspects of erosion, and how to increase farmers' awareness of problems of environmental degradation;
- degradation and, above all, restoration of the productivity of the land: the rôles of livestock, trees, micro-organisms (manure) and mineral supplements;
- development of models of the risks of runoff, drainage and erosion, but also optimal land use, taking account of the limitations imposed by production systems and farm sizes.

NEW ORIENTATIONS FOR RURAL DEVELOPMENT

Since the participation of farmers is vital for the sustainability of erosion control, farmer priorities must be taken into account, and research involve their participation in finding ways of improving land productivity and getting a better return on their labour. Erosion control should no longer be presented as the main objective, but as part of a technological package designed to improve the management of water, biomass and nutrients:

- systematically improving existing techniques while avoiding increased dependency on inputs coming from outside the village (funding, sophisticated technology, etc.);
- integrating new elements into farming systems (agroforestry, multicropping, catch fallows of legumes, accelerated rotation, supplementary irrigation and manuring);
- promoting the cheapest and most effective erosion control structures;
- taking account of market studies and the condition of the road network in order to draw the most benefit from production;

- refining methods of draining both roads and the slopes on which they are built;

- adaptation of erosion control to the land-tenure system.

The prospects for research and rural development outlined in this book call on the various parties to work together. The various activities are envisaged within a framework of close cooperation between national agencies, non-governmental organizations, development agencies and the users of the land. The rôle of national agencies in particular should be transformed from that of executing agency to that of promoter. The ideal programme directly involves the users of the land in planning and implementing their own solutions. To this end, national agencies should assume responsibility for creating an awareness of land degradation, and the users of the land should be helped to develop their own organizations.

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