WORLD BANK TECHNICAL PAPER NUMBER 221

Conserving Soil Moisture and Fertility in the Warm Seasonally Dry Tropics

Jitendra P. Srivastava, Prabhakar Mahedeo Tamboli,
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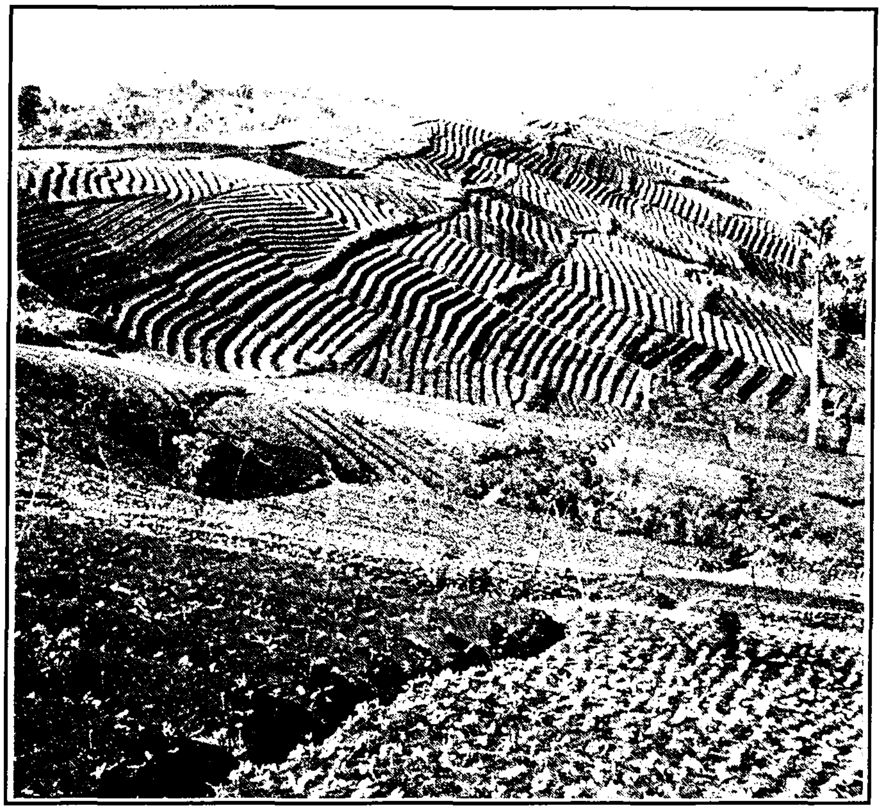

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Foreword

Achieving environmentally sustainable development is the challenge of the coming century. The Rio de Janeiro Earth Summit has raised the world's conscience to the urgency and preeminence of this task. The World Bank, as a major provider of resources to developing countries, has a responsibility to provide leadership in this area. In response, the Bank has created an Environmentally Sustainable Development (ESD) Vice Presidency to help develop a thorough understanding of, and an effective Bank response to, this challenge. As part of this Vice Presidency, and to carry out this mandate, the Agriculture and Natural Resources Department (AGR), in addition to providing special emphasis on supporting policy work and country agriculture strategies, emphasizes the adoption of sustainable strategies for land management and protection of ecosystems. Most of these strategies imply a change in farmers' practices through the adoption of new technologies.

An imbalance between natural resources, population, and basic human needs exists in many regions, but is particularly acute in the developing countries of the Warm Seasonally Dry Tropics (WSDT). This Technical Paper presents the technological options which are available for the WSDT ecoregion. The paper describes the ecoregion, identifies the main production constraints within the region, and offers technological options for increasing production, while simultaneously conserving soil and water and other natural resources.

The paper is part of a Best Practice Series of the Agriculture and Natural Resources Department, written primarily to provide Bank task managers with technical options and approaches for application in Bank-assisted projects. Additionally, the paper should be of interest to policymakers, researchers, task managers and others involved with promoting sustainable agriculture development.

Michel Petit
Director
Agriculture and Natural Resources Department

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Abstract

An imbalance among natural resources, population, and basic human needs exists in many regions, but is particularly acute in the developing countries of the warm seasonally dry tropics (WSDT). The WSDT are found primarily in Sub-Saharan Africa, Southwest and Southeast Asia, Central and South America, and northern Australia, and include approximately 21 percent of the world's population. Although the region's soil and water resources vary substantially, as a whole the dry tropics are resource-poor, and large areas are heavily exploited, leading to severe pressure on the resource base. Three factors render these regions particularly fragile: insufficient precipitation, low soil fertility, and rapid loss of soil organic matter in cultivated soils. As human and animal populations rapidly increase (except in Australia), and thus require more intensive cropping systems, traditional methods of coping with risk and drought in the WSDT—nomadism and long fallow periods—are being forced to change.

Extensive research and scientific knowledge exists which can be used for developing sustainable management systems in the WSDT. Basic principles of managing soil and water resources are known and are transferable to these countries. Site-specific technologies based on these principles, however, must be validated and fine-tuned for different sub-ecoregions. The key elements include the care and stewardship of the land through proper methods of land clearing; early sowing with viable seed; frequent use of cover crops and multiple or mixed cropping systems; and adequate fertilization. Providing guidelines about these basic principles—the objective of this publication—may facilitate local validation and adaptation of improved technologies.

The paper briefly describes the ecoregion, identifies the main constraints, and offers a series of technological options for sustainable development through the conservation of soil moisture, the prevention and control of soil erosion, and the improvement of soil fertility. The paper is designed to serve as a guide for policymakers, project managers, and agriculture operations staff in evaluating options and designing programs for the WSDT. References have been provided for those requiring additional background material or more technical information.

Acronyms and Abbreviations

CAST	Council for Agricultural Science and Technology
CGIAR	Consultative Group on International Agricultural Research
CRSP	Collaboration Research Support Programs
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographical Information System
ICAR	Indian Council of Agricultural Research
ICARDA	International Center for Agricultural Research in the Dry Areas
ICRISAT	International Crop Research Institute for Semi-Arid Tropics
ILCA	International Livestock Center for Africa
IRAT	Institute de Recherche Agronomique Tropical
NAS	National Academy of Sciences
OTA	Office of Technology Assessment
TAC	Technical Advisory Committee, CGIAR
WSDT	Warm Seasonally Dry Tropics

Units of Measurement

One quintal (q) is equal to 100 kilograms

EXECUTIVE SUMMARY

The world's population is increasing rapidly and is not expected to stabilize until the year 2100, when there will be approximately 11 billion inhabitants. In contrast, the rate of increase in world grain production has been falling in the last few years, owing to a combination of biophysical, socioeconomic, and political factors. As a result of the increasing demand on natural resources, there is widespread potential for accelerated erosion and soil degradation, climatic change, loss of biological diversity, declining water quality and availability, and a perpetual threat of malnutrition, hunger, and poverty. This imbalance between natural resources, human population, and basic human needs is particularly serious in the developing countries of the Warm Seasonally Dry Tropics (WSDT). The excessive demand on finite natural resources can be best overcome through the effective transfer of scientific and technical knowledge. This paper is intended to provide policymakers and those interested in the development of the WSDT with an overview of the region's soil, water, and climatic resources, and to describe state-of-the-art technological options for sustainable management.

The WSDT is a region delineated by latitudes approximately 25° north and south of the equator, with a mean annual temperature greater than 20° Celsius, and rainfall exceeding evapotranspiration for only two to seven months per year. The WSDT occur primarily in Sub-Saharan Africa, Southwest and Southeast Asia, Central and South America, and northern Australia. There are an estimated 1.1 billion people, approximately 21 percent of the world's population, living in these regions. The soil and water resources in the WSDT region vary greatly; but, as a whole, the dry tropics are resource poor. With the exception of Australia, the countries in this region contain rapidly growing populations of both humans and animals. Consequently, large areas are utilized beyond their capacity, placing severe pressure on the resource base.

This paper briefly describes the climate, soils, vegetation, and farming systems of the WSDT. The three major constraints to increasing productivity are: (i) insufficient soil moisture because of low levels of annual precipitation; (ii) rapid soil degradation as a result of unchecked water and wind erosion; and (iii) low soil fertility owing to a rapid loss of organic matter and intensive cropping.

Insufficient Precipitation. The WSDT region is especially limited by insufficient precipitation. A greater level of rainfall is needed in the tropics to keep the soils at the same degree of wetness than would be needed in the middle and northern latitudes. The low effectiveness of precipitation in the tropics is due to a multitude of interacting factors. Tropical rains are in general more intense and, therefore, a relatively high proportion is lost as runoff. High temperatures throughout the year also cause considerable losses by evaporation and evapotranspiration. The growth rates owing to favorable day/night temperatures are generally high, leading to high consumptive rates. Finally, soils have low water-holding capacities and the effective root volume is often restricted. As a result of these factors, seasonal and annual crops suffer from drought even within a few days following a heavy rain.

Extensive population pressures are leading to the conversion of grasslands and forests to cropland, with expansion normally progressing into less and less favorable areas. With population growth rates exceeding 2.5 percent annually in many parts of the WSDT, enormous pressure is being placed on fragile land resources. As populations grow, millions of people settle in drought-prone areas traditionally shunned by farmers. In general, drought in many cases has not moved to the people; rather, people have moved and continue to move to drought-prone areas.

Intensive pressure from a growing population requires an increase in cropping intensity. The traditional methods of coping with risk and drought in the WSDT include long fallow periods and nomadism. These methods are being forced to change, however, under the more intensive cropping systems required to support growing human and animal populations. There is also a general lack of extensive water resources in the WSDT region for irrigation. Water conservation, therefore, is the primary practice that must be adopted in the region. Unless soil-moisture conservation measures are successfully employed, benefits from other technologies cannot be realized.

Soil Degradation. Soil degradation is a complex phenomenon. It is driven by strong interaction among socioeconomic and biophysical factors. It is fueled by increasing population, fragile economies, and poorly designed farm policies, and propelled by the fragility of the soil and harshness of the climate. While this complex problem has no quick and easy solutions, there are cropping systems and management practices that can be productive and profitable without disastrous effects in the long term. Soil degradation can be subtle and slow until a certain threshold is reached, and then deterioration can occur quickly and, sometimes, irreversibly. Consequently, when planning for a higher degree of self-sufficiency and sustainability, it is essential that differences in land resource endowment and in crop production potentials be fully appreciated, and appropriate measures for the prevention and control of soil erosion be adopted accordingly.

Low Soil Fertility. Soils in the WSDT range from sandy, shallow, low-fertility soils to highly productive, medium- to fine-textured soils; the majority of soils, however, have serious constraints. Adequate soil fertility is essential to ensure the most efficient use of available water. Since evapotranspiration losses are controlled largely by meteorological conditions, seasonal evapotranspiration is nearly the same whether yields are low or high. Phosphorus is limiting in many soils of the WSDT. Unlike nitrogen, which is most deficient in high rainfall years, phosphorus responses in the WSDT are often the greatest in dry years, in shallow soils, or both. The use of fertilizers in the WSDT, however, is constrained both by availability and cost; therefore the use of organic manures in conjunction with chemical fertilizers is recommended for the WSDT.

Soil organic matter is significantly correlated with soil productivity. It acts as a storehouse for nutrients and reduces the effects of compaction. It builds soil structure and increases the infiltration of water. It serves as a buffer against rapid changes in pH and serves as an energy source for soil microorganisms. Maintaining soil organic matter, therefore, is of critical importance.

Continuous high temperatures are common in the WSDT and these lead to a rapid decline in the organic matter content of cultivated soils. The decline of soil organic matter in the WSDT is further hastened in many cases by the removal of crop residues for fuel and fodder. Unless sufficient carbon is returned to the soil to offset the loss that occurs during mineralization, the content will decline.

Technological Options. There exists a considerable body of research knowledge for the sustainable management of resources of the WSDT. These technological advances are published in a wide variety of books and technical journals, but are not available in one place in a single, easily comprehendible document. This paper is designed to address that need.

To overcome the insufficient soil moisture that characterizes the WSDT region, a number of soil-moisture conservation technologies are discussed. These include types of conservation tillage methods, groundcover management, and the design and use of bench terracing. Additional soil-moisture conservation methods presented include the practice of response farming, use of water harvesting and small catchments, and supplemental irrigation.

A number of technological measures are presented for water and wind erosion management. Water erosion can be mitigated through the use of either preventive measures (such as mulch farming, conservation tillage, or the use of vegetative hedges and vetiver strips), or through a variety of control measures (such as contour bunds or engineering structures). Wind erosion can be controlled by reducing wind velocity at the soil surface, using windbreaks or other barriers, or by covering the soil with non-erodible materials.

The low soil fertility in the WSDT can be improved through the use of chemical fertilizers, biological nitrogen fixation, and the use of organic manures such as animal waste or municipal waste. Fertilizer efficiency can be increased through agronomic practices relating to fertilizer placement, the timing of fertilizer application, and the selection of appropriate crops and cropping systems. Similarly, there exist a number of cultural practices which can be successfully employed to reduce fertilizer losses through volatilization and leaching.

Finally, there are three types of production systems which can be used for sustainable development. These are crop-based production systems, tree-based systems, and livestock-based systems. Variations of each of these are discussed.

An important strategy for developing sustainable agricultural systems in the WSDT is to maximize productivity per unit of land. This can take pressure off some of the fragile lands and at the same time reduce deforestation and CO_2 emissions and maintain biodiversity.

The information presented provides essential elements of these technologies. It also lists references where additional information can be obtained. The available literature indicates clearly that the basic principles of soil and water resource management are known, and can be employed by farmers in the region to increase production, as well as to maintain the long-term sustainability of natural resources.

Chapter 1

INTRODUCTION

Worldwide population and income growth are generating increasing demands for food and other agricultural products and will continue to do so into the next century. Most of the increased demand is in the developing countries, where it has been estimated that over the next forty years, the demand for staple foods will grow at about 2.5 percent per year (World Bank, 1992) (*see* Table 1-1). In reviewing the potential for meeting increased demands of this order, it is estimated that only 25 percent of the increase can be met through the exploitation of new agricultural lands (mostly in Latin America and Sub-Saharan Africa). As a result, most of the additional increased production required will have to be obtained by increasing the level of output from land already under agricultural use in various agro-ecological regions of the world. Increased yield through plant breeding has reached a plateau such that the high-yielding varieties can exhibit their potential only when adequate water and nutrients are available. The key challenge is how to increase production to meet this growing demand, while at the same time conserving natural resources. Many techniques have been designed for achieving such sustainable development, but are not readily available in one place in an easily accessible and comprehendible form.

An imbalance between natural resources, population, and basic human needs exists in many regions, but it is particularly acute in the developing countries of the Warm Seasonally Dry Tropics (WSDT). The WSDT region is characterized by insufficient precipitation, low soil fertility, and a rapid loss of arable land to soil degradation. These factors, in combination with the region's rapid population growth and the resultant pressure on land and water resources, are causing a rapid deterioration of these resources and undermining the region's capacity for sustained agricultural production and economic growth. As a result, there is an urgent need throughout the region for the introduction and successful implementation of agricultural technologies which can address these constraints.

This paper seeks to provide policymakers, researchers, task managers, and others interested in sustainable agricultural development with an overview of the **state-of-the-art** technological options for increased production and sustainable soil and water resource management. The available literature clearly indicates that the basic principles of soil and water resource management are known and are transferable between various ecoregions. This paper identifies technological practices which can be applied to achieve sustainable soil and water resource management in the WSDT countries.

This paper is structured as follows. In Chapter 2, the general characteristics of the WSDT ecoregion are discussed and the chief constraints on expanded production are examined. Basic guidelines and techniques for land-use management and soil-moisture conservation are provided in Chapter 3. Chapter 4 presents agricultural and engineering techniques for controlling water and wind erosion, while Chapter 5 describes methods for maintaining and improving soil fertility. Finally, alternative production systems for the sustainable management of soil and water resources are presented in Chapter 6.

This paper focuses on technological options for sustainable development of the soil and water resource base in the WSDT region. It is recognized that technologies must fit the specific characteristics of each setting, and that farmers will not adopt new technologies unless there is a clear incentive to do so. The variance in agro-ecological conditions among individual sites within the region, and the influence of the political, cultural, economic, and institutional characteristics of each setting, is well recognized.

Similarly, it is clear that in order to move from subsistence agriculture to more productive agriculture, it is necessary to have adequate marketing channels to make this transition viable. This paper, however, focuses on technical aspects only.

Table 1-1. Population growth and cereal production in WSDT in 1990

Region	Population		Cereal Production	
	Total (millions)	Growth Rate since 1976 (percent/year)	Total (millions of tons)	Per Capital (kilograms)
I **Africa**				
West	119	3.71	15.6	131
East	93	4.00	10.9	117
Southern	52	3.93	7.7	148
II **Asia**				
West	15	5.26	0.8	53
Southeast	1109	2.39	284.0	256
III **America**				
Central	69	2.42	14.3	207
South	99	2.70	24.5	248
TOTAL	**1,556**	**2.65**	**357.8**	**230**

Source: Authors

Chapter 2

THE WSDT ECOREGION AND ITS CONSTRAINTS

Before discussing the technologies available for the sustainable management of soil and water resources in the WSDT, it is useful to briefly describe the region and discuss its constraints. The Warm Seasonally Dry Tropics are delineated by latitudes approximately 25° north and south of the equator, with a mean annual temperature exceeding 20 degrees Celsius, and rainfall exceeding evapotranspiration for only two to seven months a year. The WSDT occur primarily in Sub-Saharan Africa, Southwest and Southeast Asia, Central and South America, and Northern Australia (*see* Figure 2-1), and contain an estimated 1.5 billion people, approximately 21 percent of the world's population (TAC, 1990). As shown in Table 2-1 below, the four sub-ecoregions comprising the WSDT differ in their agricultural characteristics (*see* Figure 2-2 for the geographical distribution of these sub-ecoregions).

The WSDT are characterized by a wide range of climatic, soil, vegetative, and livestock and wildlife conditions, and it supports several types of farming systems. These characteristics pose severe constraints on sustainable production within the region and will be examined in turn.

Table 2-1. Characteristic features of major sub-ecoregions in the WSDT

Subregion	Rainfall (mm)	Growing period (days)	Soil (texture)
Subhumid	1000-1250	> 200	Loamy sand, sandy loam
Semihumid	750-1000	150-200	Loamy sand, sandy loam
Semiarid	500-750	120-150	Clay
Arid	< 500	100-120	Coarse textured

Source: Authors

RAINFALL, TEMPERATURE, AND GROWING SEASON

The WSDT are characterized by the following:

- There is extreme variability of rainfall within seasons and between years.
- The range of coefficient of variation for precipitation is wide. For example, in India at Jodhpur the coefficient is 43 percent, with an annual rainfall of 382 millimeters, while at Hyderabad it is 20 percent, with an annual rainfall of 800 millimeters.
- The beginning and end points of the rainy season are highly variable.

- Tropical rains are generally more intense; therefore, a relatively high proportion is lost as run-off.[1]
- High temperatures throughout the year cause considerable losses by evaporation and evapotranspiration.
- The growth rates owing to favorable day and night temperatures are generally high, leading to high water consumptive rates.

Sanchez (1976) reports that only 28 percent of the region has adequate precipitation to support vegetation throughout the year. Lack of sufficient rainfall limits plant growth from four to six months in 42 percent of the area and from eight to twelve months in the remaining 30 percent. These rainfall characteristics pose major constraints on crop production. If the cropping season always has uniform rainfall, even if low in total amount, an efficient soil-moisture management system could be developed to utilize the precipitation. Since the average values of rainfall are skewed because of high and low rainfall months and years, however, farmers and planners must be attentive to this variation when planning systems and assessing risks, and adopt practices as suggested in response farming technology (see Chapter 3 for further discussion).

SOILS

The soils of the WSDT are diverse and varied (the predominant soil orders are shown in Figure 2-3). While low soil-moisture availability commonly restricts crop yields in the WSDT, there are several other soil, wind, and water erosion characteristics which also negatively affect crop production. These include:

- surface-soil crusting;
- compaction by tillage implements;
- low fertility and insufficient organic matter;
- restricted rooting depths;
- poor drainage; and
- salinization.

Soil degradation is a serious problem in the WSDT. It is a complex phenomenon because it is caused by a strong interaction between biophysical and other socioeconomic factors, including increasing rates of population growth, fragile economies, and poorly designed farm policies. Soil degradation can be subtle and slow until a certain threshold is reached, whereupon deterioration occurs quickly and, sometimes, irreversibly. The interdependence of soil degradation and biological and socioeconomic factors (Lal and Stewart, 1990) is illustrated in Figure 2-4. Consequently, when planning for higher degrees of self-sufficiency and sustainability, it is essential that differences in land-resource endowments and crop production potentials be fully appreciated. Various technological options for arresting soil erosion, including production and management practices, are presented in the following chapters.

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1. Alfisols in India under traditional farming systems have shown that 26 percent of the rainfall was lost as runoff, 33 percent was lost by deep percolation and evaporation during the non-growing period, and only 41 percent was lost by evapotranspiration—which determines crop production (S.A. El-Swaify and others, 1985).

Figure 2-1. Countries comprising the WSDT region

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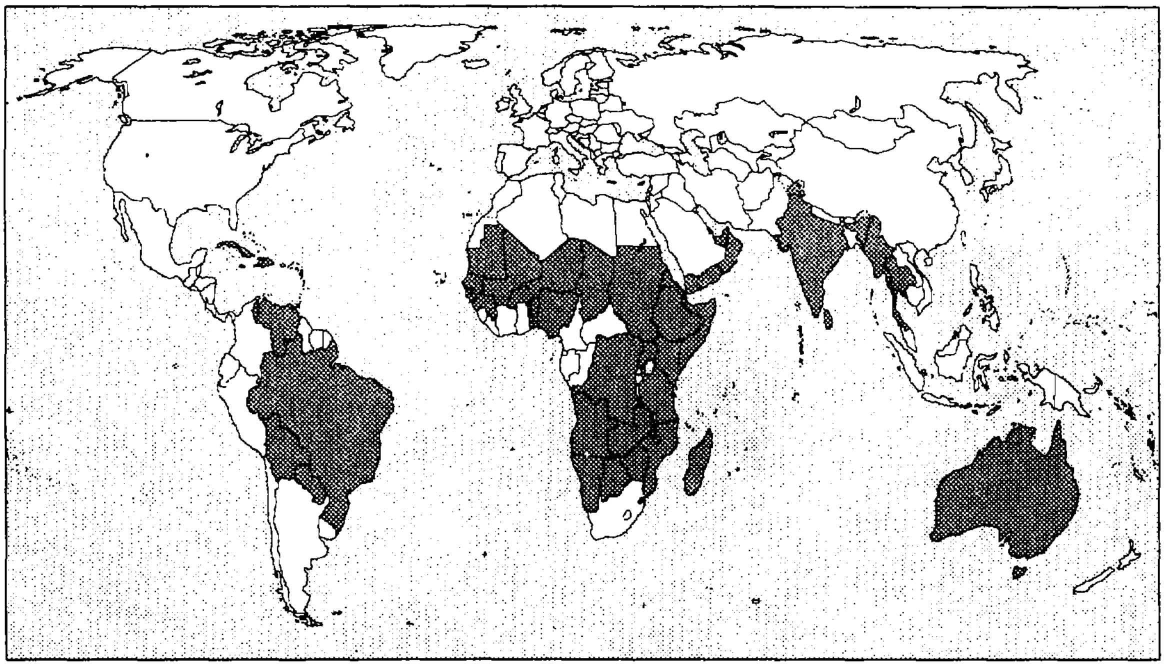


SUB-SAHARAN AFRICA

Angola
Benin
Botswana
Burkina Faso
Cape Verde
Chad
Comoros
Djibouti
Eritrea
Ethiopia
The Gambia
Guinea
Guinea-Bissau
Kenya
Madagascar
Malawi
Mali
Mauritania
Mozambique
Namibia
Niger
Nigeria
Senegal
Somalia
Sudan
Swaziland
Tanzania
Togo
Uganda
Zambia
Zimbabwe

CARIBBEAN

Antigua and Barbuda
The Bahamas
Cuba
Dominican Republic
Haiti
Jamaica

SOUTH AMERICA

Bolivia
Brazil
Paraguay
Venezuela

SOUTH ASIA

India
Myanmar
Sri Lanka

NEAR EAST

Oman
United Arab Emirates
Republic of Yemen

SOUTH EAST ASIA

Thailand

OCEANIA

Australia

JUNE 1993

Figure 2-2. Sub-ecoregions of the WSDT

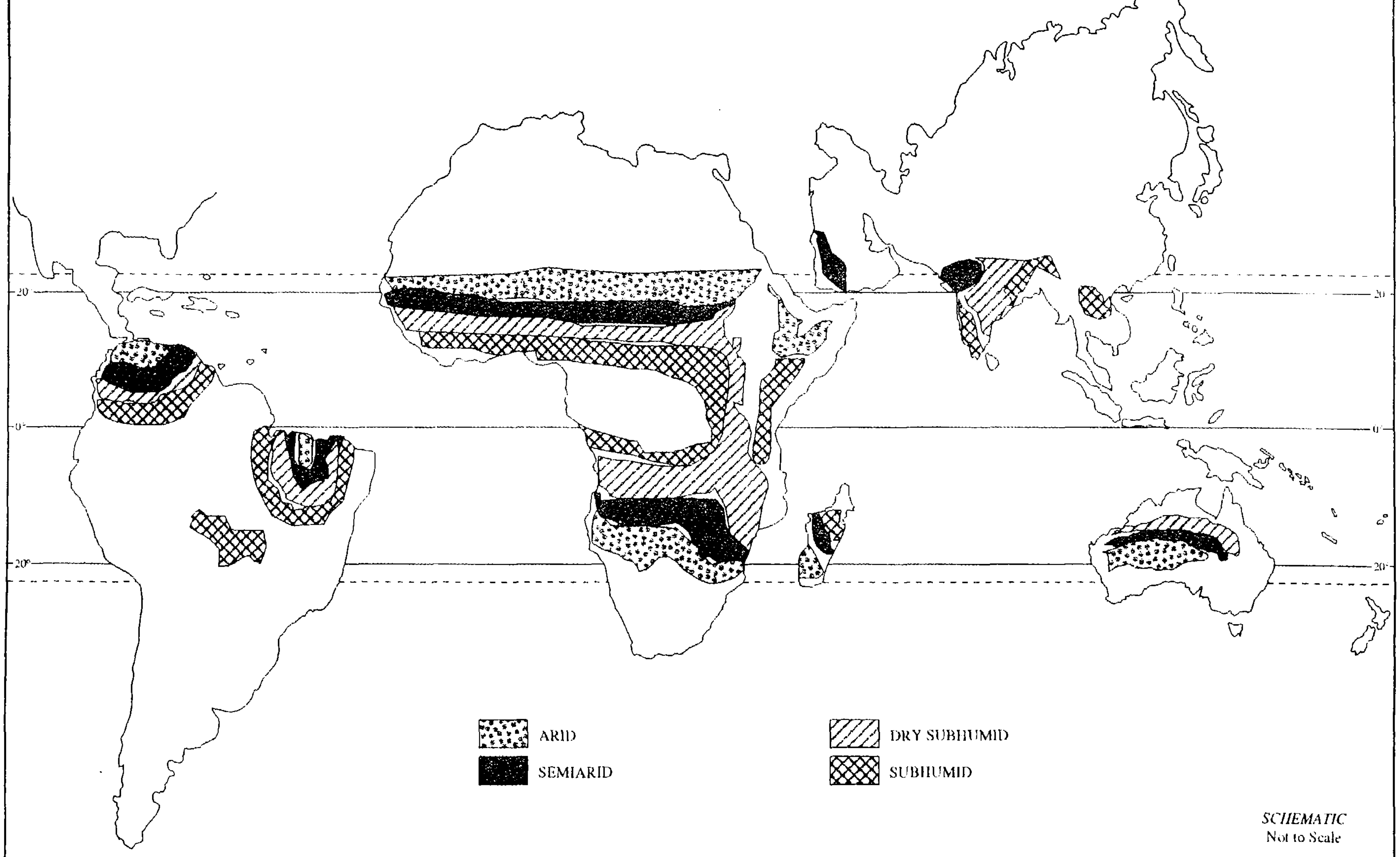


Figure 2-3. WSDT soil types

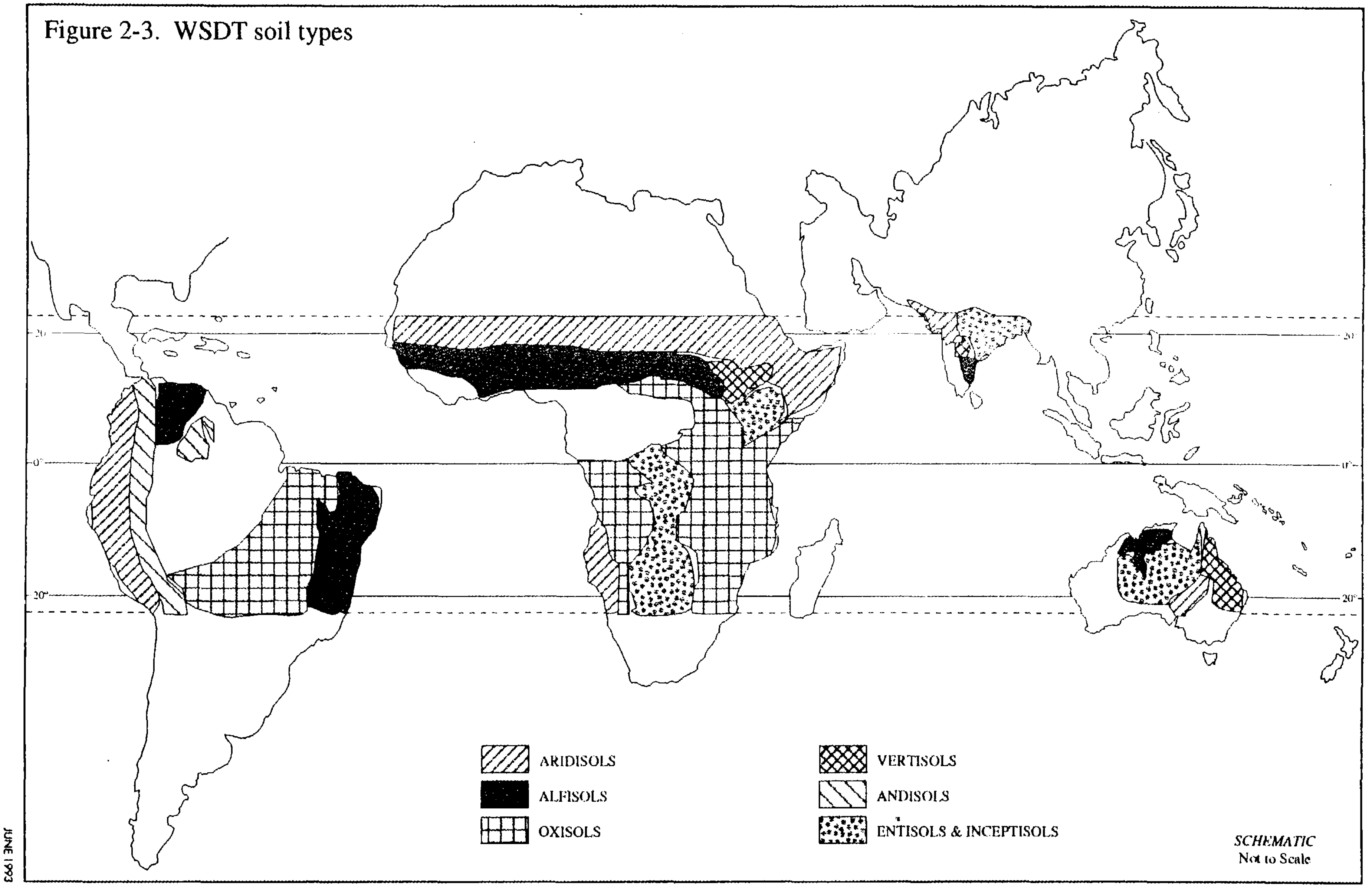
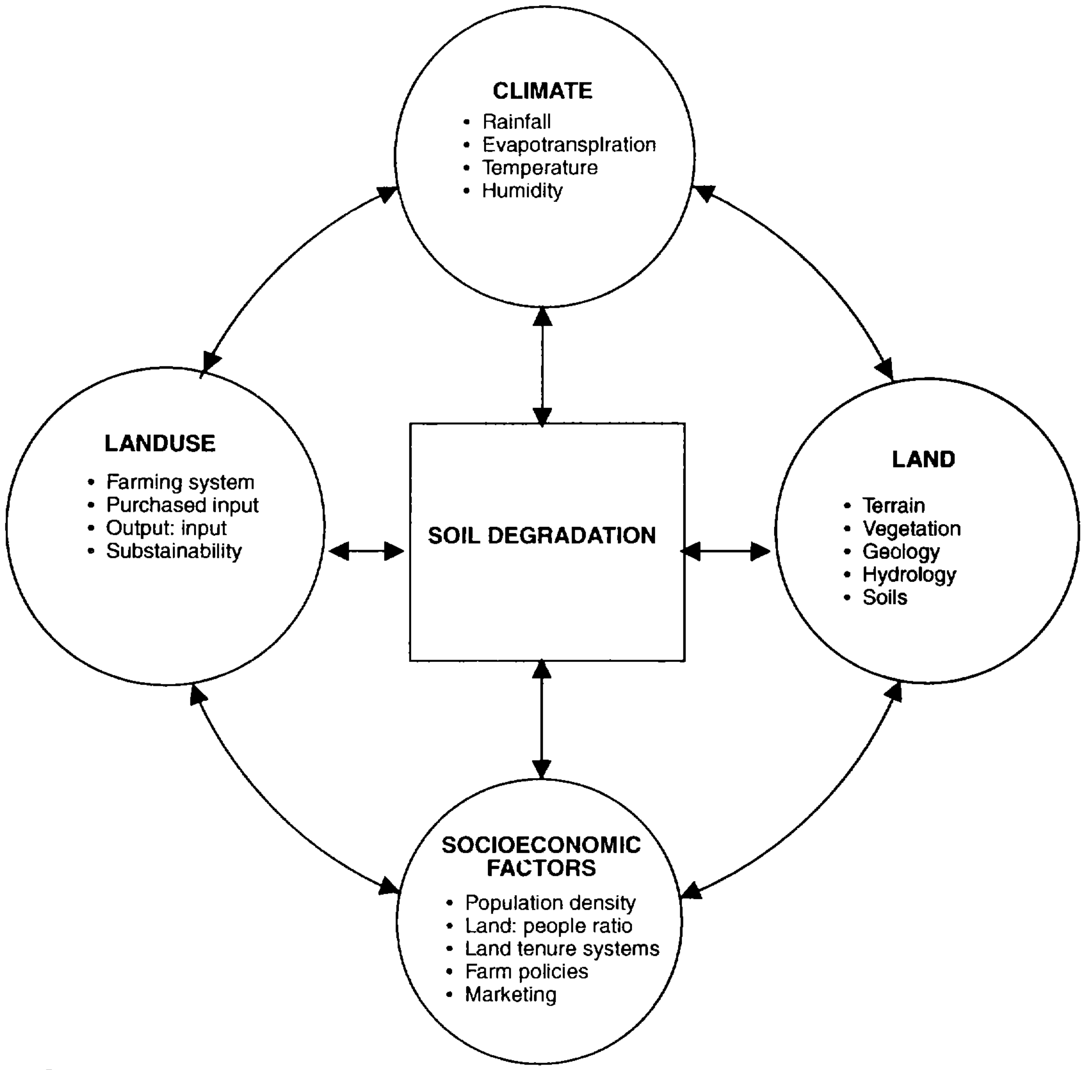


Figure 2-4. Interdependence of soil degradation and biological and socioeconomic factors



Source: Lal and Stewart, 1990

VEGETATION

Vegetation in the tropics can be grouped into five general categories (Sanchez, 1976). These categories, and the total area accounted for by each type, are:

- savannas and other grass land (43 percent);
- broad leaved evergreen rain forests (30 percent);
- semideciduous and deciduous forest (15 percent);
- desert shrubs and scatter grasses (7 percent); and
- barren lands (5 percent).

As shown in Figure 2-5, the WSDT are dominated by savannas and desert shrubs. The main factor influencing the vegetation type is the water available to meet transpirational requirements. It is difficult, however, to establish a one-to-one quantitative relationship between the available moisture and the vegetation because the condition of growth, plant density, and percentage of groundcover all interact with the available moisture on the one hand, and the soil condition on the other (Lal, 1987).

FARMING SYSTEMS

The WSDT are characterized by mixed farming systems where more than one crop is grown on the same piece of land at the same time, and in combination with trees or animals. These diverse systems provide food security under harsh climatic conditions, but are primarily subsistence or semi-commercial in nature. They are also extensive, based on the low use of commercial inputs, and are primarily labor-intensive. Farming systems in the WSDT include food crops and agroforestry in the subhumid sub-ecoregion; solely food crops in the semihumid region; food crops, cash crops (such as cotton), and livestock in the semiarid region; and livestock and tree-based systems in arid subregion.

LIVESTOCK AND WILDLIFE

The majority of livestock in the WSDT obtain their energy requirements by grazing from natural vegetation. Livestock offer an efficient means of converting otherwise inedible biomass into high-quality food. They also provide an ecological balance to the environment by recycling nutrients and enhancing vegetative growth. Increasing human populations, accompanied by growing numbers of livestock in WSDT, may result in soil degradation under improper management. These problems can be exacerbated by the lengthy dry periods characterizing the WSDT. The most critical constraints affecting livestock production and wildlife are:

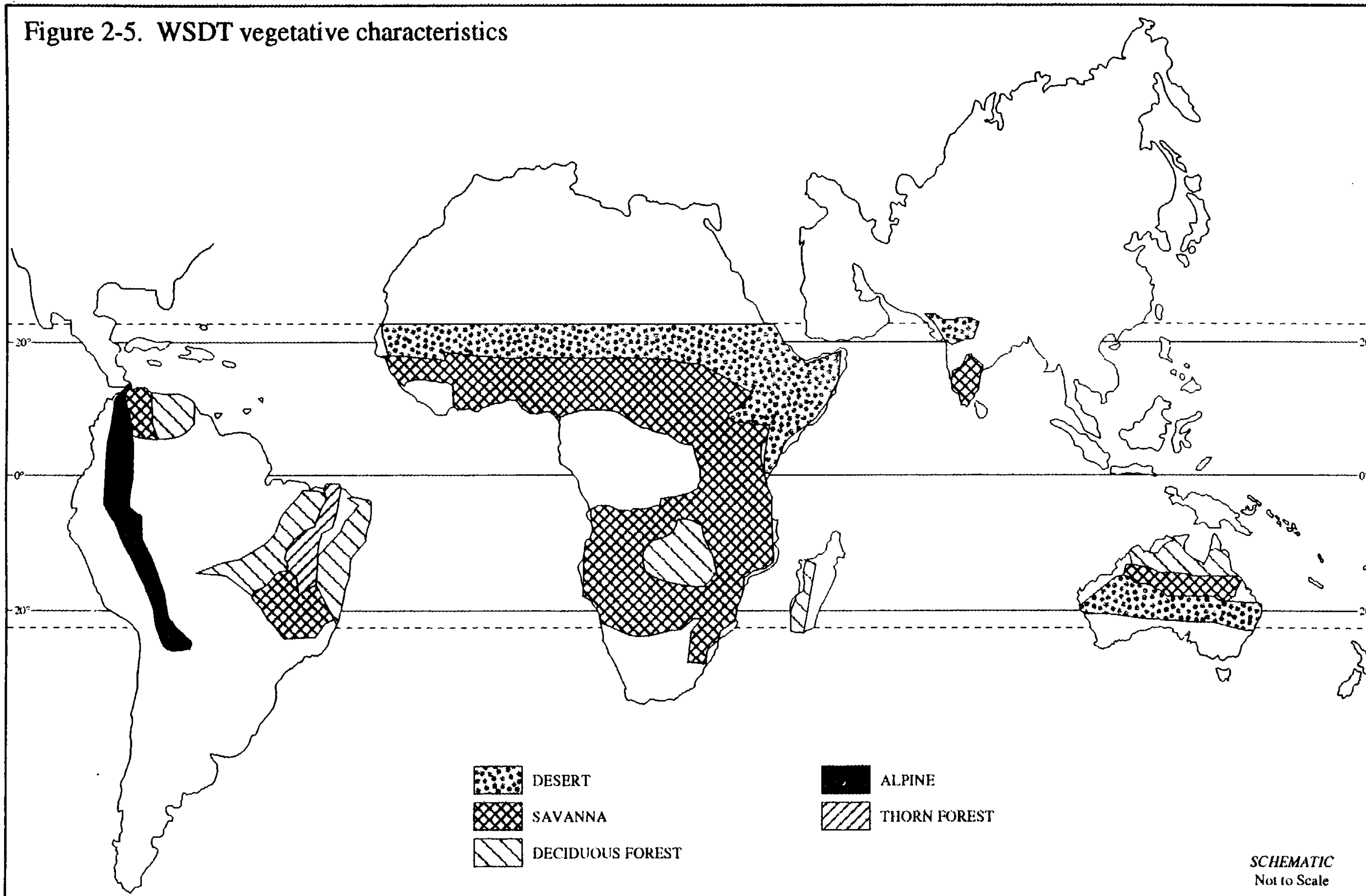
- the shortage and poor quality of feed resources;
- unpredictable, erratic, and occasionally insufficient rainfall; and
- lack of proper management, breeding, and health services.

ASSESSMENT

Insufficient water supply is the single most important factor governing agricultural production in WSDT. In addition to the low total amounts of annual precipitation, rainfall in the WSDT is highly erratic. Many of the soils in the WSDT are shallow, low in fertility, and extremely susceptible to wind and water erosion. These soils have low water-holding capacities and effective root volume is often restricted. As a result, seasonal and annual crops suffer from drought even within a few days following a heavy rain.

The scarcity of good-quality irrigation water is also a general problem, especially in countries with an annual rainfall of less than 700 millimeters. In Sub-Saharan Africa, only 5 percent of crop land is irrigated. A further expansion of irrigated agriculture on the continent is constrained by the high cost of bringing new land under irrigation. Furthermore, irrigation potentials are not well defined. Runoff in African river systems is low, and groundwater aquifers are inadequate. Therefore, it is important that soil moisture-conservation and water-harvesting technologies be successfully employed in the WSDT.

Figure 2-5. WSDT vegetative characteristics



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With annual rates of population growth exceeding 2.5 percent in many parts of the WSDT, large segments of the population have moved and continue to move to drought-prone areas. The traditional methods of coping with drought, such as long fallow periods and nomadism, are being forced to change in the face of rapidly growing human and animal populations. Consequently, large areas are under heavy pressure, thereby creating a potential for severe degradation of the resource base. The key to improving the sustainability of farming systems in the WSDT is to arrest further degradation of the natural resource base and to restore soil productivity. Several technologies have been suggested towards this end and have been tried with varying degrees of success. Ultimately, however, the adoption of technologies is site-specific. The most effective way to ensure the successful selection and implementation of those practices best suited for a specific location is to provide generally appropriate technological options and allow the farmer to use those best suited for that location. A range of such technological measures will be addressed in the following chapters.

Chapter 3

TECHNOLOGICAL OPTIONS FOR LAND-USE MANAGEMENT AND SOIL MOISTURE CONSERVATION

In the previous chapter, the WSDT ecoregion has been described and the main constraints for sustainable agricultural development have been identified. The remainder of this paper presents guidelines for the sustainable management of soil and water resources, and presents a menu of technological methods for mitigating the three main production constraints: insufficient soil moisture, soil erosion, and poor soil fertility. Table 3-1 summarizes the technological options discussed in this and the following chapters, and shows the applicability of each technology in overcoming the key production constraints in the WSDT. Each of the technologies or practices is described briefly—what it achieves and how it is adopted, followed by discussion of where it does and does not work. A few country-specific examples are also provided, as well as references for readers wishing to obtain more detailed information, to illustrate the utility of the technology. The purpose of the discussion is to provide a broad framework for sustainable resource management; the actual identification of specific practices applicable to a given site, however, still will require a site-specific technical evaluation and assessment.

Table 3-1. Technological options for achieving sustainable agriculture

Technology	Useful for			
	Soil-moisture conservation	Soil Erosion		Soil-fertility improvement
		Prevention	Control	
1. Land-use management	X	X	X	X
2. Conservation tillage	X	X	X	X
3. Ground cover management	X	X	X	X
4. Bench terracing	X		X	
5. Response farming	X			
6. Water harvesting	X		X	
7. Small catchment	X		X	
8. Supplemental irrigation	X			
9. Legumes green manuring	X	X		X
10. Vegetative hedges	X	X		X
11. Strip cropping	X	X		
12. Contour bunding and farming	X	X		
13. Engineering structures	X	X	X	
14. Fertilizer and organic matter use	X	X	X	X

Source: Authors

LAND-USE MANAGEMENT

Judicious land use is a principal factor underlying sustained agricultural production, maintenance, and enhancement of the productive potential and life-support processes of natural resources, while minimizing adverse effects on the environment. Choosing an appropriate land use is the foremost consideration in the sustainable management of soil and water resources. The choice of an appropriate use depends on the land-use capability—which is a function of the soil, vegetation, water, climate, terrain, mineral resources, accessibility, marketing, and infrastructure. A rational decision regarding the choice of an appropriate land use must rest upon an objective assessment of these resources. In conducting a natural resource inventory, land resources can be broadly classified into five categories:

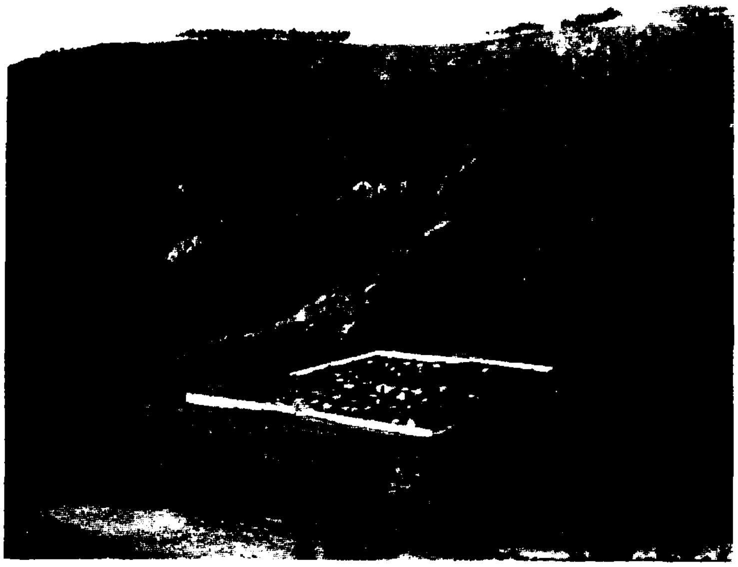
- non-agricultural land;
- marginal land;
- prime agricultural land;
- restrictive agricultural land; and
- degraded land.

The amount of available, prime agricultural land in the WSDT is finite, since these lands mostly have been developed and are being intensively used. In order for the population of the WSDT to feed itself, therefore, it is necessary that the productivity of restrictive agricultural land and degraded land be restored and improved. Some of these land restorative techniques are discussed in the following chapters. These techniques are based on the principles of conserving soil moisture, controlling soil erosion, enhancing soil organic matter content, improving soil fertility, and ameliorating nutrient imbalances.

The starting point for a national strategy of sustainable production should be to conduct a baseline inventory of natural resources. A detailed natural resource survey of soil, vegetation, and water should be conducted at a 1:100,000 (preferably at a 1:50,000 scale). Once the ground surveys are completed, the next step is the use of Geographical Information System (GIS). A GIS enables the computerized compilation into a single data base of all the information that was formerly contained in a variety of different forms such as geological surveys, soil surveys, and meteorological and hydrological records -- traditional sources of data that are not easy to combine into an easily usable format. The new GIS technique, however, allows the rapid creation of a natural resource data base.

It is insufficient to simply classify the many different types of agricultural land into "annual crops," "pastures," or "forests." This is because the way these lands are managed has a significant effect on their capacity for production and on their protective characteristics. For example, poorly managed pasture on a steep slope with compacted soil and little vegetative cover may be less productive or protective than a well-managed system of annual crops under minimum tillage, with maintenance of excellent cover and structural conditions on the same slope. Similarly, perennial crops such as citrus, coconut, and apple trees provide almost no effective protection to any bare soil beneath them. It is the low-growing grasses, legumes, or mulch covering the soil surface between the trees of a well-managed plantation that provide protection—not the trees themselves. The better the land's use is matched with the land's characteristics, the easier it will be to keep that use productive and the land stable. (*See* Figure 3-1 for an illustration of the results of appropriate and inappropriate matching of land use to land type.)

Figure 3-1. Matching of land use to land type



Inappropriate matching of land use to land type on this Peruvian hillslope led to severe erosion and subsequent abandonment of the land for cropping purposes.

A wide-spaced perennial crop (apple trees) with a good, low groundcover on conservation banks represents an appropriate match of land use to land type.

Inadequate husbandry has devastated this land in Kondoa, Tanzania.

Source: Shaxson et al., 1989.

SOIL-MOISTURE CONSERVATION

Soil-moisture conservation and control of soil erosion is crucial to alleviating the adverse effects of recurring drought on crop and animal productivity in the WSDT. While drought is a natural phenomenon in arid and semiarid climates, its effects and severity can be mitigated by the judicious management of soil and water resources through the adoption of technology for rainfed agriculture. Using varieties with short growing seasons helps maximize soil and water conservation. Rainfall effectiveness in dryland farming can be dramatically improved through the use of conservation measures and a water efficient cropping system. These measures are based on the principle of improving in situ soil-moisture conservation in the root zone through increased infiltration and crop water use and reduced runoff and evaporation.

The technological measures appropriate for maximizing soil-moisture conservation can be grouped in the following categories:

- groundcover management;
- conservation tillage;
- bench terracing;
- water harvesting;
- small catchment;
- supplemental irrigation; and
- response farming.

Groundcover Management

A continuous groundcover is an effective means to ensure soil-moisture conservation and prevent soil erosion. Groundcover is influenced by the choice of land use and farming and cropping systems. Inappropriate land use accelerates the erosion rate beyond a tolerable level. The adverse effects of inappropriate land use are further accentuated in the harsh climates of the seasonally dry tropics. Other factors remaining constant, the risk of erosion is greatest for bare ground, and is increasingly less likely with each of the following land uses: arable land before planting, perennial crops, grass-legume mixtures and other cover crops and forages, and natural vegetation. Erosion risks are dramatically increased, however, if cover crops or forages are grazed.

Crop rotations and sequences, mixed and multiple cropping, and relay cropping systems are also effective tools for groundcover management. Crop rotation is an integral component of successful conservation tillage and its benefits are widely recognized. An ideal rotation should involve sequential cropping of a cereal followed by a legume, shallow-rooted crops by deep-rooted crops, fertility-depleting by fertility-conserving crops, soil-degrading by soil-regenerating crops, and crops demanding heavy inputs by those that can survive on low inputs. The objective is to create a desired level of crop diversification. Mixed and multiple cropping should be the rule rather than the exception in the tropics. Diversified cropping systems based on multiple cropping are more conservation-effective than are monocultures or simplified cropping systems. Some relevant groundcover management systems for soil and water conservation include the following.

Cover crops. Diversifying the cropping system is necessary to create ecological stability and reduce the risks of soil erosion. Growing grass or leguminous cover crops at frequent intervals—once every two to three years in subhumid zones, and once every one to two years in the semiarid tropics—is necessary for the sustainable management of soil and water resources. Cover crops have many advantages for the sustained use of natural resources. For example, they restore fertility, control weeds, avoid repeated seeding and cultivation traffic, conserve rainwater, and reduce energy costs. In addition to controlling pests, cover crops improve soil physical properties and soil tilth and reduce soil erosion.

Cover crops are relatively more beneficial in the semihumid tropics than in the arid tropics and long have been used for soil and water conservation, especially on steep lands and in plantation crops. In addition to augmenting soil fertility, cover crops also improve soil structure and increase macroporosity. Significant benefits of grass fallow rotations for the infiltration of water into the savanna zone soil have been observed. The infiltration rate usually increases as the length of the fallow period increases. Growing cover crop is widely recommended for structure restoration. The benefits of cover crops for soil structure and tilth improvement have been demonstrated for the semiarid tropics of Africa. Similarly, experiments conducted in Panama and Brazil have shown that cover crops (such as *Avena strigosa*, *Raphanus sativus*, and *Lupinus albus*) grown in winter have beneficial effects on the control of water erosion and on the yield of the following summer crops: beans, soybeans, and maize. Yield increases of 93 percent in beans, 73 percent in soybeans, and 81 percent in maize were observed when these crops were grown after the use of an appropriate legume cover.

Mulch. A mulch tillage system ensures a maximum of crop residues on the soil surface. It is also called stubble mulch farming, and is defined as preparation of the soil such that plant residue or other mulching materials are specifically left on or near the surface. When a grain crop is seeded through the mulch of a chemically killed cover crop, it is called sod seeding. If the cover is only temporarily suppressed, or not killed, the system is called live mulch. In addition to helping to reduce soil erosion, mulches also play an important role in regulating soil temperature and reducing the soil evaporation rate (*see* Box 3.1 on the following page). Mulches increase soil-water storage through improved infiltration, decreased evaporation, and reduced losses due to weeds. Practical means to procure mulch include utilizing crop residue in situ and growing a close canopy cover crop. In addition, a wide range of material is used as mulches—from gravels and stones, crop residues, and plastic sheets to soil amendments. In general, legumes are more suited for in situ use than grasses. Grasses, however, produce more biomass and can be cut and carried for use as mulch elsewhere. Cover crops also enhance soil structure and improve soil fertility. The beneficial effects of mulching are illustrated in Table 3-2 below.

Legumes Green Manuring. Green manuring is not a viable option for the arid and semiarid regions of the WSDT. Lengthy dry seasons constrain the use of green manure, thereby depriving farmers of legumes' nitrogen fixation qualities. This is a serious loss to farmers in areas where nitrogen fertilizer is either unavailable or too expensive. In addition, the potential for land erosion is greater when neither crops nor legumes are grown.

Experiments by researchers from the Soil Management Collaboration Research Support Programs (CRSP) and the Centro de Pesquisa Agropecuária dos Cerrados in Brazil demonstrated that drought-resistant legumes planted at the end of the dry season will survive and continue to grow in the following wet season, thereby providing a source of nitrogen and controlling soil erosion. Under favorable conditions, certain types of legumes can produce dry matter in excess of 5000 kilograms per hectare and nitrogen in excess of 100 kilograms per hectare for the following maize crop. These results suggest that legumes can be matched to almost any savanna cropping system (TropSoils, January 1992).

Box 3.1 Mulch farming

Mulching is an important management tool for soils of the WSDT. Use of crop residue mulch has profound beneficial effects on soil properties, microclimate, and agronomic productivity. The principal benefits of crop residue mulch include the following:

- Soil and water conservation: Mulching conserves soil and water through improvements in soil structure and macroporosity, increases infiltration capacity, decreases losses due to runoff and evaporation, and reduces raindrop impact and soil splash. Most of the rain falling directly on bare, crusted soil is lost due to surface runoff and evaporation. Consequently, crops suffer from frequent and severe drought even during the rainy season. Mulching with plant residue conserves rainwater in the root zone and increases crop growth and yield.

- Soil structure improvement: Mulching enhances structural properties. The infiltration rate on soils with crop residue mulch may be five to ten times greater than that on crusted, unmulched soil. Crop residue mulch increases macropores through the mixing and burrowing activity of soil animals such as termites and earthworms.

- Soil organic matter content augmentation: Regular additions of crop residue to soil may also improve soil organic matter content and enhance soil fertility. Nutrient recycling and enrichment through crop residue mulch are critical to high yields on depleted and infertile soils of the WSDT.

- Soil fertility enhancement: Application of crop residue mulch also enhances soil fertility through the addition of plant nutrients contained in the biomass. Crop residue of cereals (e.g., maize, millet, sorghum) adds cations to the soil (notably potassium, calcium, and magnesium), and the residue of legumes (e.g., cowpea, pigeon pea, soybean, mucuna, crotolaria) also supplies nitrogen.

- Soil temperature moderation: In the WSDT, crop residue mulch also plays a major role in regulating soil temperature. The maximum soil temperature, often within the lethal range for young seedlings, is lowered by 15 to 20° Celsius by residue mulch applied at the rate of 4 to 6 tons per hectare. Poor crop stand is a major factor in low yields in the Sahel, and mulching drastically reduces seedling mortality and improves crop stand.

- Degraded soil restoration: Soil degradation is a major problem in the WSDT. Owing to high demographic pressure and land hunger, restoring the productivity of degraded soils is very important. The addition of crop residue can be extremely effective in restoring the productivity of degraded infertile soils. In regions prone to wind erosion, crop residue controls erosion, traps wind-borne dust, increases topsoil depth, and generates a restorative trend because trapped soil is rich in plant nutrients and improves conditions for plant growth.

Research conducted on diverse soils and sub-ecoregions of the WSDT in Africa have demonstrated substantial benefits in yields due to crop residue mulch. With good management and adoption of other recommended practices, application of crop residue mulch can increase yield by a factor of three to ten. Crop residue mulch has a yield stabilizing effect in the harsh environment and fragile soils of the WSDT. The desired quantity of crop residue mulch can be obtained through the adoption of appropriate farming systems—for example, the use of cover crops, controlled grazing, and diversified/mixed cropping.

Table 3-2. Mulching effects on infiltration rate of an Alfisol in northern Nigeria

Treatment	Percentage of rainfall penetration into soil
Bare Soil	
Undisturbed	31
Hoed at 15-day intervals	49
Hoed after every rain	57
Mulched Soil	
Dead grass mulch	90
Groundnut shell mulch	89
Sorghum stalk mulch	98

Source: Lawes, 1962.

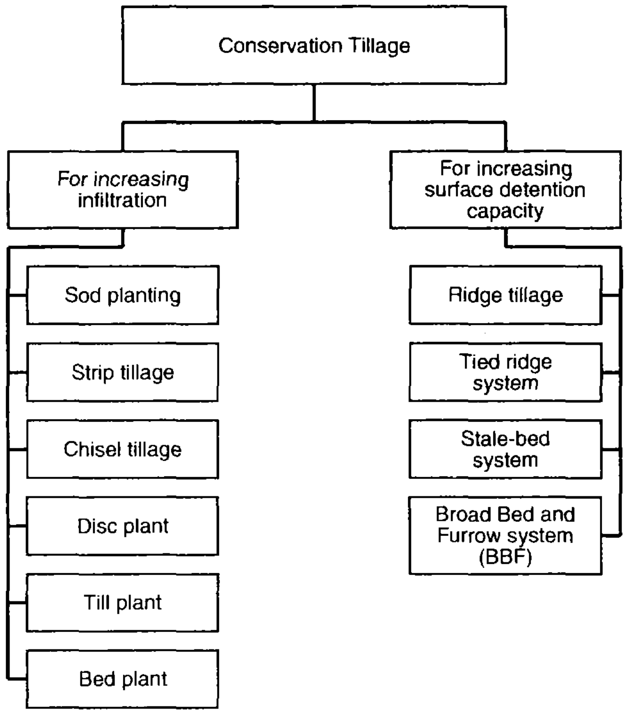
Conservation Tillage

A seedbed preparation system based on the concept of minimum soil disturbance and maintenance of crop residue mulch is known as conservation tillage. In the context of the WSDT, however, conservation tillage implies any tillage system which is more effective in reducing the loss of soil or water than the traditional system of seedbed preparation. Conservation tillage is often a form of non-inversion tillage that reduces soil disturbances and retains a protective amount of residue mulch on the soil surface. This practice of residue management (achieved by conservation tillage) intercepts runoff and results in soil-moisture conservation by:

- improving soil-structure:
- reducing crust and decreasing runoff;
- increasing the infiltration rate;
- reducing evaporation;
- increasing water storage;
- improving water-use efficiency;
- increasing effective rooting depth; and
- reducing soil compaction.

As seen in Figure 3-2, a broad range of conservation tillage systems are used to conserve soil moisture (Lal 1980, 1989b). Conservation tillage is a generic term and involves two broad categories: (i) tillage systems that improve infiltration capacity; and, (ii) tillage methods that enhance surface detention capacity and increase the time available for water to infiltrate into the soil. Since soil disturbance is minimal under conservation tillage, the maximum amount of crop residue is retained on the surface.

Figure 3-2. Types of conservation tillage systems



Weeds are controlled by chemicals, through the use of an aggressive cover crop, or by a combination of these methods. Several variants of these tillage systems are discussed below.

- *Sod planting*. Planting is done directly into unplowed soil with chemically killed sod, weeds, or cover crops, or in previous crop residue. With this method, paraquat or another contact herbicide is used to replace plowing and manual or mechanical weeding, and residual herbicides (atrazine, lasso, etc.) are used for reemergence weed control. Crops can be planted either by hand planter or by opening a narrow trench (5 centimeters to 7 centimeters wide and 5 centimeters deep) for the seed.

- *Strip tillage*. Tillage is eliminated in most of the inter-row areas, and a narrow strip is opened to facilitate planting and the placement of the fertilizer. The crop residue is left undisturbed in the inter-row zone.

- *Chisel tillage*. Primary tillage is replaced by subsoiling with a chisel plow or paraplow in the row zone. The primary objective is to loosen the compacted subsoil.

- *Disc plant*. One disking, prior to planting and leaving most of the crop residues on the surface, also can help open a crusted field and improve its infiltration, water-holding capacity, and root penetration.

- *Till plant*. Tractor-driven equipment can be used on large farms to slash and remove in one operation the previous crop residue from the row to the inter-row zone, and also to open a small trench as a seedbed.

- *Bed plant*. This method can be used for surface irrigated crops. Small furrows can be opened at a distance of 1 to 1.5 meters, raising the bed in between, and then planting manually or with a mechanical planter directly on the bed.

Tillage systems that increase surface detention capacity are based on a system of soil inversion. The principal variants of this system include:

- *Ridge tillage*. The practice of planting or seeding crops on ridges is a widely adopted system in tropical climates (*see* Box 3.2 on the following page). The crop row may be planted on the ridgetop, along both ridge sides, or in the furrow. Ridge tillage facilitates mixed cropping systems in which more than one crop is grown simultaneously on the same plot of land, a common practice throughout the tropics and subtropics (Bradfield, 1970). The ridges may be made every season. Alternatively, in a semipermanent ridge-furrow system, only necessary repairs are performed at the onset of a new cropping cycle.

  In Cinzana, Mali, ridge-tilling practices used in conjunction with fertilization impressively increased crop yields. Over a four-year period, sorghum grain yields increased threefold, from 897 to 2,310 kilograms per hectare; yields of stover grew 2.2-fold, from 2,912 to 6,725 kilograms per hectare; and the output of cowpea grains increased by 123 percent, from 412 to 921 kilograms per hectare. Similarly, cowpea hay yields increased by 87 percent, from 1,379 to 2,580 kilograms per hectare (TropSoils, January 1993).

- *Tied ridging*. In ridge tillage, the ridges may be on a contour with graded furrows draining into a grassed waterway, or the ridges may have short cross-ties to create a series of basins to store water. The latter system with cross-ties is called the tied ridge system. This system is found to be most beneficial in the West African Sahel (Hulugalle, 1990).

- *Stale-bed system*. In a stale-bed system, soil inversion through moldboard plowing is done at the end of the previous crop cycle. The next crop is seeded with a minimum of seedbed preparations, such as disc harrow, performed at the onset of the next rains. This is commonly recommended for soils of the semiarid tropics in West Africa (Charreau and Nicou, 1971). In another variant of this system, commonly observed in temperate zone climates, primary tillage operations are performed in the fall or early spring, followed by secondary tillage operations at the time of seeding.

- *Broad Bed and Furrow System (BBF)*. At the International Crop Research Institute for Semi-Arid Tropics (ICRISAT) in Hyderabad, India, a Broad Bed and Furrow (BBF) system has been developed to reduce runoff and erosion and to permit cropping during the monsoon season (*see* Table 3-3) (Kampen, 1982).

The most important consideration in conservation tillage is breaking the surface crust or seal by some form of tillage, thereby improving water infiltration into the soil. As the following examples illustrate, this practice has a number of beneficial effects:

Box 3.2 Ridge tillage and tied ridging

Ridge tillage is a method of seedbed preparation whereby the fertile topsoil is scraped and concentrated in a narrow zone to raise the seedbed above the natural terrain. Ridge tillage is an ancient cultural tradition that has evolved as an integral component of farming systems in many sub-ecoregions of the WSDT. Ridge tillage has distinct advantages in:

- Saving labor: It saves labor because only about half of the field is disturbed for making ridges, in comparison with general plowing, and fresh ridges are often made only every other season. Crops are usually sown after repairing the old ridges. Ridge planting also facilitates the harvesting of root crops.

- Enhancing soil fertility: In addition to concentrating fertile topsoil, forming ridges also incorporates ash and organic residue in the seedrow zone. Fertilizer and organic manures also are used efficiently when applied in the narrow ridged zone.

- Water management: Water management—conserving surplus water in the root zone during the monsoon season for crop use during the post-rainy season—is crucial to high and sustained yields in the WSDT. Contour ridging decreases runoff losses, increases infiltration, and conserves water in the root zone.

- Erosion control: Contour ridging is an effective anti-erosion practice, particularly if the slope gradient is gentle. A ridged seedbed, and the rough surface thus created, is an effective measure against both wind and water erosion.

- Multiple cropping: Ridge tillage facilitates multiple cropping, especially in wetlands where upland crops can be grown on ridges and wetland crops in the furrow. Ridge tillage helps create crop diversification.

- Enhancing soil depth: If cultivation of shallow soils is inevitable, ridge tillage is a practical way to enhance rooting depth. The practice is especially useful for growing root crops.

- Weed control: Ridge tillage enables weed control through animal-drawn or motorized intercultivation equipment.

In fact, ridge tillage is a versatile system. The practice is useful in increasing the effective root volume in shallow soils, conserving water in drought-prone soils, draining water on poorly drained soils, controlling weeds by interrow cultivation, enhancing fertility by residue management and fertilizer placement, and facilitating multiple cropping by crop diversification.

Tied ridging -- contour ridges with additional cross ties in the furrows -- is an improvement over the simple ridge furrow system. The system of tied ridging holds surplus rain water in individual basins and allows more time for water to infiltrate into the soil. Done properly on gentle slopes, tied ridging is an extremely effective soil and water conservation measure. Yield increases from tied ridging in drought-prone soils of low inherent fertility are attributed to improved water conservation, favorable soil physical conditions, improved soil fertility, and a favorable temperature regime.

Table 3-3. Effectiveness of Broad Bed and Furrow (BBF) system on runoff control on Vertisols in Hyderabad, India

Month (1978)	Rainfall (mm)	Runoff (mm)	
		Cropped with BBF system	Fallow
June	82.6	10.4	8.3
July	110.0	13.4	48.5
August	452.9	245.6	337.9
Total annual	706.1	272.5	410.1

Source: Kampen et al., 1981.

- Experiments conducted in the West African Sahel by the Institute de Recherche Agronomique Tropical (IRAT) have indicated that for those soils prone to crusting and compaction, deep plowing at the end of the rains, rather than traditional hoeing, is necessary (Nicou, 1979). Results have shown that the highest grain yields of peanuts, millet, maize, and rice were obtained when soil was plowed to alleviate compaction (*see* Table 3-4).

- Yield improvements by deep ripping may be due to better water conservation and deeper root system development. Klaij (1983) observed that for Alfisols in Hyderabad, India, deep tillage increased the infiltration rate, and decreased runoff and soil losses. The increase in random roughness created by moldboard plowing increases surface detention capacity and the infiltration rate. Such soil-loosening tillage techniques are not required every year. Once loosened, these restored soils may produce satisfactory yields for two to four years (Stibbe and Ariel, 1970).

- A system of raised and cambered beds, 7 millimeters to 8 millimeters apart, produced good yields over a number of years in the western cotton-growing areas of Sukumaland in Tanzania (Lal, 1989a, b).

Bench Terracing

A bench terrace is defined as a terrace system employing level contour benches and ridges to provide erosion control and to retain, spread, and infiltrate surface runoff for the enhancement of soil moisture and related crop production (Zingg and Hauser, 1959). The elements of the system, illustrated schematically in Figure 3-3, include a level contour bench (area B) constructed to serve as a catchment area for potential runoff from both the bench and contributing area (area C). The terrace ridge (area A) serves as the control for impounding and spreading runoff water. The dimensions of the system are variable according to the slope, soils, land use, and anticipated runoff.

Jones and others (1985) summarized the results of a system, used in the semiarid Great Plains of the United States, in which the contributing area was two times the width of the bench. The contributing area was cropped to a wheat-sorghum-fallow sequence (two crops in three years), while the bench was cropped

Table 3-4. Tillage effects on crop yields for different soils of the semiarid regions of West Africa

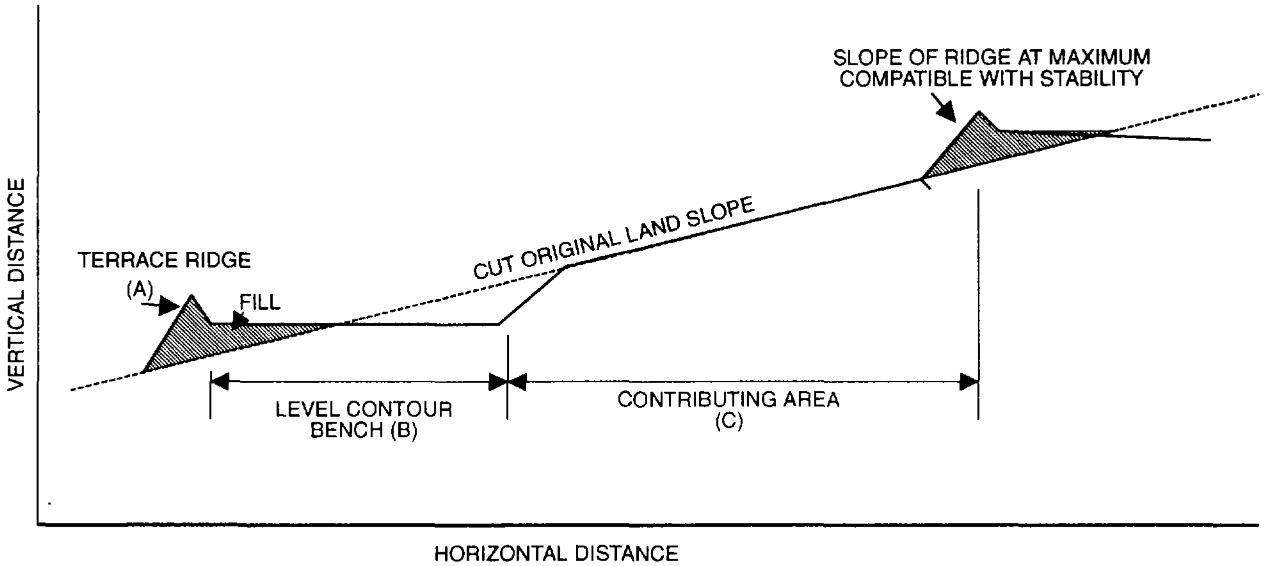
	Deep plowing (kg/ha)	Hoe-tillage (kg/ha)
Senegal		
Groundnuts	2029	1536
Millet	1635	1546
Maize	3014	1515
Rice (rainfed)	3417	1765
Togo		
Maize	1991	608
Sorghum	3392	1259
Groundnuts	1111	666
Côte d'Ivoire		
Class 1 soils[a]		
Variety IRAT 81	4355	4510
CJB	3125	2920
Class 2/3 soils[b]		
IRAT	3340	2740
CJB	2180	1800
Rainfed Rice		
Class 1 soils[a]		
Variety IRAT 13	3240	3340
Moroberekan	1700	1850
Class 2/3 soils[b]		
Variety IRAT 13	2200	1900
Moroberekan	1240	1560

[a] Class 1 soils: soils with good water retention properties
[b] Class 2/3 soils: soils with gravel content and poor water retention properties.
Source: Nicou, 1979

annually with grain sorghum, wheat, sunflowers, or alfalfa. The annual precipitation for the study area was 460 millimeters, and the leveled bench area received an average of 107 millimeters more water than the adjacent sloping land. This strategy is applicable to areas where precipitation during the growing season is often inadequate for crop production. The prevention of runoff from the bench, plus the runoff from the contributing area, results in sufficient water for a successful crop (*see* Table 3-5 on the beneficial effects of terraces on runoff and erosion).

In many areas, the best strategy is simply to have a level bench without any contributing area. Land leveling is the most effective means of conserving runoff and preventing soil erosion; however, it is also the most expensive. As a result, this method has not been used widely. As an alternative to land leveling, practical, narrow minibenches can be constructed economically on gently sloping (0 to 2 percent slope) soils (Jones and others, 1985). Soil cuts are relatively shallow when using minibench terraces (5 millimeters to 10 millimeters wide), significantly reducing the soil fertility problems that are normally associated with land leveling. More importantly, minibenches do not require much soil to be moved, making the system much less expensive to construct. This strategy is most suitable where small equipment is commonly used.

Figure 3-3. Cross section of the slope-control practice of conservation benching



Source: Zingg and Hauser, 1959

Table 3-5. Effect of terraces made from local stones on water conservation in Niger

Treatment	Runoff (% of rainfall)	Erosion (t/ha/yr)
Control (traditional hoe)	17.6	9.5
Stone line terraces	3.8	0.5
Earthen terraces with stone lines	0.9	0.2

Source: Delwaulle, 1973.

Another alternative to land leveling is the use of furrow dikes, or tied ridges (Jones and others, 1985). This is a proven soil and water conservation method and is used in many areas of the world. The furrow dams are usually destroyed by tillage, however, and must be reconstructed each year. They also can be an obstacle during cultivation or harvesting operations. Finally, runoff may also occur prior to construction of the furrow dams, or after they have been removed.

Water Harvesting

Water harvesting is a process of collecting rainwater from a modified or treated area to either maximize or minimize runoff (Perrier, 1988). Collected runoff water can be stored in soils, behind dams, in wadis, or in place on terraced or tied-ridged agricultural plots. Perrier (1988) described probability techniques that can be used to evaluate the amount of risk involved before deciding to construct a water harvesting system.

Water harvesting strategies are site-specific. The most important factors are the soil storage characteristics and the distribution of rainfall with respect to the growing season. Using Hyderabad, India, as an example, El-Swaify and others (1985) showed that the traditional cropping system on Vertisols resulted in 28 percent of the annual rainfall being lost as runoff, and 9 percent lost as deep percolation. On Alfisols, they found that the extent of runoff was similar, at 26 percent, but percolation loss was 33 percent. There were substantial losses to percolation on both soils, and this occurred for all years of the study. The reason for these losses is that rainfall in this area during the wet season exceeds the water-holding capacity of the soil profile. This is in contrast to other semiarid regions where rainfall, even if runoff is completely eliminated, is often not sufficient to fully recharge the soil profile. Therefore, although substantial runoff is common in nearly all semiarid regions, there is no common strategy for either reducing runoff losses, or recycling it for supplemental irrigation.

Small Catchments

In areas where precipitation during the early part of the growing season is generally sufficient to fully wet the soil profile, runoff prevention will result in excessive percolation. Excessive percolation reduces soil fertility, particularly because of the leaching of readily soluble nitrogen. The prevention of runoff will control soil erosion; but, unless there is a water table below that can be used for supplemental irrigation, the prevention of runoff will generally not increase the water available for crop production. Therefore, water harvesting in these areas should focus on the use of catchments that can hold the water so it can be used later for irrigation. These catchments can be cisterns or ponds. A frequent problem with these systems is seepage of the captured water before it is needed for irrigation. Also, the water must be pumped or manually lifted and applied to the crops. Despite these constraints, stored runoff water for supplemental irrigation can be beneficial, as shown in Table 3-6.

Table 3-6. Effects of supplemental irrigation on crop yield in India (q/ha)

Crop	Site	Without Irrigation	With Irrigation	Yield increase (%)
Cowpea (fodder)	Banglore	61.0	114.0	88
Cowpea (grain)	Banglore	2.7	7.7	185
Mustard	Jodhpur	0.8	2.1	163

Source: Vijayalakshmi and others, 1982

Supplemental Irrigation

Supplemental irrigation is the use of additional water to stabilize and improve crop yields in areas where crops can be grown by natural rainfall. This in contrast with irrigation, which supplies the entire water need where rainfall is insufficient for plant growth during all, or most, of the growing season. In many areas of the WSDT, supplemental irrigation can alleviate risk, increase and stabilize yields, and allow the use of inputs such as high-yielding cultivars and fertilizers.

In most areas of the WSDT, the amount of water available for irrigation is usually very limited and undependable. Limited water supplies, such as captured runoff water, can be used in three ways:

- to supplement the rainfall during the normal crop growing season;
- to lengthen the growing season so that longer-growing crops can be produced; and
- to grow crops during dry seasons.

The beneficial effects of supplemental irrigation are illustrated in Table 3-7.

Table 3-7. Effect of supplemental irrigation on yield of post-rainy season crops in India

Crop	Location	Irrigation (cm)	Yield (q/ha)	Yield increase owing to irrigation (%)
Safflower	Bellary	+	1.3	+
		5.0	2.9	123
		7.5	3.7	184
		10.0	4.6	345
Rapeseed	Ranchi	+	2.5	+
		1.0	3.5	40
		3.0	4.6	84
		5.0	5.4	116

\+ traces
Source: Vijayalakshmi and others, 1982

Supplementing rainfall during the growing season. Harvested runoff water will most likely be utilized to supplement rainfall during the growing season. Rainfall is the primary source of water for the growing crop, and irrigation is used only to supplement the rainfall during drought periods. In many situations, there is not enough irrigation water available to fully compensate for the deficit, so the limited water has to be applied very sparingly over a large area, or in larger quantities over a smaller area. The decision to concentrate a limited supply of irrigation water on a limited area is generally most appropriate when there is a high potential of increased yield, or when land-associated costs, including the cost of applying water per unit land area, are high relative to the income potential. The type of crop grown is also equally, if not more, important. Corn, for example, is highly sensitive to water stress, and the amount of corn grown in water-deficient regions should be limited to the extent that sufficient irrigation water is available to meet the requirements of the growing crop. Similarly, most vegetable crops are also highly sensitive to water stress. These crops, therefore, generally should not be considered for supplemental irrigation unless an adequate supply of irrigation water is relatively well assured.

Musick (1989) summarized over thirty years of research on deficit-irrigation cropping systems under seven principles:

- Only use deficit irrigation on soils that are relatively deep and have moderate to high water storage capacity.
- Use drought-resistant crops.
- Increase the contribution of precipitation to crop water needs.

- Consider crop growth stage and cutoff date in managing water.
- Reduce reliance on preplant irrigation.
- Consider management practices that reduce water intake and field runoff in furrow systems.
- Modify some cultural practices.

Although Musick developed these guidelines for the Great Plains region of the United States, they also apply to the WSDT. The two most important principles are to grow drought-resistant crops and to consider the most critical growth stages for applying the limited irrigation water.

Lengthening the growing season. In many areas of the WSDT, there is ample precipitation during the rainy season to meet crop needs, but the length of the rainy season is too short for most crops. The choice of crops is therefore limited in these areas. Irrigation can be used to lengthen the season so that longer-growing and higher-yielding crops can be grown successfully. This strategy is only applicable, however, when there is a dependable supply of irrigation water to meet the needs of the crop after the rainy season has ended. (*See* Table 3-8 for an illustration of the effect of irrigation on crop yields.)

Table 3-8. Effect of life-saving irrigation on critical growth stage and yield

		Yield (q/ha)		
Crop	Site	Without irrigation	With irrigation	Efficiency of water use (kg/ha/mm)
Barley	Varanasi	26.0	33.6	15.2
Sorghum	Bijapur	16.5	23.6	14.8
Sorghum	Bellary	4.3	13.7	18.2
Sorghum	Solapur	9.8	18.2	16.8
Tobacco	Anand	12.1	18.1	12.0

Source: Venkateswarlu and Singh, 1982

Growing crops during the dry season. The utilization of water harvested in semiarid regions can sometimes be insufficient during those dry seasons with below-normal rainfall. A good strategy, therefore, involves land-use planning to allocate some land specifically for growing vegetables or other short-season cash crops during the dry season, with supplemental irrigation using harvested water.

Response Farming

Response farming focuses on water and on-farm management with respect to water. Response farming has two steps. In step one, a forecast is made prior to the growing season concerning the expected amount of seasonal rainfall, its duration, and intensity index (amount/duration). The farmer modifies his preplant and planting time decisions depending on the actual start of the rains, soil-moisture availability, and other crop growing conditions in order to maximize crop yields. In step two, a revised forecast is made approximately thirty days after germination. In accordance with this forecast, the farmer adjusts the amount of fertilizer used (upward, if rains are good) or plant population (downward, if rains are poor). (For further details on this technology readers are referred to Stewart, 1988.)

Agro-climatic studies have shown that by analyzing long-term data, it is possible to estimate stochastically the variability of rainfall. Water balance models are now available which can be used advantageously to determine the length of the crop growth season and its variability. By estimating the rainfall variability and length of the growing season—the two key agro-climatic determinants of an ecosystem—ICRISAT developed crop calendars for a sustainable land-use system. Such schemes focus on inter- and relay-cropping and on the diversified use of land by incorporating an agro-horticultural or agro-forestry system suited to the available soil quality. Thus, a useful method of agro-climatic evaluation is available that can be used to suggest alternative management practices that will sustain productivity and enhance the soil resource base (Virmani, 1993).

Chapter 4

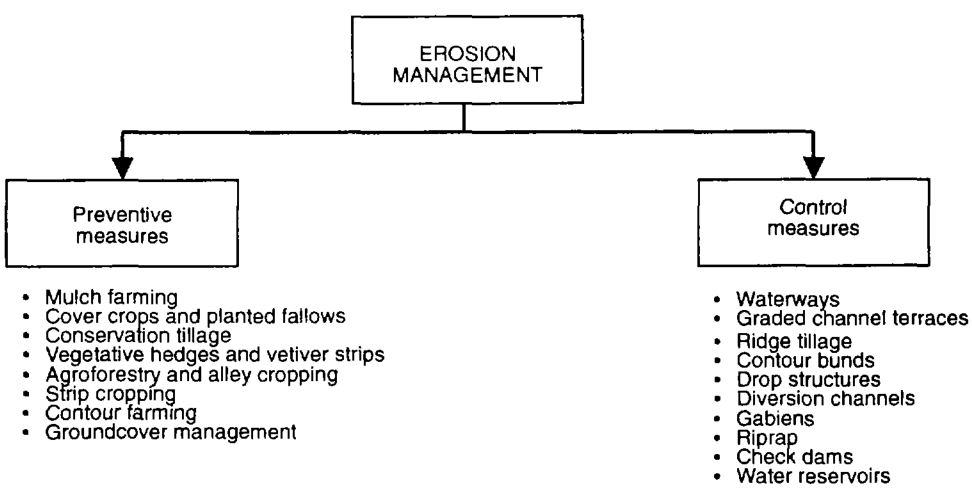
TECHNOLOGICAL OPTIONS FOR EROSION CONTROL

Erosion is a severe problem in the WSDT region and poses a serious constraint on the attainment of sustainable agricultural production by WSDT countries. This chapter discusses a number of agro-based and engineering methods which can be successfully employed in the region to control or divert the destructive effects of both water and wind erosion.

WATER EROSION

Erosion control measures are based on principles of soil-surface management and the adoption of ecologically compatible farming and cropping systems. A wide range of soil and crop management methods are available for minimizing and controlling soil erosion. These have been discussed at length by Lal (1991a) and are summarized in Figure 4-1.

Figure 4-1. Technological options for erosion management



Source: Lal, 1991

It should be noted that the groundcover management measures discussed in Chapter 3 are highly effective techniques for controlling erosion. In addition, the following methods can also be used for erosion control. Each of these will be discussed below in detail:

- vegetative hedges;
- strip cropping;
- contour bunding and farming; and
- engineering structures.

Vegetative Hedges

Vegetative hedges, comprising bunch grass or shrubs, are planted on the contour at regular intervals to decrease runoff velocity, increase time for water to infiltrate into the soil, and facilitate sedimentation and deposition of eroded material by reducing the carrying capacity of the overland flow. Vegetative hedges are generally 50 centimeters wide and are comprised of densely planted bunch grass. Commonly used grasses include:

- *Axonopus micay*
- *Brachiaria brizantha*
- *Brachiara mutica*
- *Cenchrus ciliaris*
- *Eragrostis curvula*
- *Panicum antidotala*
- *Panicum coloratum*
- *Paspalum decumbens*
- *Paspalum notatum*
- *Paspalum conjugatum*
- *Pennisetum purpureum*
- *Setaria* spp.
- *Vetiveria* spp.

These grasses can also be established on earth banks or bunds and on terraces to reinforce and stabilize these structures. Thick root systems prevent slope failure which results from rilling, gullying, or tunneling. The establishment of continuous hedges provides maximum protection. While controlling soil erosion, vegetative contour hedges also conserve soil water by enhancing infiltration and decreasing losses due to runoff.

Vetiver or khus grass is a widely adapted grass for vegetative hedges used to control erosion in the seasonally dry tropics (World Bank, 1988). Vetiver is densely tufted, awnless, wiry, and glabrous perennial grass. It has a deep, strong, fibrous root system. It grows in large clumps from the root stock and is propagated vegetatively. The grass can be planted on the contour to establish protective contour hedges. The data from experiments conducted at Akola, Maharashtra, India, indicates significant reductions in runoff and soil erosion (World Bank, 1990). As shown in Table 4-1, vetiver has a significant advantage in limiting soil erosion over a number of alternative methods. In addition to its benefits as a soil-conserving plant, vetiver grows under a wide range of environments and is therefore relatively tolerant of moderate levels of drought or inundation, as well as damage by fire. It reportedly grows in a rainfall regime ranging from 200 millimeters to 6,000 millimeters per year, and from sea level to an altitude of approximately 2,500 meters. In the WSDT most grasses, except for vetiver, dry out during grazing, making vetiver a good candidate for grazing. It also has some economic value because an aromatic oil is extracted from its roots.

Table 4-1. Effects of vetiver hedges on erosion control in Akola, India

Treatment	Soil Erosion (t/ha)
Across-slope cultivation	38.5
Leucaena hedges	22.7
Bunds	19.9
Vetiver grass	10.9

Source: Vetiver Newsletter, 1991

Growing perennial shrubs as contour hedgerows is another commonly used form of vegetative hedge. The most commonly used technique is alley cropping (Lal, 1991b). Alley cropping is a form of agro-forestry in which food crop annuals are grown between two adjacent hedgerows of leguminous shrubs and woody perennials (Kang et al., 1984). The woody perennials are regularly pruned to minimize shading and to produce nitrogen-rich mulch for food crop annuals. Satisfactory crop yields are obtained provided that compatible species are chosen and that the available reserves of soil water are sufficient to meet the evapotranspiration needs of both species. The system is normally suited for humid and subhumid regions in which precipitation exceeds evapotranspiration during the crop-growing season. Currently, the system is labor-intensive and is suited more to resource-poor farmers of the tropics than to large-scale commercial farming. Maize-*Leucaena* alley cropping can be economically promising if hired labor is available at low cost. In semiarid and arid climates, however, growth suppression and yield reduction in food crop annuals are caused by excessive competition for soil moisture (Singh and Van Den Beldt, 1986; Nair, 1984).

Contour hedges decrease runoff velocity and reduce its sediment transport capacity. Sediment trapped by contour hedges facilitates the formation of natural terraces. Experiments conducted on relatively steep lands in Machakos, Kenya, have shown that compared with croplands, contour hedges of several grass species and perennial shrubs reduce sediment transport by several orders of magnitude.

Closely spaced, narrow strips of shrubs or woody perennials are likely to be more effective in soil and water conservation than are widely spaced, single-row hedges. There is, however, an optimum spacing for erosion control and for satisfactory growth and yield of food crop annuals. The optimum spacing depends on the slope gradient, soil type and its susceptibility to erosion, rainfall, crop species, and the soil and crop management system in use. Erosion control using contour hedges depends on the sediment-carrying capacity of the water runoff. Hedges trap sediment as long as the sediment transport capacity of the overland flow is not yet fulfilled. Furthermore, closely spaced, vegetative hedges on the contour are more effective in reducing runoff and soil erosion than are widely spaced hedges.

Strip Cropping

Strip cropping is performed to divide the farmland into long narrow strips that cut across the path of erosive forces of running water. Using this system, some densely grown crops, with a close canopy established in the vicinity of the ground surface, are grown in strips alternating with open-row crops with a tall and loose canopy structure. The so-called soil-conserving crop is deliberately grown in a contour strip downslope of the erosion-promoting crop to absorb runoff, retard runoff velocity, and encourage sedimentation of the soil transported from the cropped strip upslope. To be most effective, the buffer strip must be established on the contour. There are various types of strip cropping, depending on the mode of establishment and specific functions of these strips:

- *Contour strip cropping.* Alternate strips are established on the contour. The width of open-row crops must be limited to curtail excessive runoff.
- *Buffer strip cropping.* Wherever rolling topography makes it difficult to establish contour strips, buffer strips are established by expanding the filler areas into a continuous buffer strip. Buffer strips are generally planted to permanent vegetation.
- *Field strip cropping.* Rather than establishing strips on the contour, rectangular strips are laid out parallel to one side of a field.
- *Barrier strips.* Narrow strips consisting of a single or a double row of closely growing grass or cereals are established on the contour to provide protection against runoff or wind. Vetiver hedges are a form of barrier strip.
- *Border strips.* Property boundaries are often established with hedges of perennial vegetation. These strips also control erosion.

In addition to controlling erosion, cultivating land in alternate strips or in alternate years regenerates soil fertility, improves soil structure, and restores productivity. The biomass produced in these fallow/buffer strips can be used for processing mulch and for possible grazing or stall feeding for cattle, with subsequent manuring. In order to enhance soil fertility, buffer strips are usually planted to quick-growing and easy-to-establish legumes. Some commonly grown legumes are:

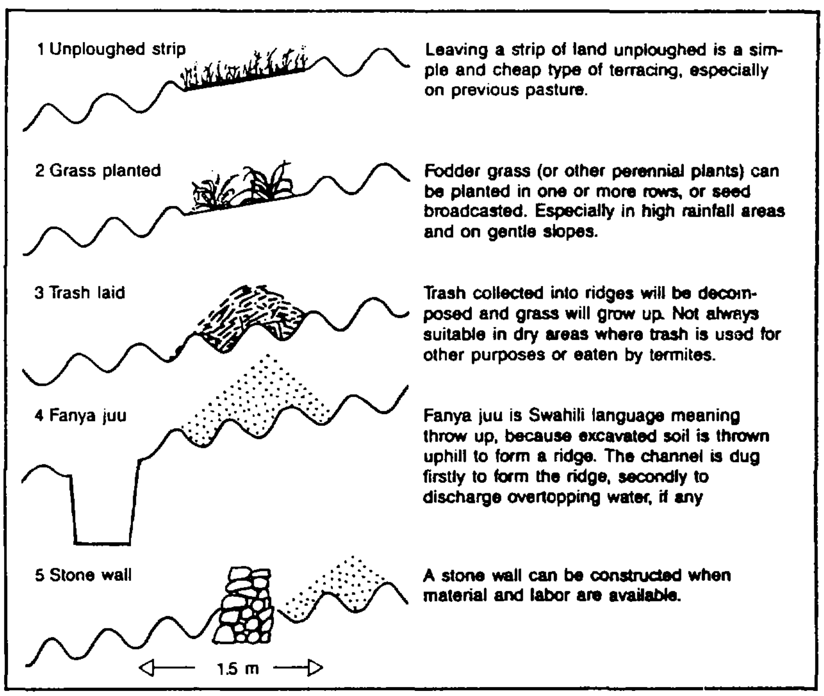
- *Centrosema pubescens*
- *Desmodium buergeri*
- *Medicago sativa*
- *Mucuna pruriens*
- *Phaseolus aconitifolius*
- *Psophocarpus palustris*
- *Pueraria phaseoloides*
- *Stizolobium deeringianum*
- *Stylosanthes guianensis*
- *Trifolium alexrium*
- *Vigna catjang*

In addition to forage legumes, other leguminous crops with some economic value can also be used in strips alternating with strips of open-row cereal crops. Important leguminous crops that can be grown in the seasonally dry tropics are pigeonpea, cowpea, chickpea, soybean, mung bean, and faba bean.

Contour Bunding and Contour Farming

A large embankment, made on the contour at frequent intervals, is a widely used system in India and Africa to contain runoff and to allow it to infiltrate into the soil. **Contour bunds** have a very specific use in India, because on Vertisols these are used to conserve both soil and water (*see* Box 4.1 on the following page). They are built with a sufficiently large storage capacity to impound all the surface runoff and hold it for slow infiltration. In Kenya, contour bunds known as "fanya juu" are constructed by digging a drain across the slope and throwing the excavated soil uphill, thereby forming a ridge. A channel is thus created on the down slope side of the bund (*see* Figures 4-2 and 4-3). A modified version of this system is being tested in Zambia, Tanzania, and Ethiopia. These bunds are stabilized against erosion by vegetative cover. Stone lines and diggets are also used in conjunction with contour bunds, especially in Niger, Burkina Faso, and Mali. Earthen bunds are also used in the West African Sahel to contain surface runoff and to facilitate establishment of native or introduced shrubs and tree seedings. An extensive program is underway in Niger to restore degraded vegetation through contour bunding.

Figure 4-2. Various methods to control erosion



Note: **Different ways of developing bench terraces in erodible soils. In high-rainfall areas conservationists have sometimes been too eager to introduce the fanya juu method, instead of leaving the choice of terrace construction method to farmers as recommended.**

Source: Moldenhauer and Hudson, 1988.

Box 4.1 Sustainable management of Vertisols

These heavy textured soils, also called black cotton soils, constitute an important soil group of the WSDT. These soils are characterized by high swell-shrink capacity, poor trafficability when wet and hard consistency with deep and wide cracks when dry, and low permeability to water—leading to excessive runoff and accelerated erosion during periods of heavy rains. Under traditional methods of management, Vertisols are left fallow during the rainy season, and crops are grown on residual moisture during the post-rainy season. Crop yields with traditional management are highly erratic and extremely low.

With the adoption of improved management systems, Vertisols can be intensively cultivated for high and sustained yields without serious soil erosion and degradation. Extensive soil and water management research, conducted by ICRISAT in India, has led to the development of improved components and subsystems as follows:

- Erosion management: Effective erosion control measures on these soils include use of crop residue mulch, conservation tillage, broad bed and furrow system, and graded ridge furrow techniques. Because of low infiltration rates, conservation-effective measures are based on the principle of safe disposal of excess runoff.

- Compaction management: Useful strategies for compaction management are deep tillage, soil inversion, guided traffic, and reduced traffic when soil is excessively wet.

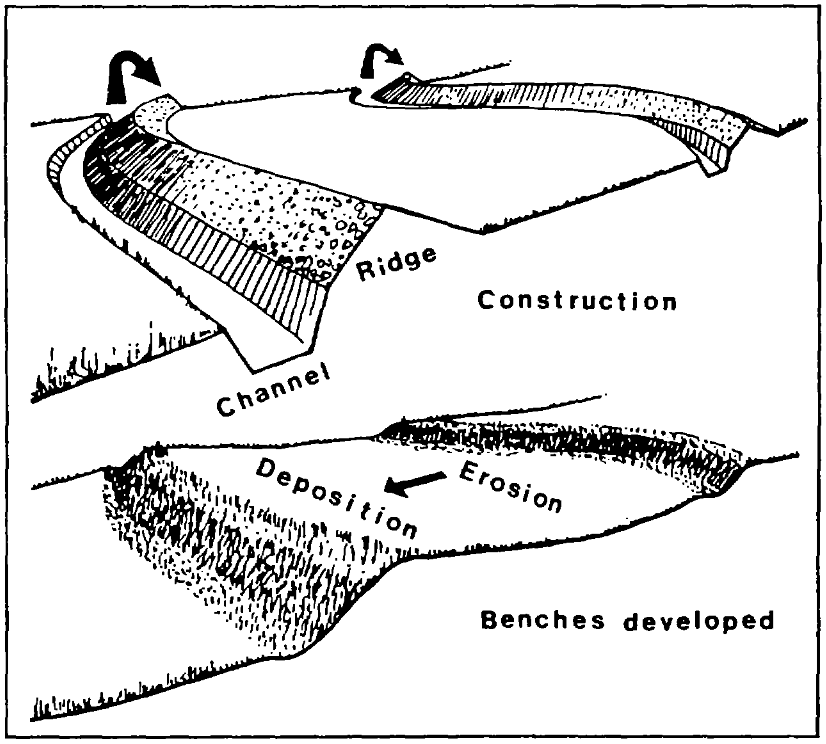
- Water conservation: Water conservation for successful and profitable rainfed agriculture can be achieved by conservation tillage and the use of crop residue mulch. In some cases, soil inversion with deep plowing is beneficial for increasing soil water storage in the root zone and improving crop yield.

- Crop management: Ensuring satisfactory crop stand, through good-quality seed and early sowing in a properly prepared seedbed, and enhancing soil fertility are important pre-requisites to obtaining high yields. Prolonging the growing season through early sowing is extremely important to obtaining high yields.

- Fertility management: Using balanced fertilizer is critical to obtaining high yields. Judicious use of chemical fertilizers, organic manures, and micronutrients is essential.

Important components of improved technology for Vertisol management are: (1) land preparation immediately after harvesting the previous season's crop, when there is some moisture in the soil to facilitate tillage; (2) tillage operations with improved animal-drawn wheel tool carriers; (3) dry seeding a few days before the onset of the rainy season; (4) a land configuration called the Broad Bed and Furrow (BBF) system, involving graded, wide beds separated by furrows which drain into grassed waterways; (5) high-yielding varieties (HYVs); (6) improved plant protection; and (7) growing crops in both rainy and post-rainy seasons, either as intercrops or as sequential crops, where one of the components is harvested earlier so that the other continues in the post-rainy season to utilize the remainder of stored water in the soil.

Figure 4-3. Contour bunds in Kenya



Note: **The bench terrace permits collection of dispersed soil particles, plant residues, water, and nutrients, which increases crop yields. Perennial grass on the edge of the terraces (or a cover of stones) will protect them, and the undisturbed riser will infiltrate water. This ingenious type of terracing fits slopes with erodible soils, especially in climates with unreliable or marginal rainfall.**

Source: Moldenhauer and Hudson, 1988

The simplest approach to erosion control is **contour farming,** also known as contour cultivation or simply contouring. In contour farming, all farming operations which could cause soil erosion are performed on the contour, rather than up and down the slope or parallel to field boundaries. These farming operations include plowing, establishment of a ridge-furrow system, sowing, fertilizer application, and inter-row cultivation by power- or animal-driven equipment. A rough seedbed, characterized by a cloddy soil surface with a large surface-detention capacity using contour plowing and contour ridging, is a very effective measure for erosion control on gentle slopes of less than 5 percent.

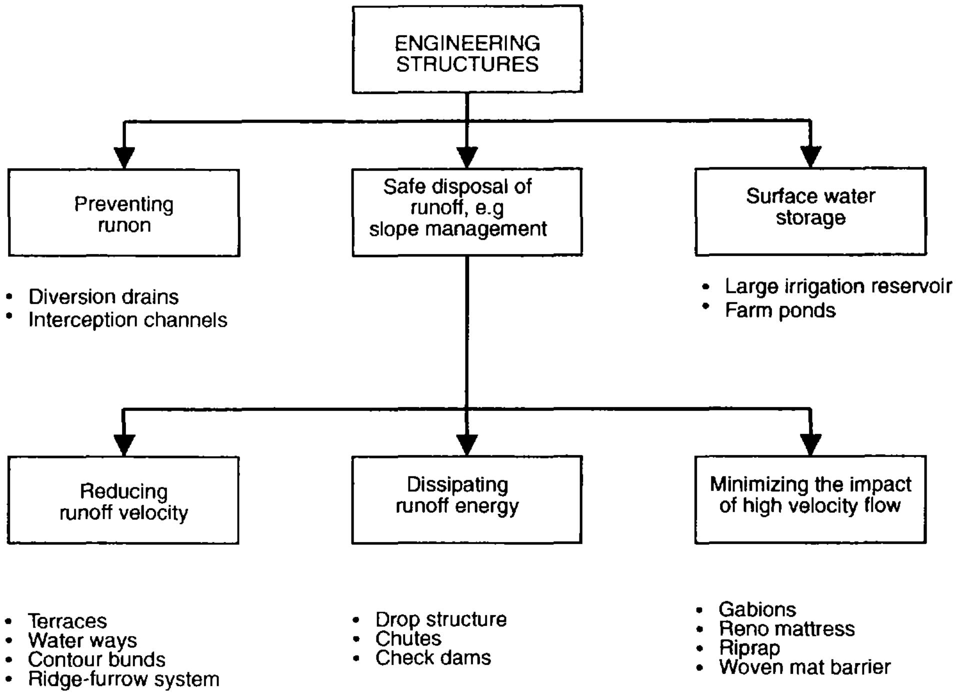
The effectiveness of contouring decreases with increases in the slope gradient, slope length, and intensity of rains. If the rainfall exceeds the surface-detention capacity of the contouring system used, concentrated runoff flowing unchecked downstream can lead to severe gullying. Contouring alone is not sufficient to control erosion on steep gradients, long slopes, erodible soils, and with erosive rains. A principal drawback of contour farming lies in the inconvenience involved in frequent turning, the extra labor and machinery time required, and the loss of some area that may have to be used as protective buffer strips.

These drawbacks, however, are more relevant to mechanized farming operations than to manual or animal-powered operations.

Engineering Structures

As shown in Figure 4-4, there are a number of engineering structures which can be used to prevent erosion by controlling the flow of water, either by diverting its flow or by reducing the impact and the

Figure 4-4. Types of engineering structures



velocity of its flow. In contrast to erosion preventive measures, which are based on the principle of reducing the raindrop impact and the shearing effect of overland flow, erosion control measures usually rely on engineering structures based on the principle of runoff management. Runoff management involves, among other things, the safe disposal of excess runoff at low velocities, energy dissipation through drop structures, and runoff storage in reservoirs to facilitate sedimentation. Whereas erosion preventive measures are based on good farming concepts, control measures are capital-intensive. Good farming entails the care and stewardship of the land through proper methods of land clearing, ecologically compatible systems of seedbed preparation, mulch farming, early sowing with viable seed, frequent use of cover crops and multiple or mixed cropping systems, adequate fertilization and pest control, and all the other agronomic measures needed to produce a healthy crop. In contrast, control measures are permanent structures. Engineering skills are required for their design and installation and they are expensive to implement and maintain.

There are several significant differences as well between the use of good farming practices and engineering structures to control or prevent water erosion. Good farming practices yield an immediate return, with the results occurring in the same or following season, whereas the use of engineering techniques provides long-term returns. The installation of engineering structures requires additional land, such as that needed for the construction of terraces, drop structures, and reservoir construction. In contrast, the entire area of farm land is usable for farming when using preventive techniques. The failure of engineering structures can be severe and often leads to deep gullying and mass movement. Engineering structures as control measures, therefore, require careful planning, meticulous installation, and regular maintenance. Damage to soil productivity caused by faulty structures, or those inadequately maintained, can be severe and often expensive, if not impossible, to repair. The utility of these structures, therefore, may be limited in many developing-country farming situations; any proposed use must be carefully evaluated. Nonetheless, in some situations, simple erosion prevention measures are insufficient to contain or reduce the amount or velocity of water runoff—engineering structures must be used.

There is a wide range of earthworks and mechanical structures which can be used to prevent erosion. They can be categorized as structures designed to prevent runon; structures designed to reduce runoff velocity; and structures designed to dissipate runoff energy. Some of the most commonly used structures, and particularly those deemed suitable for the seasonally dry tropics, are described below. A major objective of all engineering structures is to reduce the strength of the overland flow by reducing its amount and velocity, and therefore its cutting and carrying capacity.

Structures to prevent runon. Preventing runon from surrounding hills or adjacent land is an important consideration on steep lands or on land adjacent to facilities or infrastructure that generates excessive runoff. To achieve this, a storm water diversion drain is installed to intercept or divert the floodwater or runoff that would otherwise flow onto the farm land. Also called a diversion ditch or channel, it is the frontline defensive measure for protection from the runon or flood water originating outside the farm land. Possible layouts of storm water diversion drains are described in detail by Hudson (1971).

Structures to reduce runoff velocity. Runoff generated within the farm area must be disposed of at a safe velocity so that its cutting and sediment-carrying capacity are low enough to cause only minimal erosion. Commonly used slope management structures are:

- *Terraces.* Long slopes are broken with some form of earthwork installed at right angles to the steepest slope to intercept the surface runoff originating within the farmland. The earthwork primarily consists of two parts: an excavated channel and a bank or ridge on the downhill side formed with the spoil from the excavation.

  There are different types of terraces based on the design and shape of the channel and the ridge. A terrace with a channel upslope is a **channel terrace**, and one with a gentle grade in the channel for safe disposal of runoff is a **graded channel terrace**. If a terrace is constructed strictly on the contour to encourage water spread and ponding, it is an **absorption terrace**, which may be **open-** or **close-end** in nature, depending on whether the terrace is diked at the ends. Terrace design considers shape, size, and gradient of the channel and/or bank; spacing along the slope length; and volume of the expected runoff. Terrace design formulae are described by Lal (1979a) and Hudson (1991).

- *Waterways.* Excess runoff from channel terraces is discharged into artificial or natural waterways. If a suitable and conveniently located (at about the desired terrace length) natural waterway does not exist, one must be artificially made. Waterways are known as grassed or sod waterways, or as meadow strips, depending on the protective material planted to create the desired roughness. They are constructed along the slope and have protective embankments on both sides to contain the runoff. Waterway capacity (width, height of embankments, etc.) is designed on the basis of the expected runoff rate and amount using the rational formula and the manning equation (*see* Hudson (1971) for details).

- *Contour bunds*. An embankment or a dike constructed approximately on the contour to stop water running down the slope is a contour bund. Hand-dug structures have been used extensively in central and southern India, and in southern Africa. Occasionally, grass or shrubs are planted on the bank to stabilize them against wash or collapse. The grass is occasionally cut to be used as forage. Contour bunds have been used in semiarid climates, especially in soils with a low infiltration rate and high runoff potential, to conserve water. These water-conserving bunds have been extensively used in central India, especially on Vertisols. In that context, they serve as **close-end terraces**, whereby water is ponded on the upstream side of the bund. An overflow (or spillway) can be designed to safeguard against an occasional excessive storm.

  The major disadvantages of contour bunds, compared with vegetative hedges, are that they are labor-intensive and expensive to dig and construct, occupy large areas which are taken out of production, and cause crop damage as a result of inundation of large areas toward the upper side of the bund. Furthermore, bund failure can lead to severe gullying. As with terraces, subsequent maintenance is essential to the proper functioning of contour bunds. Unmaintained contour bunds and terraces are destined to fail and can cause more damage to soil and landscape than if there were no mechanical structures.

Structures to dissipate runoff energy. Special mechanical structures are needed in watersheds to prevent erosion from concentrated runoff, flood water, or long-duration flows. Permanent structures are required to dissipate the energy of such flows. Some of the commonly used structures are (for details see Blaisdell, 1981):

- *Drop structures*. These are small dams designed with the following objectives: to stabilize steep waterways and other channels; to level waterways so that they need not be planted to grass; to serve as outlets from concentrated flow from sods and drainage culverts; and to serve as sediment traps. Drop structures can be **low** (in which the bed drop height is equal to or less than the upstream specific head), or **high** (in which the upstream water levels are normally unaffected by downstream conditions).

- *Chutes*. These are specially designed spillways which collect flow at one elevation and discharge it down a slope at a lower elevation. There are two types of chutes: a **plain chute** to transport the flow at high velocity with minimum energy dissipation, and a **baffled chute** to dissipate the energy as fast as it is generated. For short slopes of low gradients, chutes can be built without forms by excavating and pouring in the mixed concrete on prepared soil. For long slopes of steep gradients, wire mesh reinforcing is required. The shape of the inlet and outlet is important to stabilize chutes and prevent failure. Some form of energy-dissipating structure is necessary at the outlet of the chutes; a box-like device filled with stone is generally suitable for most conditions.

- *Check dams*. There are several types of check dams. Check dams are constructed to stabilize waterways, store excess water, or trap sediment. Sediment storage (trap) dams are designed to intercept sediment. These dams have a spillway to discharge runoff slowly and facilitate the settling of sediment. Dams are also designed to stabilize waterways or prevent gully formation. These dams are constructed at the site of the overfall. If the site of the overfall or gully head is unsuitable, dams can also be located a short distance downstream. For long gullies, it is advisable to construct a series of dams at frequent intervals. Dam stabilization is usually more effective when some land forming is done toward the upstream side. Flood control dams are usually constructed in small watersheds with two objectives: flood control and grade stabilization. They also trap sediment. The design criteria for flood control dams are based on a storm with a 10- to 20-year return period.

WIND EROSION

Conditions conducive to wind erosion exist when the soil is loose, dry, and finely granulated; the soil surface is smooth, and vegetative cover is sparse or absent; the susceptible area is sufficiently large; and the wind is strong and turbulent enough to move soil (Lyles et al., 1985). These conditions often prevail in the arid and semiarid portions of the WSDT. Wind erosion can be controlled by reducing wind velocity at the soil surface, or by covering the soil with non-erodible materials (Fryrear, 1990).

Reducing Wind Velocity

Windbreaks or wind barriers function as surface barriers and take up or deflect a sufficient amount of the wind force to control wind erosion. The wind velocity is lowered below the threshold required for the initiation of soil movement. The effect of the barrier depends on many factors, including wind velocity and direction, and the shape, width, height, and porosity of the barrier. Nearly all barriers provide maximum percentage reductions in wind velocity at leeward locations near the barrier, with a gradual decrease in wind velocity reduction in locations farther from the barrier. These percentage reductions for rigid barriers generally remain constant regardless of how hard the wind blows. Dense barriers provide large reductions in velocity for relatively short leeward distances, whereas porous barriers provide smaller reductions for more extended leeward distances. Generally, some porosity is desirable to gain extended protection; however, large openings must be controlled because too much openness causes air jetting with serious erosion in the immediate leeward zone (Chepil and Woodruff, 1963).

Covering the Soil with Non-erodible Materials

The use of crop residue, or other forms of non-erodible material, is very effective in controlling wind erosion. Fryrear (1985) established the relationship between soil loss and the percent of soil cover. Covering 20 percent of the surface reduced soil losses by 57 percent, and a 50 percent cover reduced soil losses by 95 percent. Fryrear concluded that the cover can be any non-erodible material such as large clods, gravel, cotton gin trash, or any diameter stick between 3.1 millimeters and 25.4 millimeters in size. For 50 percent groundcover, approximately 1,000 kilograms per hectare of wheat straw are required (Van Doren and Allmaras, 1978). To achieve the same rate of cover, however, an estimated

3,000 kilograms per hectare of sorghum stalks, and 9,000 kilograms per hectare of cotton stalks, are required (Unger and Parker, 1976).

The use of crop residues for controlling wind erosion in the WSDT should be encouraged, but there are often serious constraints. The primary constraint is often simply that sufficient crop residues are not produced in areas where wind erosion is most hazardous because of insufficient water for crop production. Also, these regions are often deficient in sufficient materials for animal feed and cooking and heating fuels, so the residues are removed from the land. The long-term consequence of removing the residue is extremely negative because it renders wind erosion control more difficult and greatly accelerates the decline of organic matter.

The use of residues for controlling wind erosion also has added benefits. Surface residues increase infiltration, reduce evaporation, and conserve organic matter. Unger (1990) summarized the benefits of surface residues for increasing soil water storage and crop yields under water-deficit conditions. He found that crop residues, particularly those from small grain crops such as wheat, used as a surface mulch increased water storage significantly. Although water storage increased with increasing amounts of mulch, significant increases occurred even at the level of 1,000 kilograms per hectare, which is sufficient to control wind erosion under most situations. Unger (1990) also reported that the increased water storage resulted in increased crop yields, which in turn resulted in additional crop residues. Consequently, the use of crop residues as a mulch results in an upward spiral of benefits by controlling erosion, increasing infiltration, reducing evaporation, increasing crop yields, and sustaining the soil resource base.

Chapter 5

TECHNOLOGICAL OPTIONS FOR IMPROVING SOIL FERTILITY

Soil is the primary source of plant nutrients. Most soils in the WSDT region, however, are low in fertility, and continuous cropping has led to declining fertility and productivity (*see* Table 5-1 for the effect of continuous cropping on soil fertility in Senegal). In Kenya, for example, yields in long-term experiments have declined over a 19-year period from 14.6 tons per hectare to 3 tons per hectare on red earth clays, and from 12.5 tons to 4 tons per hectare in a 9-year period on transitional soils (*see* Figure 5-2). Nitrogen and phosphorus content are the most important limiting factors; however, potassium, sulfur, iron, zinc, and other essential plant nutrient deficiencies are also commonly observed in the WSDT. The maintenance and improvement of soil fertility is therefore of critical importance for sustainable development. If lost nutrients are not replenished, productivity inevitably will fall. This chapter addresses the following technological methods for maintaining and improving soil fertility:

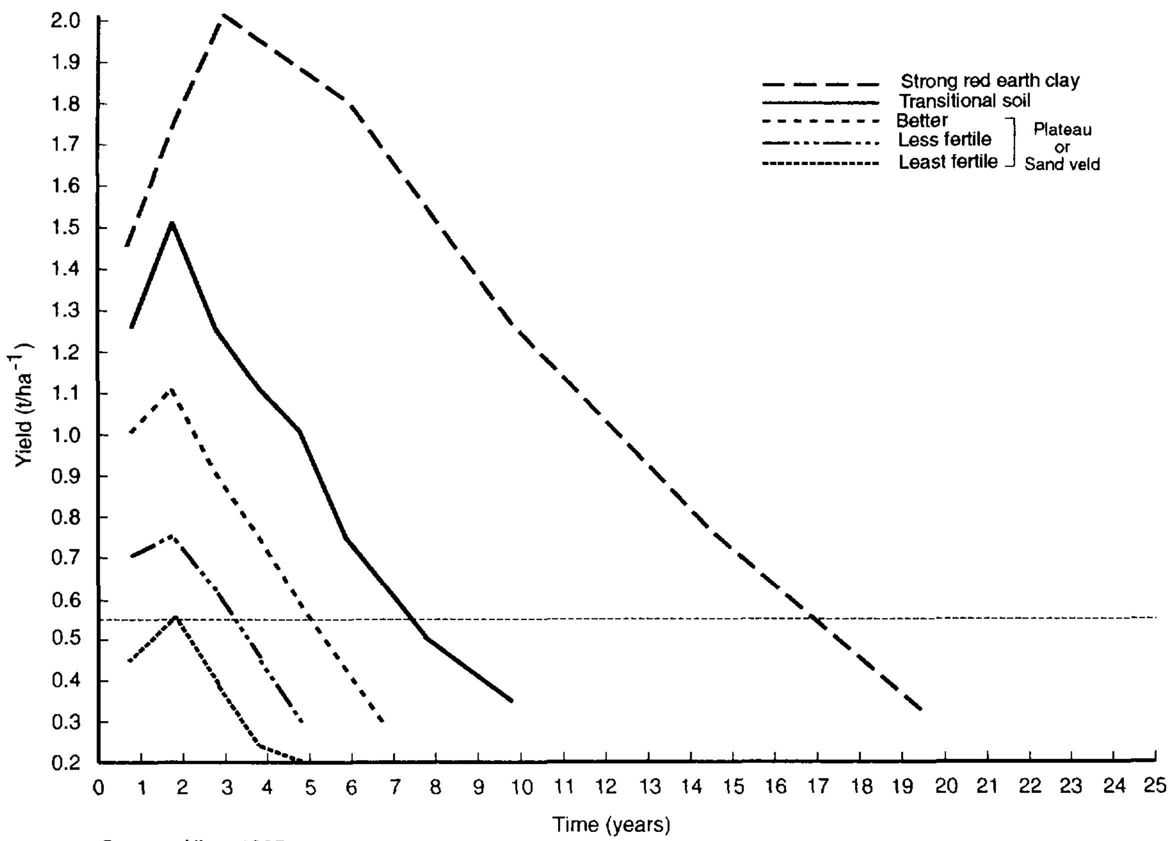
- use of chemical fertilizer;
- biological nitrogen fixation;
- use of organic manures, such as animal and municipal wastes;
- cultural practices to increase fertilizer efficiency; and,
- cultural practices to decrease fertilizer loss.

Table 5-1. Soil fertility decline with continuous cropping in Senegal

	Village Sale Bidji			Village Dionkancounda		
Soil Property	5 yr	16 yr	80 yr	2 yr	15 yr	50 yr
Available water (%)	5.70	4.50	4.40	5.60	5.80	5.00
Organic matter (%)	2.40	1.50	1.30	1.50	1.30	1.10
Total nitrogen (%)	0.73	0.54	0.43	0.67	0.49	0.41
pH	6.50	6.40	6.00	6.60	6.20	5.60
Cation exchange capacity (meq/100g)	4.70	3.50	2.60	3.50	3.20	2.30
Base saturation (%)	86	80	69	81	69	52

Source: Siband, 1972

Figure 5-1. Effect of continuous cropping on productivity in Kenya



Source: Allan, 1965

CHEMICAL FERTILIZERS

Commercial **nitrogen** fertilizers have been increasingly used since the mid-1940s. They are highly responsive and have perhaps been the single most important technology for increasing crop yields, particularly when water is not a major constraint on crop growth. Under water-limiting conditions, however, higher doses of nitrogen fertilizer are risky and are not cost effective. Therefore, major nitrogen inputs for much of the WSDT will continue to be from traditional sources. **Phosphorus** is deficient in many areas of the WSDT and must be applied from an external source. Environmental conditions such as warm climates and moist soil increase the effectiveness of rock phosphate. The use of rock phosphate will be more successful, therefore, in the wetter zones of the WSDT. Some crops, particularly red and sweet clovers, when used in rotation with other crops, can improve the phosphorus status of the soil by utilizing rock phosphate and then cycling some of the phosphorus through other crops. Researchers in Australia have developed a granular material containing rock phosphate and finely ground elemental sulphur which is inoculated with the sulfur-oxidizing bacteria *thiobacillus thiooxidans*. This fertilizer has great potential for use in the WSDT where there is no sophisticated fertilizer industry. **Potassium** is absorbed by plants in large amounts; however, except for few areas, potassium is not a limiting factor on soil fertility in most of the WSDT.

The use of chemical fertilizers is a proven technology that results in rapid and significant benefits. Many small landholders and resource-poor farmers -- who are predominate in the WSDT -- cannot afford or find chemical fertilizers. The high cost, coupled with the fact that an insufficient water supply is a more serious limitation than a lack of nutrients in some years, makes fertilizer use a high-risk technology in much of the WSDT. Nonetheless, many of the soils in the region are so deficient in nitrogen and phosphorus that it is imperative that strategies be developed for adding these nutrients. Otherwise, sustainable cropping systems cannot be developed.

BIOLOGICAL NITROGEN FIXATION

The three basic biochemical processes in nature are photosynthesis, respiration, and biological nitrogen fixation. Even with the tremendous expansion of nitrogen fertilizer production and use since World War II, legumes are still regarded as the main means of fixing nitrogen. This is particularly true for developing countries. The total nitrogen returned to the earth each year through biological nitrogen fixation has been estimated at 175 million tons, of which about one half is contributed by nodulated legumes (Stevenson, 1982). The amount of nitrogen fixed by various leguminous cover crops is presented in Table 5-2. Nitrogen fixation by blue green algae is of important economic significance in the WSDT. Blue green algae occur under a wide range of environmental conditions, including on rock surfaces and barren wet lands. They are autotrophic and require only light, water and free nitrogen, carbon dioxide, and salts containing the essential mineral elements. A symbiotic relationship between *Anabaena azolla* (blue green algae) and *Azolla* (water-fern) in temperate and tropical waters has been reported by Tisdale et al. (1985). The blue green algae located in cavities in leaves of the water fern are protected from external adverse conditions and they are capable of supplying all of the nitrogen needs of the host plant.

Table 5-2. Nitrogen fixed by various leguminous cover crops

Leguminous Crop	kg N/ha
Crotolaria juncea (Sanhemp)	84.0
Sesbania aculeata (Dhaincha)	77.2
Cymopsis tetragonolobe (cluster bean)	62.4
Vigna unguiculate (cowpea)	56.3
Vigna radiata (greengram)	38.6

Source: Singh and Das, 1982

USE OF ORGANIC MANURES

Tisdale et al. (1985) summarized the beneficial effects of organic manure use. They are:

- added supply of ammoniacal nitrogen phosphorus;
- greater movement and availability of potassium and micronutrients;
- increased moisture retention;

- improved soil structure with a corresponding increase in infiltration rate and decrease in soil bulk density;
- higher levels of carbon dioxide in the plant canopy, particularly in dense stands with restricted air circulation;
- increased buffering capacity against drastic changes in pH; and,
- complexation of aluminum, reducing its toxicity.

Both animal waste and compost and municipal waste are sources of organic manure.

Animal Waste and Compost

The best sources of organic manures are animal waste and compost containing significant amounts of economically valuable plant nutrients. These also add humus and organic matter to soil (*see* Box 5.1 on the following page on organic matter maintenance). The continuous and judicious use of manure improves the physical and chemical properties of nearly all soils, particularly those which are shallow, coarse textured, or low in organic matter (*see* Table 5-3 below for the effect of manure application on maize yields in Kenya). Manure use is extremely important in areas where the crop residues are removed for animal feed. Unless the manure is managed and returned to the land, the soil organic matter content and overall soil quality may decline.

Table 5-3. Effect of manure application on maize yields in Kenya

Treatment (t/ha of farm yard manure)	Maize yield at different sites		
	Kampi ye Mawe	Ithookwe	Katumani
Control	1.8	0.8	3.4
8, applied once in 3 yrs	3.2	1.0	4.1
16, applied once in 3 yrs	4.6	2.7	4.4
4, applied in first and 3rd yrs	3.3	0.9	4.1
8, applied in first and 3rd yrs	3.0	1.2	4.3
2, applied every year	2.1	0.7	3.9
4, applied every year	3.0	1.1	4.3
Chemical fertilizer 40 kg N, 18 kg P	3.4	3.3	4.6
F - Test	*	*	NS

* Significantly different at 10 percent level of probability
NS Not significant
Source: Ikombo, 1983

Box 5.1 Organic matter maintenance

Soil organic matter has over the centuries been considered by many as an elixir of life -- in this case, plant life. Since the dawn of history, man has appreciated the fact that dark soils, found chiefly in river valleys and on broad level plains, are usually (but not always) productive soils. Man also realized at a very early date that soil color and productivity are commonly associated with organic matter derived mainly from decaying plant materials.

Since a sustainable land management system requires the conservation or enhancement of the soil resource base over the long term, it is imperative that the organic matter content of soils be sustained. A decrease in organic matter content is an indicator of a lowered soil quality in most soils. This is because soil organic matter is extremely important in all soil processes -- biological, physical, and chemical.

- Benefits: Soil organic matter acts as a storehouse for nutrients, increases the cation exchange capacity, and reduces the effects of compaction. It builds soil structure and increases the infiltration of water. It serves as a buffer against rapid changes in pH and serves as an energy source for soil microorganisms. Organic matter tends to make very fine-textured soils behave like coarser-textured ones; the reverse is true for sandy soils.

- Cultivation effects: Frequent and thorough cultivation was until comparatively recently considered a criterion of good farming. Since more prosperous farmers generally cultivate their soils more frequently, it was generally assumed that this was of major importance. Tillage was important because it controlled weeds, and more importantly, it released nutrients from the soil, mostly from soil organic matter. Cultivation increases biological activities in the soil, and this is often due to better aeration. But cultivation also exposes fresh topsoil to rapid drying, and after each drying there occurs a burst of biological activity for a few days following remoistening. This is because the drying process releases organic compounds from the breakdown of soil aggregates that are bound together by humic materials. Unless the organic matter supply is replenished, however, the system is not sustainable.

- Climatic effects: Soil organic matter formation is very complex, but it is essentially residual plant and animal material, and microbial synthesized material resulting from microbial decomposition of the added residues. Organic matter depletion in hot, dry areas is very rapid because decomposition processes are accelerated by rising temperatures, and the amount of plant roots and residues available for replenishing the lost soil organic matter is insufficient, particularly when extensive tillage is used that hastens organic matter decomposition.

- Rate of decline: An annual loss of 1 percent to 2 percent of the organic matter in the surface 15 centimeters of topsoil by decomposition is not uncommon. This decline can only be checked by leaving crop residues on the soil or by adding manure or other organic materials. The removal of crop residues hastens the rate of organic matter decline, and can cause arid and semiarid ecosystems that are inherently marginal to pass quickly from a state of fragility to one of total exhaustion. The rate of decline under continuous cropping is closer to 4 percent that 2 percent (Pieri, 1992).

Municipal Waste

Municipal wastes includes industrial and sewage sludges. Sludge is a heterogeneous material varying in composition from one city to another and even from one day to the next in the same city. The end products of all sewage treatment processes are sludge and effluent. The sludge is the solid product produced during the treatment of sewage, while the effluent is the water that contains low concentrations of plant nutrients and traces of organic matter. Sludge is a source of nitrogen, phosphorus, potassium, and micronutrients, including boron, copper, iron, manganese, and zinc. Sludge also provides organic matter. Sewage effluents are generally low in plant nutrients and organic matter. Nevertheless, effluents are valuable, particularly in areas where water is limited, as a source of irrigation water. The use of municipal wastes requires caution, however, because there is a possibility of disease transmission due to the presence of bacteria, parasites, or viruses. Composting the sludge prior to land application can greatly reduce the pathogen content. Sewage sledges and effluents can also contain heavy metals such as lead and cadmium that can be hazardous. It is essential, therefore, that the characteristics of municipal wastes are known before they are utilized for crop production. Technologies are being used in several countries to treat municipal wastes to improve water quality for irrigation.

CULTURAL PRACTICES TO INCREASE FERTILIZER EFFICIENCY

Since low soil-fertility levels are common in the WSDT and sources of nutrients for raising the levels are limited and expensive, efforts must be made to increase fertilizer efficiency. Fertilizer placement, the timing of fertilizer application, and the selection of crops and cropping systems are agronomic practices used for this purpose.

Placement

The placement of fertilizer in relation to the plant is an important consideration in the efficient use of fertilizers (Tisdale et al., 1985). Proper placement is critical to the efficient use of nutrients from plant emergence to maturity. A fast start and continued nutrition are essential for sustained growth; merely applying fertilizer does not ensure that it will be utilized by the plant. It is usually important to place some of the fertilizer where it will be intercepted by the roots of the young plant, and to put the bulk of the nutrients deeper in the soil, where they will more likely be in a moist zone during much of the growing season.

Fertilizer placement is also important in order to prevent salt injury to seedlings. Soluble nitrogen, phosphorus, potassium, or other salts close to the seed may be harmful. There should be some fertilizer-free soil between the seed and the fertilizer band, especially for small-seeded and/or sensitive crops such as rapeseed, flax, peas, and sunflowers. An important exception is that of low rates of fertilizer placed directly with the seed of some crops, particularly small grains. As will be discussed later, fertilizer placement is also important in order to decrease losses resulting from volatilization and other processes.

The two main methods of fertilizer application are broadcasting and banding. **Broadcasting** consists of applying the fertilizer uniformly over the area. This is often done prior to seeding, and the fertilizer is incorporated by cultivation. Broadcasting is often the preferred method because the fertilizer can be applied during periods when labor is available. The time for seeding is often limited, and the application of fertilizer slows the operation. Broadcasting should not be employed, however, when small amounts of fertilizer are being used, particularly when phosphorus is one of the fertilizer nutrients. Plants need adequate phosphorus during the seeding stage, and small amounts of fertilizer must be strategically placed near the seed if it is going to be of value. For this purpose, **banding** of fertilizer is suggested. Ideally, fertilizer is applied in bands about 5 to 7 centimeters beside, and 2 to 5 centimeters below, the seed. For some crops, especially small grains like wheat, small to moderate amounts of fertilizer can be placed directly with the seed at sowing.

Timing

The proper time for applying fertilizer depends on the soil, climate, nutrients, and crop. Some soils have the undesirable ability to fix nutrients, particularly phosphorus, rendering them unavailable to plants. Under these conditions, it is critical that the fertilizer be applied at or very near the time of seeding. For highly soluble nutrients, timing is important because these nutrients can be quickly leached from the soil profile during wet periods, particularly in sandy soils. The data in Table 5-4 show that losses of applied fertilizer were reduced from 53 percent with point-placed urea applications to 37 percent with split applications of calcium ammonium nitrate. For much of the WSDT, fertilizer responses are highly variable owing to the extreme variability in rainfall among years. Stewart (1988) stated that rainfall may range from a low of around one-third of the long-term mean to a high of approximately double the mean. Thus, rainfall during the wettest seasons may be six times as much as during the driest seasons. Stewart (1988) developed a technological approach called **response farming** (see Chapter 3) for coping with seasonal rainfall variability in semiarid regions of the developing world. This strategy appears promising, particularly for nitrogen use. It is less promising for phosphorus use, however, because phosphorus added thirty days after germination for many crops is not likely to be used very efficiently.

Table 5-4. Method and timing of nitrogen application on fertilizer recovery on pearl millet in Niger

Treatment	Nitrogen recovery (%)			
	Grains	Plants	Soil	Loss (%)
Calcium ammonium nitrate	13.0	28.8	34.2	37.0
Urea split banded	9.0	22.8	39.2	38.0
Urea point placed	8.0	22.0	25.3	52.5

Source: Bationo et al., 1989

Crops and Cropping Systems

Crops vary in their ability to use plant nutrients. These variations include the ability of one crop to absorb nutrients from compounds unavailable to other crops, as well as the ability to absorb nutrients from deep depths in the soil profile which are unreachable by other types of crops. Rotations that include such crops, therefore, can benefit subsequent crops -- because of nutrient cycling -- as well as the current crop. Li and Xiao (1992) reviewed many of the practices used in China for improving soil fertility. A common strategy is to give priority to leguminous crops, because they can supply nitrogen by themselves and thus promote full use of the phosphorus fertilizer. Researchers in China have found also that phosphorus fertilizer promotes the activity of the nitrogen fixation enzyme nitrogenase and increases the amount of nitrogen fixed. For this reason, application of phosphorus fertilizer to leguminous crops, including green manures, forage, and grain crops, is considered an effective way to improve soil fertility and to increase crop production.

This practice is appropriately referred to as the "application of P fertilizer to increase N" (Li and Xiao, 1992). This strategy has promise for much of the WSDT. It is even more promising if crops such as red and white clovers can be grown on soils treated with rock phosphate or partially acidulated rock phosphate that is readily available and relatively inexpensive in many areas. The use of these inexpensive phosphorus forms, coupled with crops of legumes, can significantly increase soil fertility. This strategy will not be successful, however, unless a considerable amount of the legume crop is left on the soil or incorporated so that the nutrients can be cycled for the use of subsequent crops.

CULTURAL PRACTICES TO DECREASE FERTILIZER LOSS

Nutrient loss from agricultural land has severe economic and ecological consequences. Economically, the loss of plant nutrients affects crop yields and increases production costs because high rates of supplemental doses are required to produce the same yield. Ecologically, the loss of plant nutrients leads to enrichment of natural waters. Eutrophication of waters results in deoxygenation and environmental pollution (Stewart and Rohlich, 1977), while an increase in the nitrate content of drinking water creates health hazards. In addition, the ozone layer in the stratosphere is affected by nitrous oxides derived from biological denitrification.

Owing to intensive leaching and other losses of plant nutrients, the recovery of nitrogenous fertilizer by crops grown in the seasonally dry tropics is usually less than 50 percent. Furthermore, less than 10 percent of applied fertilizer is recovered by a succeeding crop. The unrecovered fertilizer is easily lost in runoff and seepage flow. Factors affecting nutrient losses are classified into two broad categories: ecological and management factors. Ecological factors, related to land and hydrological characteristics, are given and are difficult to manipulate. These factors govern the magnitude and intensity of losses due to erosion, leaching, and volatilization. The interaction between soil properties and climate also determines the rate and magnitude of losses due to denitrification. Preventing the loss of plant nutrients out of an ecosystem is an important strategy for soil-fertility management for resource-poor farmers of the seasonally dry tropics. A system of integrated plant nutrient management is an ecologically sound practice for soil-fertility management. This involves combining organic recycling, biological nitrogen fixation, and the use of mineral fertilizers to meet nutrient requirements for a desired level of yield and cropping intensity. In addition, practices that decrease losses of plant nutrients and increase their efficiency are crucial.

Practices to Reduce Volatilization

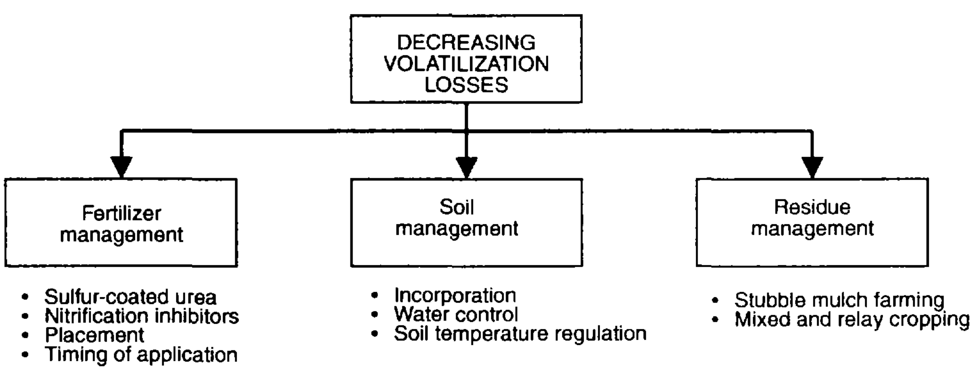
A soluble form of nitrogen, applied as inorganic fertilizers or organic manures, can be easily volatized. Surface application of nitrates in a hot and dry climate accelerates the volatilization process. Losses of nitrogen through volatilization are generally higher when considerable nitrate nitrogen is present in the soil and when fertilizer is applied on the soil surface. Experiments conducted in India have shown that up to 60 percent of applied nitrogen can be lost through ammonia volatilization (ICAR, 1984). The losses can be decreased if soil nitrogen is maintained in ammonium rather than in nitrate form. Technological methods which can be used to reduce volatization are shown in Figure 5-2 and include the following:

- *Use of nitrification-inhibiting compounds to inhibit oxidation of ammonia into nitrates.* Two commonly used compounds are **nitrapyrin** and **etridiazol**. These compounds are usually effective in low rates of 0.5 kilograms per hectare or less. The effectiveness of nitrapyrin decreases at high soil temperatures exceeding 25° Celsius.

- *Coating urea with material that will decrease its solubility.* Coating urea pellets with elemental sulfur is effective in decreasing its solubility and the losses due to volatilization. These slow-release formulations reduce the rate of hydrolysis of urea to ammonia, oxidation of ammonia to nitrates, and volatilization of nitrates.

- *Adoption of cultural practices which decrease losses due to volatilization.* There are a number of soil and residue management practices which can adopted, including regulating soil temperature and preventing extremes in moisture regimes, incorporating organic or inorganic fertilizers within the root zone, and providing a continuous crop cover.

Figure 5-2. Management practices to decrease volatilization losses



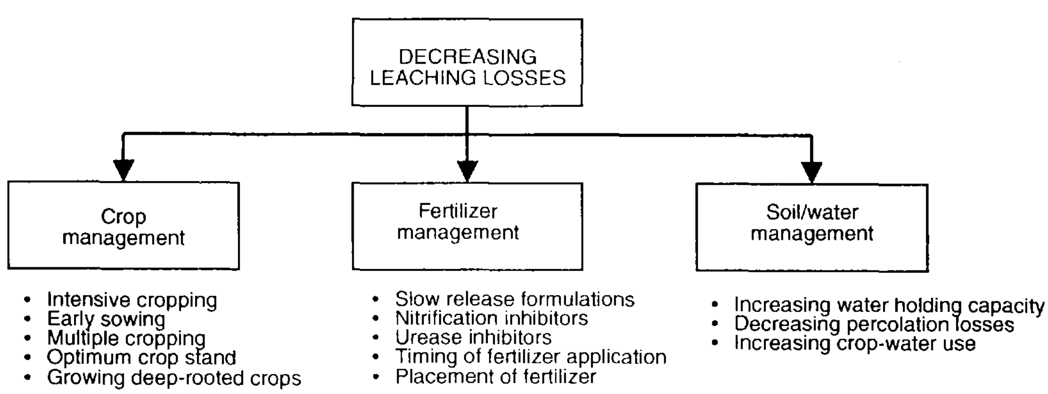
Practices to Reduce Leaching

Leaching involves the mass flow of soluble nutrients along with percolating water and is the reverse of salt accumulation. It occurs in soils with a high percolation rate, free drainage, and predominantly low-activity clays. In addition to nitrogenous compounds, soluble cations may also leach out of the root zone either in solution or as absorbed/adsorbed cations on the exchange complex of elluviating colloids, mainly clay and humus. Leaching may be vertical or oblique, depending on the relative proportion of percolating water moving vertically down the soil profile, or horizontally along a gradient. Lateral or oblique drainage often occurs in layered profiles with drastic differences in permeability among soil horizons or layers. The leached horizon not only loses bases and nitrogen, but also clay and soil organic matter content. The leached soil, therefore, has low chemical fertility and low plant-available water reserves. Leaching is the principal means by which readily soluble forms of nutrients are lost out of the root zone. Percolating water translocates readily soluble nutrients out of the root zone into the subsoil and eventually into the groundwater or stream. Sandy or coarse-textured soils of the wet and humid tropics are more prone to losses due to leaching than are heavy-textured soils of the arid regions or seasonally dry tropics.

Nitrate-nitrogen is most easily lost by leaching. Leaching losses of nitrogen in tropical environments can be high. Experiments conducted in India and Sri Lanka have shown that leaching losses can be as high as 70 to 100 kilograms of N/ha/yr from fallow unfertilized plots; 300 to 500 kg/ha/yr from uncropped fallow fertilized plots; and only 3 to 50 kg/ha/yr from cropped plots (Martin and Skyring, 1962; Lal, 1980). In Colombia, Suarez and Rodriguez (1958) reported leaching losses of inorganic nitrogen from a lysimetric experiment to be as high as 360 kg/ha/yr from bare uncropped plots and only 60 kg/ha/yr from cropped plots. High leaching losses have also been reported for Malaysia (Bolton, 1968); Australia (Martin and Cox, 1956); Nigeria (Lal, 1980); and Thailand (Yoshioka et al., 1987). Experiments conducted on rice paddies in India showed that leaching losses can be as high as 50 to 70 percent of applied nitrogen (ICAR, 1984).

Soil type, crop type, fertilizer type, and water management are major factors in determining the level of leaching losses. Losses are most severe from uncropped fallow land. Intensive cropping and maintenance of a continuous groundcover are important strategies to curtail leaching losses of plant nutrients. Once the cause-effect relationship is established, cultural practices can be developed to reduce leaching losses. Important strategies to lower leaching losses of plant nutrients are outlined in Figure 5-3 and include the following:

Figure 5-3. Cultural practices to decrease leaching losses of plant nutrients



Crop management. Crop management is crucial to reducing leaching losses of plant nutrients. Continuous groundcover and actively growing crops remove easily available plant nutrients and decrease losses. A high proportion of the annual loss of nutrients due to leaching usually occurs during fallowing or in the initial establishment period of crop growth. Crop management practices for reducing leaching losses include early sowing; establishment of an optimum crop stand through the use of good seed; mixed and relay cropping; and frequent inclusion of a deep-rooted crop in the rotation. Planted fallows or natural fallow (i.e., weed growth) are better than no vegetation cover. Utilization of available water through intensive cropping is also an important strategy.

Fertilizer management. Soil nitrogen can be lost by leaching, runoff, and denitrification. The latter results in emissions of nitrous oxide into the atmosphere. Tropical forests, woodlands, and agricultural lands are important sources of nitrous oxide emissions. The amount of nitrogen lost through denitrification varies widely among soil types, drainage conditions, management practices, and the type of soil fauna and flora. The loss may range from 5 to 10 kg/ha/yr in well-drained soils, to 25 to 50 kg/ha/yr in poorly drained soil where urea and ammonia are used as nitrogenous fertilizers. The rate of deacidification of urea to ammonium nitrogen can be decreased by curbing the action of urease enzyme in the soil. Urease inhibitors delay the hydrolysis of urea and allow it to diffuse deeper into the soil. Organic manures should be incorporated into the soil rather than broadcast on the surface in order to control denitrification. The rate, time, and methods of fertilizer application in relation to crop requirements are important considerations in minimizing losses. Early sowing, good crop stand, continuous groundcover, and a deep and vigorous root system are important to decreasing losses.

Soil/water management. Reducing the percolation and deep seepage losses of water also reduces the leaching of plant nutrients. Cultural practices that increase the water retention capacity of the root zone and decrease the permeability of the subsoil horizons should reduce leaching losses. Enhancing soil organic matter content, increasing the relative proportion of water retention pores, rather than transmission pores, and improving interaggregate porosity through structural amelioration are important to increasing the water retention capacity of the root zone. In rice paddies, puddling, which is the destruction of structural aggregates through mechanical manipulation when the soil is saturated, is performed to decrease percolation. In coarse-textured soils with a loose and single-grain structure, mechanical compaction is carried out to achieve the same effect as puddling in structured soils (Ogunremi et al., 1985). Light compaction of coarse-textured soils for cultivation of upland crops is also done to enhance water retention in the root zone and decrease percolation losses.

Practices to Reduce Nutrient Loss

One of the severe on-site effects of accelerated erosion is a decline in crop yield. Reduction in crop yield is partly due to a loss of plant-available nutrients through surface runoff and erosion. The principal mechanisms by which erosion leads to nutrient loss include: (1) loss of dissolved nutrients in surface runoff or overland flow; and, (2) entrainment of plant nutrients along with soil solids. Nutrients transported with soil solids may be in the form of loose adsorption (physical attachment), or chemical bonding/absorption. Chemically absorbed nutrients are firmly tied to soil colloids on either exchange sites (exchangeable cations and anions) or those fixed within the lattice structure of clay minerals. In addition to causing a reduction of crop yield, a loss of nutrients into runoff and eroded sediment is a major cause of environmental pollution. As noted above, eroded plant nutrients lead to water pollution with an enrichment of nitrates in surface water.

In order to reduce the loss of nutrients as a result of soil erosion, it is necessary to control water runoff and sediment transport from agricultural lands. Both the concentration of nutrients and the total amount of water runoff and sediment transport must be decreased. The basic strategy is to decrease the erosive agents and nutrient concentration in runoff and sediments. Reductions in the runoff amount and its velocity will lower the total amount of water and sediment loss. Cultural practices effective in achieving these goals include conservation tillage, mulch farming, and the use of tied or contour ridges. It should be noted that lowering the velocity or amount of runoff does not necessarily imply a reduction in nutrient concentrations in runoff or sediment. On the contrary, nutrient concentration in runoff may be inversely related to the total amount of runoff (Lal, 1976). Fertilizer management is critical to reducing concentration in runoff. An important strategy to reduce nutrient loss through soil erosion is to ensure a good crop cover and to apply fertilizer in the correct amount at the correct time. Split application and proper placement are necessary to achieve these goals.

The basic methods for lowering nutrient losses due to wind erosion (as discussed in Chapter 4), are similar to those for water erosion. The principal strategy is to lower wind velocity, sediment detachment and transport, and the concentration of nutrients in eroded sediment. Cultural practices which can be used to achieve these objectives are outlined in Table 5-5 on the following page. A reduction in wind velocity near the soil surface is usually achieved through the installation of wind breaks, use of vegetative hedges, and provision of groundcover in the vicinity of the soil surface (Lal, 1990b). Cultural practices found effective in reducing sediment detachment and transport include a rough seedbed, conservation tillage, and moisture conservation through mulch farming. As with water erosion, fertilizer management is crucial to reducing nutrient concentrations in wind-eroded sediments.

Table 5-5. Cultural practices effective in controlling nutrient losses by soil erosion

Strategy	Recommended cultural practice
Water erosion	
Reduce runoff amount	• conservation tillage • mulch farming • tied-ridges/contour ridges
Decrease runoff velocity	• terracing • grass waterways • drop structures
Curtail sediment transport	• rough seedbed • reduced tillage • mulch farming • agro-forestry • vegetative hedges or vetiver hedges
Minimize fertilizer concentration in runoff sediment	• split application • soil test and designed rate • continuous crop cover • vegetative hedges
Wind erosion	
Reduce wind velocity near the ground	• wind breaks/shelter belts • vegetative hedges • crop cover
Decrease sediment movement	• rough seedbed • conservation tillage • mulch farming • groundcover • moisture conservation
Minimize fertilizer load	• timing of fertilizer application • split application • fertilizer incorporation • crop cover

Chapter 6

TECHNOLOGICAL OPTIONS FOR ENHANCING THE SUSTAINABILITY OF PRODUCTION SYSTEMS

Sustainable management of the natural resource base depends as much on the overall production systems in use as it does on the soil and water management systems discussed in Chapters 3 to 5. Production systems entail several aspects pertinent to productivity on the one hand, and to the resource base and environmental quality on the other. Three major production systems of the WSDT region (crop-based, livestock-based, and tree crop-based) are briefly discussed in the context of sustainable development. It is necessary to adopt appropriate farming systems which match the available natural resources and socioeconomic conditions of the farmer in order to sustain long-term agricultural productivity.

CROP-BASED PRODUCTION SYSTEMS

Crop-based production systems should be based on the principle of optimizing production from suitable land and minimizing the use of marginal land. The objective should be to match the land use with the crop. Crops grown indiscriminately on marginal land cannot be sustained in the long term, and will cause soil degradation. There are many examples where such practices have depleted soil fertility or caused erosion, including the cultivation of barley in dry areas of the Middle East and North Africa, and the cultivation of various crops on steep hillsides in the Philippines.

Efficient cropping production systems can be developed through the introduction of crop rotations which include legumes. There is potential for the introduction of new and efficient crops. For example, in India, Vertisols previously left uncropped and sown with low-yielding sorghum during the rainy season are now sown to high-yielding crops of soybean. Table 6-1 demonstrates that the introduction of soybean in Madhya Pradesh and Guijurat has revolutionized agriculture in the region and has drastically reduced the risk of erosion. The area under soybean has increased 100 times in the last 15 years and production has increased by almost 160 times, while productivity has been doubled.

Improved technology for food crops can be introduced at various levels. Table 6-2 shows the synergistic effect of variety, soil management, and fertilizer application in a maize-pigeonpea intercropping system on Vertisols in Hyderabad, India. The data indicate that maize yields in low input technology is 450 kilograms per hectare, which can be raised to 3,470 kilograms per hectare through the introduction of high-input yet sustainable management. The data indicate there is potential for a seven- to eight-fold increase in maize yields in the same arid regions of the WSDT, thus raising the possibility of a second Green Revolution in South Asia.

Table 6-1. Soybean expansion in Madhya Pradesh

Year	Area (in thousand hectares)	Production (thousand tonnes)	Productivity (q/ha)
1973	13.4	5.9	4.4
1978	198.6	86.8	4.4
1983	613.8	461.6	7.5
1985	1096.5	829.0	7.6
1987	1319.4	n.a.	n.a.

n.a. not available
Source: FAO, 1979

Table 6-2. Synergistic effect of variety, soil management, and fertilizer application in a maize-pigeonpea intercropping system on Vertisols in Hyderabad, India

Treatment	Yield (kg/ha)	
	Maize	Pigeonpea
A. Maize Variety: Local		
Traditional inputs and management	450	320
Improved soil and crop management alone	600	614
Fertilizer application alone	1900	452
Improved soil and crop management and fertilizer	2100	837
B. Maize Variety: Improved Hybrid		
Traditional inputs and management	630	500
Improved soil and crop management alone	960	640
Fertilizer application alone	2220	540
Improved soil and crop management and fertilizer	3470	604

Source: Dillon and Virmani, 1985

TREE-BASED PRODUCTION SYSTEMS

Trees play an important role in production systems. They fulfill varied functions:

- providing timber and other forestry products, including fuelwood;
- serving as nurse crops to protect shade-loving crops;

- providing shelter animals and game; and,
- serving as a source of feed and forage, and as pastures.

Most importantly, trees provided much needed diversity to stabilize an ecosystem by regulating its principal processes of nutrient cycling and water and energy budgeting. Moreover, as perennials -- once established -- trees do not require the continued disturbance of the soil.

Trees and man-made forests and plantations also place heavy demands on an ecosystem for nutrients, water, and light. As with crops, improper management or mismanagement of trees and tree-based systems can lead to severe soil compaction, nutrient depletion and fertility decline, and utilization of water from deep layers within the soil profile. In fact, the water requirement of tree plantations can be drastically greater than that of food crop annuals or seasonals. With good management, however, the chances of establishing an ecologically stable system are greater with tree-based than with crop-based systems. Most tree-based systems provide a protective cover against soil erosion, have a built-in nutrient cycling mechanism, and prevent extremes of temperature and humidity conditions within the canopy-covered landscape. The major types of traditional tree-based systems commonly used in the seasonally dry tropics are briefly described below.

Natural Forest and Tree Savannah

Natural stands of trees and shrubs play an important and supportive role in pastoralism and agriculture. Important trees in arid and semiarid tropics include *Prosopis africana*, *Lannea* spp., *Ximenia americana*, *Adanosonia digitaria* (baobab), *Putyrospeimum paradoxum* (shea-butter), *Parkia clapperto niana* (locust tree), *Calotropis procera*, *Acacia* spp., *Tamarindus indica*, *Ficus* spp., *Zizyphus* spp., *Balanites* spp. (dates), *Azadirachta indica* (neem), and *Sesbania grandiflora*. Bush fires, annual burning, and prolonged periods without rain, coupled with high temperatures and low humidity, have played a decisive role in the selection and adaptation of trees in these regions. Natural forests and woodlots play an important role in protecting ecologically sensitive regions within a watershed, where trees stabilize the shallow soils and steep terrain, and protect embankments along streams and waterways. Natural forest regrowth is also used as a restorative measure for fertility improvement in forest-fallow and bush-fallow systems. In steep lands, however, even if there is sufficient soil moisture and good soil quality, it is often better to leave such land under natural growth rather than bringing them under cultivation in order to avoid the risk of severe erosion.

Trees in Monoculture and Man-Made Plantations

Many tree species are also profitably grown in pure-stand plantations; for example, coffee, tea, rubber, and coconut. Important among these are fruit trees, *Mangifera indica* (mango), citrus spp., *Zizyphus* spp., and *Tamarindus indica* (tamarind). Pure-stand plantations are also established with other trees used for land restoration; for example, *Azadirachta indica* (neem) is widely grown on soils with hardened plinthite exposed at the surface. Plantations of *Acacia senegal* are also established to harvest a variety of products, including gum arabica, and the tanning industry is based on products harvested from several types of *Acacia* spp.

Improved Agroforestry Systems

The concept of mixtures to create ecological diversity and optimize utilization of limited water and nutrient resources is appropriately extended by growing woody herbaceous and perennials in an orderly association with seasonal annuals and animals (*see* Box 6.1). Agroforestry can be defined as "a system combining agricultural and tree crops of varying longevity (ranging from annual through biannual and perennial plants), arranged either temporally (crop rotation) or spatially (intercropping) to maximize and sustain agricultural yield" (Vergara, 1982). It is a land use that involves the deliberate retention, introduction, or mixture of trees or other woody perennials in areas of crop or animal production in order to benefit from the resultant ecological and economic interactions. Livestock can also be an important component of agroforestry systems.

The root system of trees and woody herbaceous vegetation is deeper, and the canopy is taller, than that of food crop annuals. Therefore, appropriate mixtures can be managed to optimize the utilization of both above- and below-ground resources in both space and time. Although appropriate mixtures may utilize limited resources most efficiently, this does not imply that there is no competition between annuals and perennials for water, nutrients, or light. With the proper management of trees, crops, and animals, however, economically productive and ecologically compatible mixtures can be, and have been, developed. Leguminous woody shrubs and trees can fix atmospheric nitrogen that can be utilized by food crop annuals and forage grasses; in addition, some trees and shrubs also produce allelopathic compounds that can suppress weeds. Finally, deep-rooted trees utilize nutrients and water from deeper layers without competing substantially with shallow-rooted annuals, and appropriate types of trees can be selected in order to establish compatible canopy structures and physical requirements.

LIVESTOCK-BASED PRODUCTION SYSTEMS

The annual average proportion of total cash income derived from livestock is much higher in semiarid and subhumid regions than in more humid regions, where crop production is the principal source of income. Sandford (1988) reported that the semiarid and subhumid regions of Sub-Saharan Africa contained 40 percent of the continent's human agricultural population and an estimated 57 percent of the ruminant livestock. Income from livestock in these drier regions accounted for more than 50 percent of farmer incomes, compared with less than 10 percent in the humid regions. The development of sustainable livestock-based systems, therefore, is vital in the WSDT. Livestock systems are usually less variable than grain systems in these areas, and they also often provide opportunities for increasing the efficiency with which the region's limited water resources are used.

Controlled Grazing

The greatest constraint to livestock production in the WSDT is the shortage and inadequacy of feed resources. Rainfall is unpredictable, erratic, and occasionally insufficient for plant growth. Some grass species mature rapidly and become unavailable to the animal later in the growing period. With the expansion of cropland, pastoralists are often confronted with a reduction in the areas available for grazing. The productivity of the remaining rangeland is also generally lower because the more productive rangeland is usually converted to cropland. As a result, large areas of rangeland are often subjected to overstocking, deterioration, and degradation. A principle of grazing management is to permit the herbage

Box 6.1 Agroforestry

The term agroforestry refers to "farming systems that combine trees with food crops and livestock on the same piece of land in appropriate combinations to optimize productivity, and conserve soil and water resources." It is a form of land use that involves the deliberate retention, introduction, or mixture of trees or other woody perennials in crop or animal production systems to create ecological diversity. The two forms of agroforestry systems practiced in the tropics include: (1) rotational agroforestry or traditional shifting cultivation; and, (2) inter-cropping systems. There are several types of agroforestry systems based on the intercropping of trees and woody perennials with growing food crops and raising livestock. These include: (1) growing trees and woody perennials along field boundaries; (2) growing trees in rows at regular intervals; (3) growing trees in strips; (4) growing trees in a random fashion scattered within the field; and, (5) growing trees in a contiguous area set aside for this purpose. Whatever the arrangement, intercropping systems imply the co-existence of food crops or animals with trees or woody perennials on the same site at the same time. Under ideal conditions, agroforestry systems have several benefits:

- Deep rooted trees facilitate nutrient recycling from sub-soil to the surface for utilization by shallow-rooted annuals.
- Leguminous trees or woody perennials can also fix atmospheric nitrogen which can be utilized by annuals when prunings of trees are applied to the soil as mulch or are incorporated into the top layer.
- When established on the contour, vegetative hedges formed by rows or strips of trees and perennials can slow down runoff velocity and decrease soil erosion by water.
- When established perpendicular to the predominant wind direction, vegetative hedges decrease wind erosion and minimize crop damage due to blowing sand.
- Agroforestry systems can enhance biomass productivity and provide diverse products of economic importance; for example, forage, fuel, fencing/staking poles, construction material, etc.

Agroforestry systems are, however, soil- and site-specific. In regions of moisture deficit, trees can strongly compete with seasonal or annual crops and can suppress their growth and yield. Maintenance of trees and woody perennials can also increase labor requirements. In some cases, trees may also enhance the incidence of pest problems (e.g., damage to crops by birds). The choice of appropriate tree species is critical, therefore, to the success of an agroforestry system. The tree species chosen should be preferably multi-purpose which can met diverse needs of the farm household, and be compatible with the crops grown. Management of trees and food crops should be complementary and optimize productivity. The spacing of trees is also important, as it should be wide enough to reduce competition by trees with food crops. Because trees have a much larger feeding zone, the area allocated to trees should be progressively smaller the lower the amount of annual rainfall. In the West African Sahel, an agroforestry system based on widely spaced trees is more appropriate than one using closely spaced trees.

Suitable tree species for agroforestry systems in the WSDT include: *Acacia* spp., *Azadirachta indica, Balanites segyptiaca, Bombex costatum, Calotropis procera, Commiphora africana, Euphorbic balsamifera, Maerue crassifolia, Parkia* spp., and *Tamarandus indica.*

to grow to adequate bulk before it is consumed. This principle is the basis for the following successful management practices.

Rangeland management. In China, aerial seeding of rangeland with improved species has been very successful. Application of phosphoric fertilizer in the Middle East and North Africa has been shown to improve biomass production from rangelands.

Stocking rate. Livestock numbers are usually the most critical issue in range management. Much of the deterioration of rangeland, particularly in precipitation-limited regions, is caused by poor management rather than overstocking. Rangeland recovery, however, depends on a rest from grazing, and this requires both management and control of livestock numbers. A reduction in stock numbers is often both difficult and unpopular owing to social, economic, and traditional patterns, but it is an inescapable requirement for sustaining or restoring rangeland productivity. A potential method for ensuring rangeland recovery in the WSDT is the use of the Hema system. The Hema system is an ancient management system used successfully for centuries in the Arab countries of North Africa and the Middle East. Draz (1980) has studied this system and reported on its modern developments. Areas using Hema systems are often closed to grazing in succession for five years or more. There are various types of Hema systems. For example, in some cases where grazing is prohibited, the cutting of grasses is allowed. In other situations, grazing is restricted to certain seasons of the year.

Control and use of fire. Grasses in the WSDT pass rapidly from young growth of good digestibility and high protein content to bulky growth with moderate protein content. By the end of the dry season, protein content is very low, and the stems have lignified to the point where they are not readily digestible by ruminants. This material is often burned in anticipation of new growth of high-quality grass. If the anticipated rains are not adequate, however, an important resource has been lost. Even the coarse dry material provides useful bulk and some energy for hungry ruminants. Preserving at least part of the area as a reserve provides opportunities for animal feed during drought years and for the ripening of plants and subsequent distribution of the grass seeds by the wind.

Forages. Fallow is practiced in many regions for conserving water and increasing soil fertility. Water conservation, however, is minimal in agro-ecological zones such as the WSDT where there is a long dry period during the fallow period. Moreover, fallow, particularly if vegetation is controlled during this period by tillage, leads to a decline in the organic matter level and soil structure. As an alternative, forages can be used in place of fallow to increase both the use efficiency of the limited precipitation and the amount and quality of livestock feed. The International Livestock Center for Africa (ILCA) in Addis Ababa, Ethiopia, has successfully demonstrated the utility of areas as small as 0.25 hectares, sown with forage legumes such as *Stylosanthes guianensis*, and fenced as dry-season reserves and allowed to mature and set seed. These areas were then consumed by a dense stocking of grazing animals. This practice not only provided feed for the livestock, but also provided manure for the soil. In addition, the seed was churned into the soil by the cattle hooves so that cultivation and seeding were not needed in subsequent years.

Ley Farming

The ley farming system alternates cereal production with grazed pastures of annual legumes. The annual legume pastures regenerate spontaneously from seed that lies dormant during cereal production. As a low input and integrated system that has proved sustainable in some low rainfall areas, ley farming offers considerable potential for other areas, such as the dryland Mediterranean regions of North Africa and West Asia, and for the semiarid dryland tropics of Sub-Saharan Africa. Following this method's success in southern Australia, attempts to introduce ley farming were initiated on a large scale in North Africa and the Middle East; these attempts were based on the assumption that since the Mediterranean climate is similar to that of southern Australia, only a simple demonstration of its principles would be needed. Nonetheless, despite considerable efforts by Australian researchers, ICARDA, and the south Mediterranean countries, farmers have not adopted ley farming systems, due to social customs and the tradition of free grazing rights, as well as the special land preparation requirements entailed in this practice.

Cocks (1988) analyzed the constraints to the use of this system and concluded that the poor adaptation of Australian medic cultivars was one of the system's limitations. He proposed that the successful introduction of ley farming systems must include the use of locally adapted pasture cultivars and rhizobia strains; the provision of facilities to produce them in amounts adequate to meet demand; and the availability of local research backup that can solve problems as they arise. In addition, projects should be based on sound economic data which illustrate where and under what socioeconomic conditions ley farming is likely to succeed. Finally, the focus should be on farmers with livestock who grow cereal grains, have appropriate tillage and weed control machinery, control their land, and are interested in increasing their feed resources.

ASSESSMENT

Tremendous possibilities exist for enhancing production in an ecologically compatible and sustainable manner through the use of production systems involving some combination of trees with agricultural crops and/or animals. Full exploitation of this potential, however, depends on the successful adaptation of basic technological principles to site-specific environments, using farmer participation and involvement in all phases of technological development, validation, and adaptation. A failure to tailor farming systems to the specific natural resource base and socioeconomic characteristics of each location will make impossible sustainable agricultural development.

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