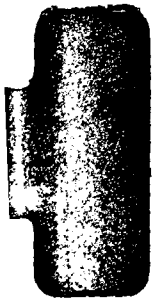
Environmental Change in the West African Sahel



Environmental Change in the West African Sahel

Advisory Committee on the Sahel
Board on Science and Technology for International Development
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Board on Science and Technology
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National Research Council
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CAROL CORILLON, Writer/Research Associate
JEFFREY A. GRITZNER, Professional Associate

CONTRIBUTORS

EDMOND BERNUS, Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), Paris, France
KARL BUTZER, Departments of Geography and Anthropology, University of Chicago, Chicago, Illinois, USA
ROBERT FISHWICK, Western Africa Regional Office, World Bank, Washington, D.C., USA
SHARON NICHOLSON, Graduate School of Geography, Clark University, Worcester, Massachusetts, USA
WOLF RODER, Department of Geography, University of Cincinnati, Cincinnati, Ohio, USA

PREFACE

In 1968 a major drought struck the West African Sahel. By the early 1970s, the tragic dimensions of the event had gained worldwide attention; some 25 million people faced hunger and disease as well as social and economic dislocation. Despite ambitious international relief efforts, death rates in the region rose substantially. Losses of the more poorly adapted forms of livestock, particularly cattle, were substantial, and the resource base of the region was severely degraded.

How typical was that drought? What is the nature of Sahelian climatic regimes? How do Sahelian ecosystems function, and what caused the ecological imbalances throughout the region? To what extent is human activity, rather than climatic fluctuation, responsible for the widespread degradation of Sahelian ecosystems? How are essential ecological processes and genetic diversity in the Sahel most effectively restored?

Sound development planning in the Sahel requires that these questions be thoughtfully examined. Sustainable development and environmental stability--the twin goals of the governments of the region and technical and economic assistance efforts--require that project decisions be based on scientifically sound analysis. It is also clear that development projects must be reconciled with environmental and social realities in order to build on the strengths of existing systems and achieve positive ecological and socioeconomic results.

The Advisory Committee on the Sahel (ACOS) was organized by the Board on Science and Technology for International Development in 1978 at the request of the Agency for International Development (AID) to formulate a long-term strategy for environmental rehabilitation and development in the Sahel. This study was undertaken by ACOS at the request of AID's Office of Sahel and West African Affairs to provide a better understanding of environmental change in the West African Sahel and to serve as a resource for the identification of measures that would help restore critical ecological processes and thereby increase sustainable production in the areas of dryland farming, irrigated agriculture, forestry and fuelwood, and animal husbandry.

To interpret environmental change, the committee called upon acknowledged experts in the environmental and social history of the

Sahel region. They were asked to conduct independent studies or prepare papers on particular topics judged to be of critical importance by the committee. Their individual and collective contributions to this study are acknowledged below.

Karl Butzer of the University of Chicago prepared a paper that appears as Chapter 1, Late Quaternary Environmental Change in the Sahel. Sharon Nicholson of Clark University contributed a study that served as the basis of both Chapter 2, Climate and Man in the Sahel During the Historical Period, and Appendix B, the Climatology of Sub-Saharan Africa. Chapter 3, The Impact of Human Activity on Sahelian Ecosystems, was a collaborative effort by Edmond Bernus of ORSTOM and Jeffrey Gritzner of the BOSTID staff. The discussions in Chapter 4 reflect the experience of the committee members, and that of invited experts Robert Fishwick of the World Bank and Wolf Roder of the University of Cincinnati, who participated in the final meetings of the committee. Appendix A, Shelterbelt Establishment in the Drylands of West Africa, is based on a study jointly undertaken by Robert Fishwick and Fred Weber. All committee members have reviewed and support the report as a whole.

The committee greatly appreciates the contributions made by other individuals to this report. Comments by George Taylor II and Dayton Maxwell of AID's Office of Sahel and West African Affairs were very helpful in relating the report to AID needs. Representatives of AID, the U.S. Department of Agriculture, the congressional Office of Technology Assessment, the Department of State, the World Bank, and other interested organizations attended the committee meetings and provided information and observations that proved very useful to the committee in preparing this report. Jean Maley of the French Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), Michael Watts of the University of California at Berkeley, F. Kenneth Hare of the University of Toronto, and William Clark of the Institute for Energy Analysis provided valuable criticisms and suggestions on various drafts of the report.

In addition to the invaluable support of our staff, Carol Corillon and Jeffrey Gritzner, we were also assisted in many ways by others. Michael G. C. McDonald Dow attended our meetings and made important intellectual contributions based on his years of experience in the Sahel. Alverda Naylor willingly and capably performed the many clerical tasks necessary for the completion of the study. The report was edited by Sherry Snyder. Cheryl Hailey assisted with the design and artwork. Irene Martinez typed various drafts and prepared the final version for printing.

Because of the critical importance of agro-silvo-pastoral systems to Sahelian economies, and the potential importance of better integrated production systems to rehabilitative strategies, the committee has prepared a companion report, Agroforestry in the West African Sahel. The report further explores many of the concerns and suggestions contained in Chapter 4.

Leonard Berry
Chairman
Advisory Committee on the Sahel

CONTENTS

INTRODUCTION

An inadequate understanding of Sahelian climatology, environmental history, and ecosystem function has consistently hindered the formulation and successful implementation of environmental and agricultural projects in the Sahel. Millions of dollars in donor assistance have been ineffectively spent, and Sahelian populations are increasingly vulnerable to economic adversity and natural hazards. In this study the Advisory Committee on the Sahel has attempted to clarify the environmental history of the region and provide needed baseline information for the formulation of projects to rehabilitate Sahelian ecosystems and promote sustainable agricultural and livestock production.

A paleoenvironmental review and historical analysis were employed to assess the nature of environmental change in the Sahel: the long-term characteristics of the region were determined by examining the evidence provided by stream deposits, fossil sands, and lake beds and their related, abandoned shorelines. This evidence, which is presented in Chapter 1, reveals that little significant long-term climatic change has occurred in the Sahel during the last 2,500 years, although rapid short-term changes are characteristic of the region. The nature of Sahelian climatic regimes is touched on in Chapter 2 of the report and is treated in greater detail in Appendix B.

Chapter 2 also discusses the interaction of climate and man in the Sahel by examining the rainfall characteristics to which human activities must be adapted. The chronicles of medieval geographers and historians, the journals of early European travelers, the archaeological record, and other sources reveal that rainfall in the Sahel is generally low, unevenly distributed, and highly variable. Drought is an inherent feature of the region. These records indicate that major droughts, persisting for 12-15 years, evidently occurred in the 1680s, the mid-1700s, in the 1820s and 1830s, the 1910s, and since 1968. Generally arid conditions characterized the period from 1790 through 1850, and comparatively minor droughts apparently occurred in the 1640s, 1710s, 1810s, the beginning of the twentieth century, and the 1940s. Relatively wet periods occurred during the ninth through thirteenth centuries, the sixteenth through eighteenth centuries, from 1870 to 1895, and during the 1950s. In all development planning in the Sahel, high levels of climatic variability and inevitable drought should be accepted as being "normal."

In examining the impact of human activity on Sahélian ecosystems, it has become evident that man's role in transforming the region's environment has been significantly underestimated. As discussed in Chapter 3, ancient and medieval societies had a substantial impact through activities such as setting bush fires, producing charcoal for local needs, and in connection with trans-Saharan trade, iron smelting, and the establishment of settlements on easily destabilized sites. In modern times, many of these same activities, often on a larger scale, as well as activities associated with development and modernization, have caused further environmental degradation.

A more complete knowledge of Sahelian environments and the historical impact of human activity on Sahelian ecosystems allows development planners greater appreciation of the nature, causes, and spatial extent of environmental degradation. This knowledge permits planners to better assess the biological potential of the Sahel and identify specific measures that would help restore essential ecological processes and contribute to the development of more stable and productive agro-silvo-pastoral systems. It also allows planners to distinguish between destructive and environmentally sound activities in the Sahel and to combine historical analysis with modern ecological knowledge to develop useful guidelines for project design. Chapter 4 identifies research programs and other measures that would enhance current knowledge of Sahelian ecosystems and promote environmentally sound development activities.

Shelterbelts have proved effective in supporting higher crop yields and provide fuelwood, building material, and other products of importance to Sahelian populations. They also support wildlife populations, and thereby increase the availability of bush meat and help reestablish the role of wildlife in seed dispersal. Appendix A briefly discusses successful examples of shelterbelt establishment in the drylands of West Africa. Appendix B amplifies the material presented in Chapter 2, providing a more detailed and somewhat more technical description of sub-Saharan climatic regimes.

ENVIRONMENTAL PROFILE

Sahel (Sahil) is an Arabic term signifying coast or border. In this report the area referred to as the Sahel is a zone approximately 200-400 km wide, centered on latitude 15°N in sub-Saharan Africa. Although examples of environmental change from various regions of this extensive zone are used in this report, the focus of the study is the West African Sahel (Figure 1). Within West Africa, several Sahelian enclaves are found beyond the strict limits of the zone; for example, in the Adrar des Iforas, the AÏr, and in the southwestern Tibesti highlands. Within the Sahel, the interior delta of the Niger River and Lake Chad are atypical of the region as a whole.

Since the initiation of international efforts to combat the effects of drought in the arid and semiarid zones of West Africa in the 1970s, the term "Sahel" has been more broadly applied to non-Sahelian regions of the member states of the Permanent Interstate Committee for Drought Control in the Sahel (CILSS). The states include Cape Verde, Senegal, The Gambia, Mauritania, Mali, Upper Volta, Niger, and Chad. In these states, the Sahel proper covers approximately 2 million square kilometers, constituting 27 percent of Senegal, 39 percent of Mauritania, 40 percent of Mali, 7 percent of Upper Volta, 50 percent of Niger, and 32 percent of Chad.

Recent research on the long-term climatic characteristics of the Sahel indicates that the region was repeatedly subject to change during the Late Quaternary.* For example, wind-driven sand encroached far into the present Sudanian and Guinean zones to the south of the Sahel between 20,000 and 12,000 years ago (B.P.),** while between 9000 and 5000 B.P. the rivers of the region had greater discharge and the lakes substantially greater volumes. The climate of the Sahel has been relatively constant during the last 2,500 years. It has been characterized by short- to medium-term oscillations toward drier or more humid conditions (Figure 2), with rapid, highly variable climatic change occurring within these more predictable fluctuations.

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*The Quaternary Period is the most recent major subdivision of geological time. It is a relatively short interval of 2 or 3 million years within the approximately 5 billion years of earth history.

**Most isotopic dates are quoted with B.P. (before the present) rather than B.C. values. By international agreement, the "zero" date for this system is A.D. 1950.

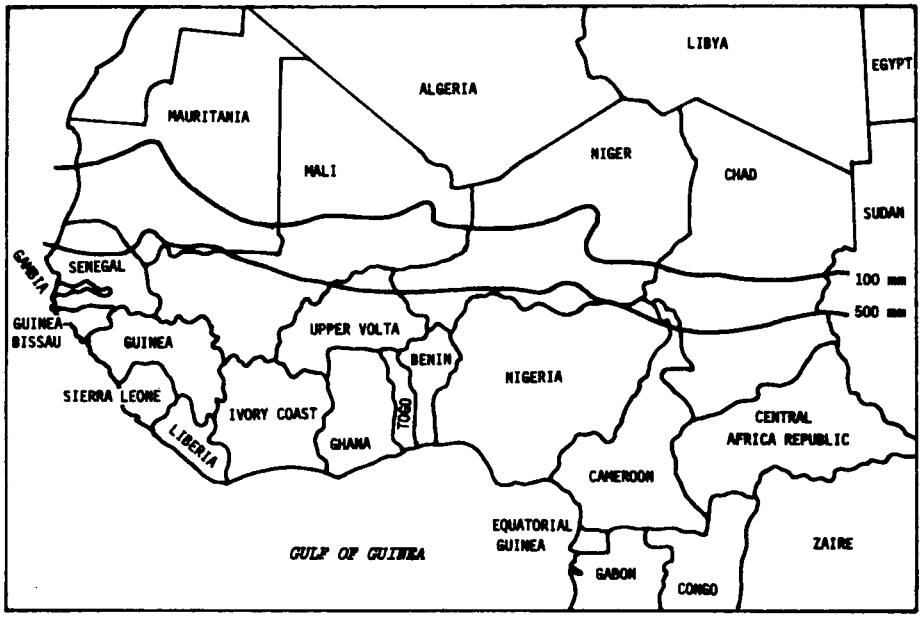


FIGURE 1 The West African Sahel.

Variation in precipitation from year to year is also a characteristic of the Sahel; successive years of severe drought are often followed by years with torrential rains. The Sahelian drought that began in 1968 falls within the norm of at least six earlier periods of low rainfall verified since 1400 A.D. In addition to secular, short-term droughts, some researchers believe that major droughts occur cyclically in the Sahel at intervals of approximately 30 years.

Although precipitation varies with latitude and local conditions, it is generally restricted to a period of 3-5 months. Storms are frequently violent in nature, and the rain is often erratically distributed--both in terms of when and where it falls--with variability increasing from south to north within the Sahel. The rainy season is followed by an extended, unrelieved dry season.

In some regions of the Sahel, precipitation variability is partially compensated for by groundwater reserves. The most important regional aquifer is the Intercalary Continental found in Niger and in northern Mali. Another important aquifer is the post-Eocene Terminal Continental. This formation is largely associated with the Adrar des Iforas in Mali, southwestern Niger, various areas north of the Niger River, and Senegal. The same aquifer apparently exists in southeastern Mauritania, but it is too deep for practical exploration. Similarly,

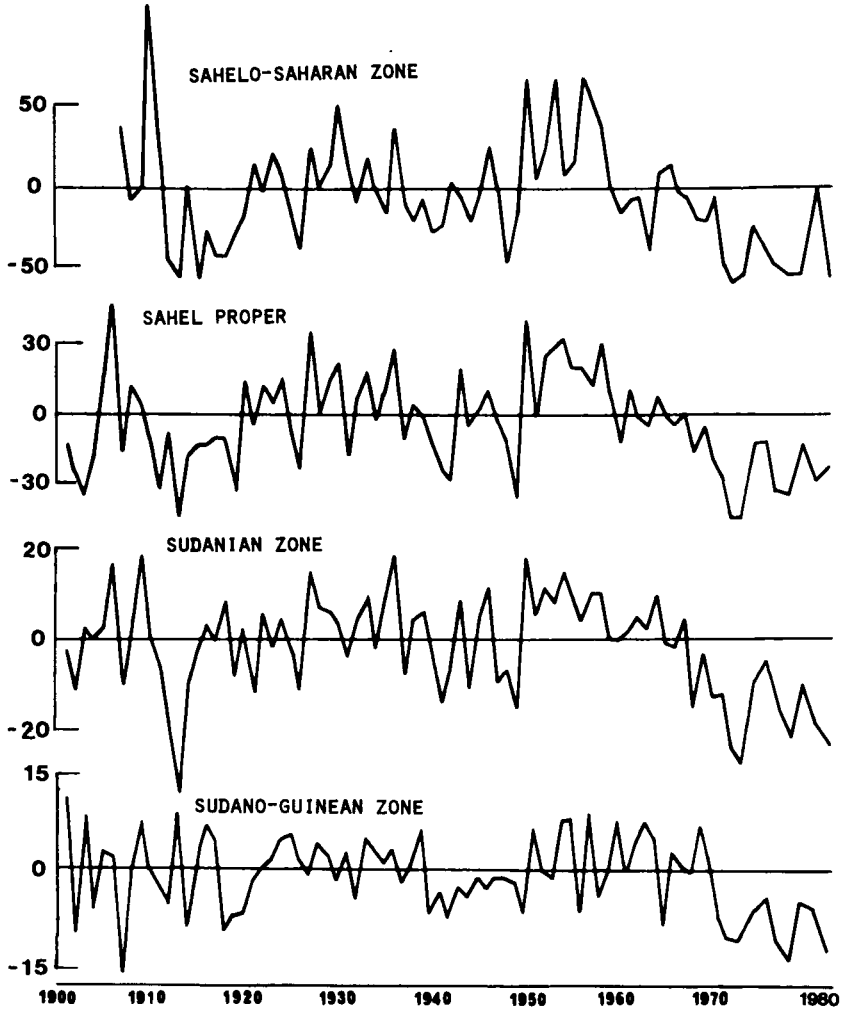


FIGURE 2 Rainfall fluctuations (1901-1980) for the Sahelo-Saharan, Sahelian, Sudanian, and Sudano-Guinean zones (percentage above or below normal). (Source: Nicholson 1982)

erratic rainfall in the western Chadian Sahel is compensated for by the northerly trending subsurface discharge of Lake Chad, a major body of water fed largely by the Chari and Logone rivers issuing from the Central African highlands. The Sahel is also traversed by two major rivers, the Senegal and the Niger, whose sources are in the highlands of Guinea.

Most of the Sahel lies below 400 meters in elevation. Its surface is largely composed of worn, folded Precambrian rocks. These formations are characteristically aligned from northeast to southwest, with the alignment reflected in the limited relief of the region. The soils of the region range from ferruginous tropical soils in the south, to brown tropical dryland soils and weakly developed sandy soils on shifting and stabilized sands in the north.

The modern Sahel has often been described as a transitional zone--a territory in which an enriched Sahara and an impoverished Sudan meet in a hybrid no-man's land lacking its own characteristics. This view has been challenged by Theodore Monod, Edmond Bernus, and others who have studied the region. They view the Sahel as an ecoclimatically autonomous region largely defined by its highly variable precipitation and its characteristic seasonal therophyte ("summer prairie") vegetative communities.

There are no universally accepted delimiting criteria or terms for the various climatic and vegetation zones of West Africa. For the purposes of this report, the Sahel is defined as a zone roughly bracketed by the 100 and 500 mm isohyets. It is described as containing three phytogeographical divisions: the northerly Sahelo-Saharan zone (grass steppe), between the 100 and 200 mm isohyets; the Sahel proper (tree steppe), between the 200 and 400 mm isohyets; and the southerly Sudano-Sahelian borderlands (shrub savanna), extending to the 500 mm isohyet. The Sahel is bounded to the north by the Sahara Desert, and to the south by the Sudanian zone (wooded savanna). Finally, the Guinean zone (woodland) extends from the Sudanian zone to the Gulf of Guinea. Most zones contain coastal subregions (such as the Senegalese Coastal Sahel) and are commonly referred to in combination (for example, the Sudano-Guinean zone)--sometimes to describe a transitional area between zones, perhaps more often to group zones as a matter of convenience.

The Sahelo-Saharan zone has relatively few trees; examples include *Acacia ehrenbergiana*, *A. tortilis*, and *Balanites aegyptiaca*. Sparse grass such as *Panicum turgidum* is found on dunes. The Sahel proper is more heavily vegetated. Characteristic species include *Acacia ehrenbergiana*, *A. laeta*, *A. nilotica*, *A. senegal*, *A. tortilis*, *Balanites aegyptiaca*, *Maerua crassifolia*, *Salvadora persica*, *Zizyphus mauritiana*. Annuals such as *Aristida adscensionis*, *A. funiculata*, *Panicum laetum*, and *Schoenefeldia gracilis* are found on silty soils; *Aristida mutabilis*, *Cenchrus biflorus*, and *Tribulus terrestris* are found on sandy soils. The vegetative cover increases in the Sudano-Sahelian zone, reaching 10-12 percent on sandy soils and over 60 percent on silty soils. *Andropogon gayanus* and *Zornia glochidiata* are representative grasses of the Sudano-Sahelian zone; representative trees include *Acacia albida*, *A. seyal*, *Adansonia digitata*, and *Combretum glutinosum*.

CHAPTER 1

Late Quaternary Environmental Change in the Sahel

One of the more catastrophic and well-documented recent famines occurred during the severe drought that struck the southern Saharan borderlands in 1968. Relatively little attention has been devoted to whether this drought was unique, with its impact increased as a consequence of recent changes of land use patterns and population growth, or whether it was but another example of severe and recurrent environmental stress in the area. A paleoenvironmental review, which places the drought in a historical context, can address this question.

No other region of Africa has as conspicuous a record of environmental change as the semiarid and subarid zones along the southern margins of the Sahara, between the Senegal and Nile rivers. This record is best expressed in great expanses of active or immobilized sand dunes on the one hand, and dry lake beds on the other. Such evidence is not unique to the Sahel, but nowhere else in Africa is the surface record of ancient climates so extensive.

Three basic categories of evidence can be examined: (1) stream deposits, exposed in well-studied river valleys and in the offshore sediment cones of the principal rivers (fluvial record); (2) fossil sands, in vegetated dunefields and as struck by cores beneath Lake Chad or in the deep sea (the dune record); and (3) lake beds and related, abandoned shorelines found in the major tectonic depressions, as well as in the swales between fixed or active dunes (the lake or lacustrine record). This primary record is complemented by a number of paleosols, by fossil pollen, and by lake microorganisms such as diatoms. The timing of the major events has been reasonably well determined by an unusually large number of dates based on radiocarbon measurements. The emphasis of the discussion is on the amplitude and wavelength of environmental change, not on paleoclimatic reconstruction or interpretation. Appendix B provides a detailed discussion of the Sahelian climatic regimes.

The Fluvial Record

In the Senegal River valley the datum for Late Quaternary events is provided by gravelly alluvium, 2 m above the modern floodplain, related to a relatively high world sea level before 31,000 B.P. (Michel 1973,

Beaudet et al. 1976). The sea level later fell, and the river was able to remove much of this gravel infilling and cut down into its bedrock floor, suggesting periodically strong floods. Eventually, however, the lower valley was drowned by dunes advancing southwestward out of the Saharan fringe, building up sand forms with a relief of 30 m and extending out onto the edge of the continental shelf; the Senegal River was unable to reach the coast at this time. Later, a deep red soil, indicative of a complete vegetative mat and intensive biochemical weathering, developed on these dunes while the Senegal and other rivers once again cut through the dunefield to reach the sea. During the period between 5000 and 4000 B.P. a rising sea level flooded into the new Senegal Delta, and the reduced river gradient favored sandy alluviation as much as 250 km upstream. Sea level then dropped a little and, from 3000-1650 B.P., was again slightly higher, resulting in development of a series of beach ridges along the delta, while the river had a regime similar to that of today.

This picture of alternating drier and wetter conditions is paralleled farther south in central Sierra Leone (latitude 8°N), where dating is somewhat more precise (Thomas and Thorp 1980). In this wetter environment, broad swampy valleys with poorly defined channels were flooded by high and protracted monsoonal runoff from before 36,000 until about 20,500 B.P. A subsequent absence of sediments and organic matter indicates drier conditions without forest. River discharge increased about 12,500 B.P., first eroding bedrock, then depositing gravelly alluvium increasingly interbedded with swamp clays, by 9000 B.P. About 6000 B.P., river activity had stabilized and soils began to develop on the uplands. Renewed, increasingly swampy deposition is indicated from 3300-1750 B.P. and during the last 900 years or so.

This pattern is pinpointed in deep-sea core M-12345, off the Senegal Delta, where windborne sands and dust with Saharan pollen were deposited between 16,300 and 12,500 B.P., after which river discharge contributed abundant sediment, with tropical pollen, particularly during several millennia after 8600 B.P. (Sarnthein et al. 1982). A similar pattern is indicated in core KW-31 off the Niger Delta, where discharge was very low between about 20,000 and 15,000 B.P.; thereafter, flow increased markedly and, with brief fluctuations, remained high until about 4000 B.P. (Pastouret et al. 1978).

At about the same latitude (8°N), the White Nile appears to have been deprived of Ugandan runoff between about 25,000 and 12,500 B.P., so that a body of still, saline water was ponded up in the lower White Nile floodplain (Williams and Adamson 1980). Subsequently, massive White Nile floods built up silts to 4 m above the modern floodplain until 11,400 B.P., when discharge again declined and dunes were able to move across the valley onto the east bank. Stronger floods resumed by 8400 B.P., and local watercourses became more active than they are today. Relatively high discharge is identified in the later record around 7000, 5500, 3000, 2700, and 2000-1500 B.P. The Blue Nile record and that of the combined Nile drainage below the Atbara confluence (Williams and Adamson 1980, Butzer 1980a) mainly reflect trends in upland Ethiopia and are peripheral to the present discussion.

Preliminary evaluation of the fluvial indicators reviewed here points to an exceptionally dry climate in the Sahel between about 20,000 and 12,500 B.P., when the area evidently was an extension of the Sahara. Subsequently, conditions have been relatively moist but subject to considerable variation. The details of this later variability are only poorly resolved in the fluvial record.

The Dune Record

Taken together, the windborne sands of the Sahel and the record of increasing and decreasing stream activity help date the expanse of immobile and vegetated dunefields or sand sheets so common in much of the Sahel (Grove and Warren 1968, Mabbutt 1977, Mainguet et al. 1980, Talbot 1980). In northern Nigeria today, such dunes are well developed in areas with as much as 750 mm of rainfall, although few active sand fields can now be identified in areas with more than 150 mm. This suggests that desert conditions extended an average of 3° latitude farther south than is the case today. But such extreme aridity has not been experienced during the last 12,500 years.

Dust of Saharan origin first became abundant off the coast of Senegal during two protracted episodes between about 7.5 and 5.5 million years ago (Sarnthein et al. 1982). After 2.5 million years, windborne dust fluctuated considerably but generally remained quite prominent, suggesting an arid Sahara comparable to that of the present day. Deep cores under the Chad Basin record a dominance of clays, lake diatomites, and alluvial sands from the late Oligocene or early Miocene until the end of the Pliocene (Servant and Servant-Vildary 1980). Thereafter, windborne sands are dominant but repeatedly interbedded with lenses of lake deposits.

The dune sands and windborne dust thus serve to document the development of the Sahara Desert at the onset of the Quaternary period, some 2 million years ago. As interwoven with marine, stream, and lake deposits they indicate a relatively dry climate, as a deteriorating vegetative cover repeatedly allowed windborne Saharan sands to advance into what is now a savanna environment. The last major advance of dunes and sandfields, across a belt up to 500 km wide, predates 12,500 B.P. Latitudinal shifts since about 7000 B.P. have been comparatively limited in extent.

The Lake Record

The distribution of dry lake beds in the Sahel and even in parts of the Sahara is quite remarkable and provides the most detailed record of climatic fluctuations during the past 12 millennia. The best-studied record, serving as a key indicator of Sahelian climate, is that of the Chad Basin (Servant 1973, Servant-Vildary 1978, Servant and Servant-Vildary 1980, Maley 1981, 1982).

During the last millennium, Lake Chad has had a seasonally fluctuating surface area of 10,000-20,000 km^2, with a mean depth

varying from 3-7 m. Situated some 500 km northeast of the modern lake are two lower depressions, the Bodélé and Djourab, which are separated from the lake by a low divide. Overflow from Lake Chad into these depressions can occur when the lake level rises above the +4 m shoreline (around 286 m above sea level). The highest shorelines, however, are at +40 m, revealing the former presence of a great inland body of water of about 350,000 km^2, about the size of the modern Caspian Sea. This extensive "Paleo-Chad" was primarily fed by the discharge of the Chari and Logone rivers, which rise in the forested highlands of Central Africa between latitudes 6° and 10°N, as well as by precipitation falling elsewhere within the Lake Chad Basin. Despite its vast surface of evaporation, the Paleo-Chad maintained various high levels from 7500 to about 5000 B.P. and not only supported a substantially higher water table throughout its basin but probably also indirectly fed innumerable seepage lakes between the dunefields to the west and north and major aquifers that extend beyond the basin.

The history of Lake Chad episodes first acquires detail with intermediate to high levels about 30,000-20,000 B.P. During the first lacustrine phase--about 30,000-26,000 B.P.--the associated diatoms were of montane or high-latitude environments, but the pollen data indicate a desert vegetation with very few tropical taxa. Later--about 25,000-20,000 B.P.--the "cool" diatoms persisted but in association with several tropical species; the pollen indicate a strong increase in tropical elements and a corresponding decline of desert taxa.

During the period of maximum aridity between 20,000 and 13,000 B.P., the southern Chad tributaries were characterized by perennial discharge and, after 17,000 B.P., by a major extension of swampy floodplains. North of the lake, lacustrine deposits, mainly of saline facies, reappear between 13,000 and 12,500 B.P. and probably reflect in part a rise in the water table, fed from a southerly source. Between 12,500 and 9200 B.P. several modest lacustrine phases were interrupted by several dry interludes between 12,400 and 9400 B.P. A rapid rise of the lake to an intermediate level began about 9200 B.P., lasting until about 8500 B.P. From about 12,500 until 7000 B.P. the diatom fauna indicates cool waters and oligotrophic conditions. After a fall of the lake level to its modern position around 7400-7000 B.P., the Paleo-Chad maximum was achieved at +40 m, fluctuating below this high level until 5200-5000 B.P. The associated diatoms indicate temperatures similar to those of today, with eutrophic waters. After a long and important regression centered about 4000 B.P., a last high lake level is dated between 3500 and 3000 B.P. Subsequent levels fluctuated around those of the last millenium.

Palynological study of various lacustrine sedimentary sequences (Maley 1981) shows that Sahelian forms began to slowly replace desert shrub after 12,500 B.P., gaining dominance by 10,100 B.P. At this time the 12 verified Sahelian taxa included 5 tree species. Nonetheless, until 7000 B.P., tree pollen account for only 7 percent of the available spectra. Thereafter tree pollen increase rapidly, and around 5000 B.P. they exceeded nonarboreal types, clearly documenting a tree-savanna. This matches the sedimentary record, which indicates maximum precipitation and Chari-Logone river discharge during the same period.

It is possible to estimate rainfall and moisture levels for the high lake stands of about 7500-5200 B.P., assuming radiation, temperature, and wind conditions similar to those of today. Kutzbach (1980) has suggested that rainfall averaged a little over 650 mm per year across the basin, compared with only about 350 mm today. But he adopted a nonempirical estimate of lake surface evaporation of 1,297 mm per year, whereas this figure is actually over 2,200 mm (J. Maley, personal communication). Perhaps more significant than this conservative modal value is the repeated evidence of sharp periodicities in lake level. Servant and Servant-Vildary (1980) suggest four scale models for such variability: fluctuations of (1) several tens of meters over time spans of several millennia, (2) 1-5 m over several centuries, (3) up to 3 m over several decades, and (4) about 50 cm between seasons. This scale of change is broadly replicated in other, smaller lakes of the Chad Basin fed by groundwater or by a combination of runoff and water table. That it is characteristic of a broad climatic belt spanning the African continent from west to east can be seen by comparing the trace of Lake Turkana (formerly known as Lake Rudolf), which has had a history similar to that of Lake Chad since 10,000 B.P., with similar abrupt fluctuations (Butzer 1980b).

Comparison of measured stream discharge and lake level changes since 1900 (Faure and Gac 1981, Maley 1981) indeed shows that the history of Lake Chad is fully representative of hydrological changes across the Sahel. Basic details in the area west of Lake Chad are reviewed by Talbot (1980) and Maley (1981). Another, less precisely dated local sequence has been reported from the caldera of Gebel Marra (13°N latitude) in the western Sudan (Williams et al. 1980). Here a +25 m lake of considerable longevity shrank about 19,000 B.P. but reconstituted at +5 to +8 m about 19,000-16,000 B.P. After another drop, the level regained +9 m about 14,000 B.P. and then maintained an intermediate level until about 3000 B.P.; since then the level has fluctuated between -2 and +2.5 m. This record to some degree reflects special conditions, but it is interesting because it shows that the time between about 20,000 and 12,500 B.P. was not uniformly arid, confirming local lacustrine beds from the Tibesti mountains that indicate that climate at higher elevations and higher latitudes has been predominantly wetter since as early as 16,000 B.P. (Jäkel 1979), even while the Saharan lowlands and Sahel were desert.

Lake Chad history for the last 800 years has been reconstructed in detail by Maley (1981). Using dune history, pollen, fluctuations in lake level, flood data for the Niger and Nile rivers, and population movements, he has established broadly synchronous climatic anomalies for the Sahel (Figure 3). The lake level dropped some 5 m within a few decades before 1450 A.D., then recovered 3 m by 1500, only to fall again by 1550. A level of +5 m was maintained throughout the seventeenth century. Subsequent levels have fluctuated in the 0 to +3 m range, with two lows during the eighteenth century, one about 1850, another after 1913, and again during the 1970s. This scale of variation is more rapid than that revealed by the older, generalized lake trace but corresponds better with the major oscillations of the

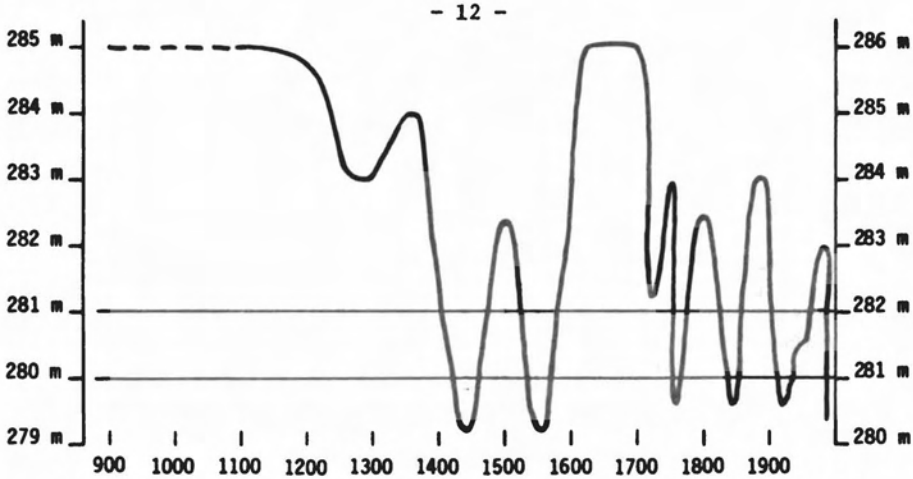


FIGURE 3 Diagram of fluctuations in the level of Lake Chad during the last millennium. The shift of 1 meter between the modern shoreline and that of 900 A.D. reflects the accumulation of sediment in the southern basin of the lake during the last 1,000 years.

parallel pollen records that were frequently compressed within 1-3 centuries (Maley 1981). Even more detailed are the smoothened discharge data of the Sahelian rivers, which indicate major dry anomalies every 30 years or so since the turn of the century (Faure and Gac 1981). Together with the historical evidence and oral tradition (Nicholson 1979), this hydrological information points up the following significant differences:

- Short-term severe droughts such as that which struck in 1968 are generally reversed within less than a decade and appear to be too brief to show up in most sedimentological or biotic records.
- Intermediate-scale dry anomalies lasting several decades are more likely to be revealed by detailed geological or biological studies. However, even though their impact on productivity, biomass, and carrying capacity may be severe, they most commonly represent no more than temporary oscillations in the highly variable climatic regime of monsoonal Africa (see Butzer 1971b).
- Long-term drying trends over several centuries or millennia are primarily responsible for the simplified trace of stream, dune, and lake records reviewed here; they comprise many positive and negative oscillations of intermediate scale that cumulatively effect fundamental changes in hydrology, biotic distributions, and regional geomorphologic threshholds. These are the magnitudes of change reflected in the history of Lake Chad over the last 12 millennia.

The lake records discussed here are among the most detailed available for the Late Quaternary of Africa. They show that much of the period 9000-5000 B.P. was substantially wetter than today, providing a counterpoint to the evidence for drier Sahelian climate in the period before 12,500 B.P. They further place recent climatic oscillations in context: anomalies comparable to the drought beginning in 1968 have been verified on at least six occasions since 1400 A.D. and may recur three times per century.

Concluding Discussion

In paleoclimatic terms, the Sahel drought of 1968 evidently falls well within the range of short- and medium-term variability directly documented for the last few centuries and indirectly shown for the last 12 millennia or so. Kates (1981), in fact, argues that the human impact of a similar drought in 1911-1914 was of similar or greater proportions. Other authors, however, believe that colonial and postcolonial changes in land use and sustained population growth since the turn of the century have dramatically increased pressures on the ecosystem, rendering it unusually vulnerable to periodic stress (Glantz 1976, Dalby et al. 1977). Without addressing the issue of whether the rapid technological and social transformations defined as "development" serve to increase systemic fragility, it is pertinent here to explore the degree to which recent desertification has had tangible geomorphic impact.

It is reasonable to expect that overgrazing, devegetation, soil erosion, and even secondary mesoclimatic change will follow in the wake of ecological disbalance, accentuated by years of extreme drought. Yet the "historical" (i.e., geomorphological) context for desertification remains hopelessly fragmentary. Only a few examples of such analyses have been published thus far.

Near Niamey, Niger, Talbot and Williams (1979) studied the cycles of erosion and deposition that periodically account for the buildup of small fans below gully systems that cut back into fixed dunes. The most recent cycle switched from fan accumulation to geomorphic stability over 300 years ago, but stream incision is now active, with gullies cutting back into the partly devegetated dunes. Two earlier cycles of cutting seem to have proceeded at similar rates, suggesting that ecological recovery is merely a matter of time.

On the Adamawa Plateau of north-central Cameroon, Hurault (1975) used an interpretation of aerial photographs, ground controls, and local informants to show that streams of intermediate scale were perennial about 1900 A.D., with low flood peaks, and had deposited suspended sediment. As a result of overgrazing and degraded ground cover during the twentieth century, channels have been incised and are now lined with rocks and gravel. They function intermittently, mainly during flash floods following rains. This set of processes is found in several other contemporary and historical settings--for example, in the American Southwest, the Mediterranean Basin, and upland Ethiopia (Butzer 1981)--and therefore are not unique to the 1968 drought.

In central Sierra Leone, Thomas and Thorp (1980) established several alluvial episodes that span the last 12,500 years. Although artifacts related to agricultural settlement are evident since 4000 B.P. and imply a measure of deforestation, there is no qualitative difference in the development of earlier and later alluvial sediment suites.

These examples do not accurately reflect the extent and severity of ecological degradation by rapid population growth in West Africa during the last 50 years. They do caution, however, that environmental trends since the advent of agriculture and pastoralism in the Sahel cannot automatically be attributed to human intervention without verification by meticulous local studies. They also suggest that there is an urgent need for systematic geomorphological examination of modern desertification processes in a historical context in order to determine the extent to which these events are unique or simply cyclical.

CHAPTER 2

Climate and Man in the Sahel During the Historical Period

The chronicles of medieval geographers and historians, the journals of early European travelers, the archeological record, and other sources reveal that rainfall in the Sahel is generally low, unevenly distributed, and highly variable. Drought is an inherent feature of the region. These records indicate that major droughts, persisting from 12-15 years, evidently occurred in the 1680s, the mid-1700s, the 1820s and 1830s, the 1910s, and since 1968. Generally arid conditions characterized the period from 1790-1850, and comparatively minor droughts apparently occurred in the 1640s, 1710s, 1810s, the beginning of the twentieth century, and the 1940s. Relatively wet periods occurred during the ninth through thirteenth centuries, the sixteenth through eighteenth centuries, from 1870-1895, and during the 1950s.

This chapter considers the interaction of climate and man in the Sahel by examining the rainfall characteristics to which human activities must be adapted. (A more detailed description of sub-Saharan climatic regimes appears in Appendix B.) The discussion attempts to underscore several points about the Sahel that are too rarely kept in mind. First, the region is part of a global climatic system, and it must be treated as such in any attempt to understand it. Second, it is an environment that can sustain only cautious use, as rainfall is low, spotty, and highly variable (Vermeer 1981); recurring droughts are inherent, and dry years are more prevalent than wet ones. Finally, the interplay of various parts of the climatic system are involved in producing the extreme rainfall fluctuations in the region; therefore, narrowly based attempts to understand and forecast the region's climate and to comprehend its relation to man and environment are generally unproductive. Throughout this chapter, remarks applicable to the true Sahel are appropriate for the entire sub-Saharan region from approximately latitude 10°N to latitude 20°N.

THE HISTORICAL PERIOD: 850-1900 A.D.

While it is apparent from modern meteorological records that the Sahel experiences marked changes of rainfall distribution on the scale of decades, other classes of data confirm this variability as an inherent characteristic of the region and illustrate that conditions differing

significantly from the "average" ones can persist over longer periods of time. It is, of course, more difficult to reconstruct the climate of earlier centuries, but historical accounts and geographical texts, together with various classes of environmental data, provide a fairly reliable picture of times before instrumental observations were made.

The types of information useful for a historical reconstruction of Sahelian climate are sketched in Table 1. By identifying independent indicators of the same event or trend, by comparing evidence from many areas, and by recording anomalous events, it is possible to determine a number of drier and wetter periods during the last three centuries and to broadly describe conditions during the last millenium.

Relatively little material on the Sahelian climate is available for periods prior to the sixteenth century, and what can be found is general and somewhat speculative. Nevertheless, the level of the groundwater table, the extent of lakes, archaeological studies, descriptions of landscapes and caravan routes from medieval Arabic sources, and climatic descriptions found in the journals of early European travelers all provide evidence of past conditions (Nicholson 1979). Tentative conclusions drawn from these sources are that the Sahel probably experienced wetter conditions in the ninth through thirteenth centuries, and that these conditions may have set in as early as the eighth century and declined sometime during the fourteenth century.

Several indicators suggest that the sixteenth through eighteenth centuries were generally wetter than subsequent centuries (Nicholson 1979). They include the level and extent of numerous lakes, historical accounts, and descriptions of landscape and climate. As indicated in Chapter 1, perhaps the best point of reference is the level of Lake Chad (Maley 1981), which often stood 4-5 m above modern levels, although within the present century fluctuations have been on the order of 1 or 2 m. Also, historical chronicles from Mauritania, Mali, Nigeria, and Chad indicate a relative absence of drought throughout the period (Nicholson 1979). Early geographical accounts tell of the verdure of many Sahelian regions, suggesting greater rainfall and higher groundwater levels. When such indicators are taken individually, the interpretation of each can often be challenged. Collectively, however, they present an accurate picture of the past and indicate that generally wetter conditions prevailed throughout much of the sixteenth, seventeenth, and eighteenth centuries.

Nevertheless, drought did occur (Cissoko 1968). A major drought apparently occurred in the 1680s. It also appears that droughts at least as severe as that of 1968 occurred in the Sahel from the mid-1730s to the mid-1750s and again in the 1820s and 1830s--persisting for 12-15 years in many areas. The latter drought was continental in extent. Lake Chad was partially desiccated, and signs of increasing aridity appeared throughout much of southern Africa. Generally dry conditions prevailed during most of the period from around 1790 to 1850. Less significant droughts occurred in the 1640s, 1710s, and 1810s (Nicholson 1980).

Such climatic indicators as lake levels and river flow, rainfall, and harvests (Figure 4) indicate extreme fluctuations during the late

TABLE 1 Types of Data Useful for Historical Climatic Reconstructions

I. Landscape Descriptions

(1) Forests and vegetation. Were they as they are today?

(2) Conditions of lakes and rivers

(a) Height of the annual flood, month of maximum flow of the river
(b) Villages directly along lakeshores
(c) Size of the lake (e.g., as indicated on maps)
(d) Navigability of rivers
(e) Desiccation of present-day lakes or the appearance of lakes that no longer exist
(f) Floods
(g) Seasonality of flow condition in wet and dry seasons

(3) Wells, oases, bogs in presently dry areas--also, drying up of wells

(4) Flow of wadis

(5) Measured height of lake surface (frequently given in travel journals, but optimally some instrumental calibration or standard should accompany this).

II. Drought and Related Information

(1) References to famine or drought, preferably accompanied by the following information:

(a) Where occurred--as precisely as possible
(b) When occurred--as accurately as possible
(c) Who reported it--whether the information is secondhand
(d) Severity
(e) Cause of famine
(f) Localized or widespread
(Note: Some sources mentioning the "very severe drought" may simply be referring to the normal dry season.)

(2) Agricultural prosperity

(a) Condition of harvest
(b) What produced this condition
(c) Months of harvests--in both bad years and good years
(d) What crops are grown

(3) Rainfed agriculture in regions presently too arid

TABLE 1 Continued.

III. Climate and Meteorology

(1) Measurements of temperature, rainfall, etc.

(2) Weather diaries

(3) Descriptions of climate and the rainy season. When do the rains occur, what winds prevail?

(4) References to occurrence of rain, tornadoes, storms

(5) Seasonality and frequency of tornadoes, storms

(6) Snowfall. Is this clearly snow or may the reporter be mistakenly reporting frost, etc.?

(7) Freezing temperatures, frost, hail

(8) Duration (or absence) of snow cover on mountains

(9) References to dry or wet years, severe or mild winters

(10) References to wind. Particularly important is the prevalence of the harmattan or a steady northeast wind in areas south of the Sahara (in West Africa) because this is an unambiguous sign of a dry period. Conversely, steady southwest winds (associated with the rainy season) are also important indicators in this region. Important: Does the reporter suggest this is a common or uncommon occurrence?

(Note: Even very isolated references may be quite important. Also, "tornado" generally refers to the frequent West African wind storms or squalls.)

SOURCE: Nicholson 1979.

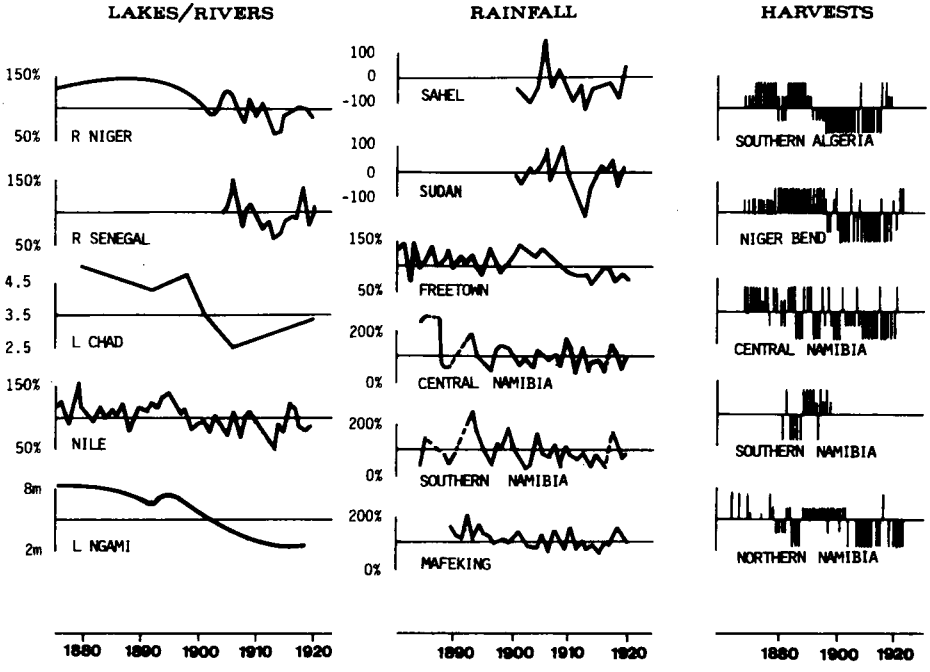


FIGURE 4 Trends of African climatic indicators (lakes and rivers, rainfall and harvests), 1880–1920. Lake levels, river discharge, and rainfall are expressed as standardized departures from normal. Harvest quality: above the axis = good; below the axis = poor. (Source: Nicholson 1981)

nineteenth and early twentieth century. A wet episode, comparable to or more extreme than the 1950s (Kimble 1962), lasted from about 1870–1895 (Nicholson 1978, 1981). The harvests of the agriculturalists associated with the nomadic Kel Tamacheq (Tuareg) were abundant during this period; droughts were local and of short duration. The Niger Bend region near Timbuktu yielded abundant crops and became the "breadbasket" of West Africa, whereas current annual rainfall in the area averages 228 mm. The discharge of the Niger and Senegal rivers was higher during this period (1870–1895) than during the twentieth century; and lowland areas of Senegal, Mali, and southern Africa, which are now dry, contained lakes or ponds. The surface of Lake Chad stood several meters above its present level.

The picture is similar for other parts of Africa. Throughout East Africa, Rift Valley lakes maintained levels several meters above modern ones, and the Nile carried considerably more water than at present. In southern Africa, Lake Ngami, now an expansive marsh, was a deep and extensive body of water. Harvests were consistently good in semiarid regions of Namibia, southern Angola, and some areas of South Africa.

THE TWENTIETH CENTURY

Around 1895, conditions became markedly more arid throughout the tropics. A serious drought occurred at the turn of the century. Although Senegal, Mali, and Niger were particularly hard hit (Sidikou 1973), the Ahaggar region of the Sahara was also influenced, and Lake Chad was reduced considerably (Alexander 1907). Lakes, rivers, and rainfall throughout Africa progressively diminished, and harvests were fair to poor. The "desiccation" culminated in severe drought, which was most intense in 1911 and 1914 and which persisted for about a decade (Bernus and Savonnet 1973, Sircoulon 1976, Kates 1981). At Freetown, Sierra Leone, in coastal West Africa, annual rainfall was 30–35 percent lower during the period 1910–1940 than between 1880 and 1895. The discharge of the Nile was reduced by 35 percent, and the mean depth of Lake Chad was reduced by about 50 percent. West African rivers also carried less water. Lake levels dropped rapidly in many areas of the continent. A less intense and less widespread drought occurred in the 1940s. Following a period of greater rainfall in the 1950s, drier conditions recommenced in the early 1960s. They set in first around 1960 in the most northerly areas and spread progressively southward. By 1968 the impact of drought was felt throughout the region. The drought continued, with some amelioration in 1974 and 1975, into the 1980s.

The contrast between the 1950s and the subsequent drought is extreme. It would appear that the sequence of these two episodes was responsible for much of the tragedy associated with the drought, as the wet conditions of the 1950s promoted use of more marginal lands. Rainfall was consistently high throughout the 1950s (Figure 2); as much as 50–60 percent above the mean in the Sahelo-Saharan zone, 20–30 percent above the mean in the Sahel proper, and 10–20 percent above the mean in the Sudanian zone to the south.

Conditions changed abruptly around 1960, and rainfall continually declined until 1973. During that year rainfall was about 60, 40, and 30 percent below the mean in the Sahelo-Saharan zone, the Sahel proper, and in the Sudanian zone respectively. Thus, in some marginal areas, tropical rainfall in the 1950s was more than twice that for the period 1968-1973; in the Sahel proper, rainfall averaged nearly 350 mm/yr in the 1950s but only 200 mm/yr from 1968-1973. The drought continually spread and intensified from 1968-1973. Even 1969, considered by some to be a year of relatively good rainfall, was abnormally dry in all areas except the far western portion of the Sahel. In the 1950s, rainfall in northern Africa was below average in only 7 of 37 regions but was above average in only 5 regions during the period 1968-1973 (Figure 5). Thus, the drought extended well beyond the Sahel.

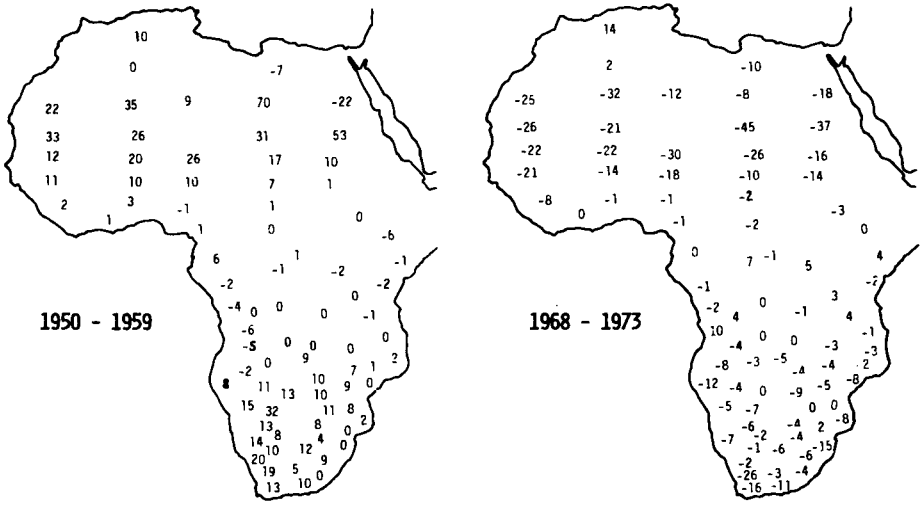


FIGURE 5 Rainfall (percentage above or below (-) normal) for 84 African regions for the periods 1950-1959 and 1968-1973. (Source: Nicholson 1982)

It is commonly thought that the drought ended in the mid-1970s, but a recent analysis of more current data contradicts this. The years 1974 and 1975 were wetter than the preceding ones, but rainfall totals were still below normal. The years 1976-1980 were consistently dry, with certain years apparently matching the worst ones earlier in the decade. In the Sahelo-Saharan zone, rainfall was more than 50 percent below normal in 1977, 1978, and 1980, and 40 percent below normal in 1976 (Figure 6). The Sahel proper and the Sudanian zone were extremely dry in all 5 years (1976-1980), with deficits ranging from 15-35 percent in the Sahel and 10-25 percent in the Sudan. At individual stations, even larger deficits were recorded. These relatively dry conditions have persisted for approximately 2 decades, and it now appears that the present century may be the driest one in the Sahel and its borderlands in over 1,000 years (Figure 7).

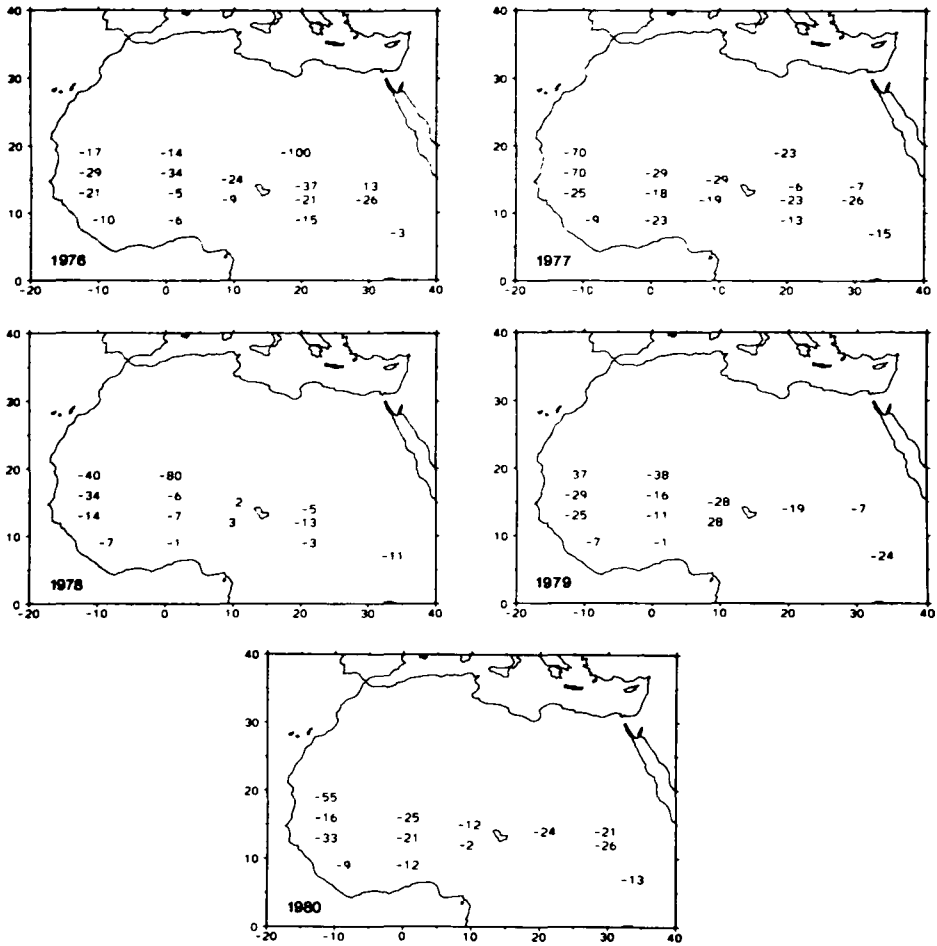


FIGURE 6 Rainfall in the years 1976-1980 for sub-Saharan Africa (expressed as a percent departure from the average annual rainfall). (Source: Nicholson 1982)

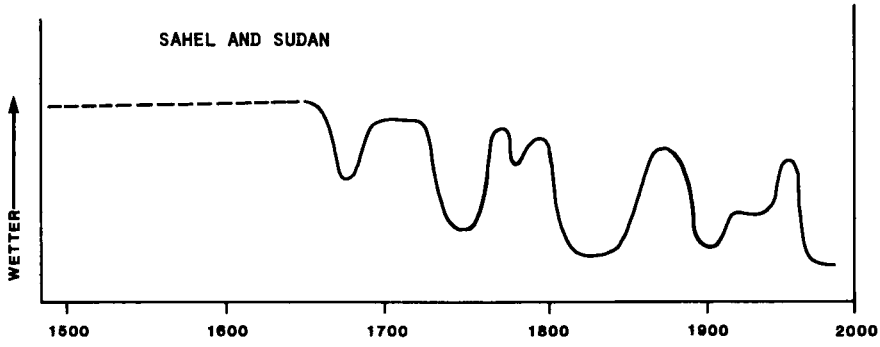


FIGURE 7 Probable long-term rainfall trends in the Sahel and Sudan (no quantitative interpretation should be given to this curve). (Source: Nicholson 1982)

BIOGEOPHYSICAL FEEDBACK

Perhaps the most satisfactory explanation for the prolongation of the 1968 drought is to be found in a hypothesis initially proposed by J. G. Charney (1975). This hypothesis maintains that Sahelian rainfall is strongly influenced by "biogeophysical feedback." According to the hypothesis, drought would be reinforced either through the changes it evokes in the Sahelian land surface, usually through devegetation, or through similar changes produced by human impact on Sahelian ecosystems. Charney's hypothesis is discussed by Nicholson in Appendix B.

CHAPTER 3

The Impact of Human Activity on Sahelian Ecosystems

Problems of environmental degradation in the Sahel are frequently attributed to recent droughts, population pressures, or overgrazing, with little appreciation of the duration and spatial dimensions of man's impact on Sahelian ecosystems. Evidence of human occupation in the Sahel dates from approximately 600,000 B.P. Since that time, selective hunting and gathering, bush fires, agriculture, herding, charcoal production, the destructive exploitation of forest products, and other activities have contributed greatly to the modification of Sahelian ecosystems. No areas, however remote from human settlement, have been left undisturbed. These activities have led to progressive reductions in biological diversity and productivity and, in recent years, serious breakdowns in essential ecological processes. The restoration, enrichment, and sound management of Sahelian ecosystems is basic to sustainable economic development in the region.

Because climatic change and variability are regular features of the Sahel, the native plant and animal communities of the region are generally well adapted to the range of climatic variation existing in the region. The ecological imbalances that have been exposed by recent droughts can be better understood by looking at the Sahelian people, their livestock, and their agriculture. While the Sahelians are the victims of drought, they have also contributed greatly to their growing vulnerability. Many efforts in "development" or modernization have also contributed to their plight. An appreciation of man's impact on Sahelian ecosystems is of basic importance both to our understanding of the declining ability of the region to support human populations and to the development of strategies to correct this trend.

In order to provide a better understanding of the role of human activity in modifying Sahelian ecosystems, this chapter briefly explores nine agents of anthropogenic change: bush fires, trans-Saharan trade, site preferences for settlements, gum arabic trade, agricultural expansion, proliferation of cattle, introduction of advanced firearms, development of modern transportation networks, and urbanization. These agents illustrate the breadth and diversity of the human impact on the region.

Bush Fires

The vegetative changes that have coincided with episodes of prehistoric human occupation in the Sahel might well have been caused by the use of fire to support hunting activities. Fire has long been used as a tool in hunting, to improve grazing, and to clear land for cultivation. Perhaps the earliest historical record of bush fires in the region is contained in Hanno's Periplus, a document that records a Carthaginian attempt to establish commercial colonies along the western coast of Africa during the fifth century B.C. The document's reference to the "big and little fires flaming up at intervals everywhere" (Harden 1963) is widely accepted as evidence of bush fires in the interior.

Primitive hunters often used fire in the belief that tender, green forage would be more readily available to wildlife in areas cleared of the coarse, largely inedible vegetation remaining from the previous season. The same rationale is often applied by modern herders. Unfortunately, while fire can serve as an important management tool, burning volatilizes organic nitrogen compounds, and the excessive leaching of tropical soils during the rainy season results in the loss of salts from the ashes of the burned grass and burned animal manure (Bartlett 1956). According to H. N. Le Houérou (1977), it has been estimated that bush fires in the African grasslands burn more than 80 million tons of forage per year--an amount sufficient to maintain 25 million cattle for a period of 9 months.

Regardless of when burning was first employed in the Sahel, its use has definitely altered the region's vegetational history. Fast-growing, light-loving trees and shrubs are gradually replaced by less readily disseminated trees and shrubs; and if burning is regularly repeated, normal ecological successions are deflected to permanent grassland, with some trees and shrubs entering from neighboring, drier floristic zones. These species are termed "pyrophytes" and characteristically have their greater mass below ground rather than above the burned-over surface (Kuhnholz-Lordat 1939). Similarly, fire favors perennial grasses with underground stems that regenerate rapidly and produce new green shoots.

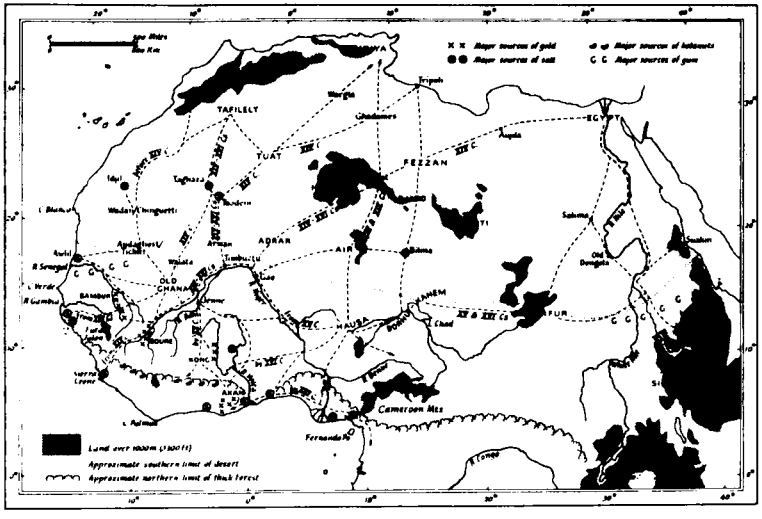
In general, the results of bush fires are a reduction and simplification of vegetation, soil depletion through losses of nitrogen, reduced nutrient cycling through deep-rooted trees and shrubs, and critical breakdowns in soil ecology. In areas where cattle are maintained, this in turn characteristically results in the overgrazing of the perennial grasses, a further reduction of biological productivity, and declining carrying capacity. Cattle are generally replaced by goats and sheep and, finally, when the grasslands have been reduced to desert, camels gain in importance. This transition from woodland to desert has occurred within living memory in many parts of Africa (Cloudsley-Thompson 1977).

The Trans-Saharan Trade

Herodotus, writing around 450 B.C., the geographer Strabo, writing some 400 years later, and other classical authors describe an active

trans-Saharan trade based on precious stones called "carbuncles," gold dust, and slaves. While the commodities transported have changed through time, the trans-Saharan trade has continued to the present day (Figure 8).

The environmental impact of this trade on the Sahelo-Saharan zone and the Sahel proper has been surprisingly great. Perhaps the principal impact has been the widespread destruction of Acacia tortilis through the production of charcoal. Such charcoal production on the desert margin is described by Sidi Hamet, a Moroccan active in the trans-Saharan trade during the late eighteenth century. In describing a caravan ". . . of about three thousand camels and eight hundred men," Sidi Hamet recalled that ". . . we stopped ten days, and let our camels feed on the bushes, while half the men were employed in getting wood from the mountain and burning it into charcoal, which we put into bags, as it was light, and laid it on the camels over the other goods." The charcoal was apparently used for roasting the flesh of desert antelopes and camels, for trade, and as emergency rations for the camels. Describing a later journey involving ". . . about four thousand camels, and more than one thousand men," Sidi Hamet again indicates that the caravan stopped at the desert margin ". . . and cut wood and burned coals for the camels, for the caravans never attempt to cross the desart [sic] without this article . . . " (Riley 1817).



11 Trade Routes of Northern Africa, Xth to XVIIIth Centuries

FIGURE 8 Trade routes of Northern Africa, tenth to eighteenth century. (Source: Fage and Verity 1978)

It is noteworthy that various sources indicate that axes were standard equipment for cameleers engaged in the trans-Saharan trade. The writings of Marsh, Bobek, Jorgensen, Darby, Mikesell, and others who have explored the question of deforestation in antiquity convincingly support the claim that charcoal production in relation to the trans-Saharan trade could have had a most profound impact on the ecology of the Sahel region. Furthermore, with the degradation of the desert margin, the dry-season mechanisms of seed dispersal within Sahelian ecosystems--effective northeasterly winds, southerly trending animal movement, etc.--would encourage a progressive southward shift of dry-steppe vegetation leading to a compression of the zone. This, in turn, would alter critical ecological relationships, lead to decreased genetic diversity and, ultimately, amplify the impact of hazards such as drought (National Research Council 1981).

Site Preferences for Settlements

The Arab and Berber populations of the Sahel historically have demonstrated a preference for establishing their settlements on elevated sandy surfaces (Figure 9). The reasons behind this preference include the following: health, the ritual purity of "high" sand within the context of Islam (Qur'anic sura IV.46), the perceived security afforded by higher elevations (A. Andrawis, personal communication), and the water storage capacity of sand dunes. Of these, considerations of health are perhaps the most frequently cited. Because Arab and Berber populations do not possess the sickle-cell trait, they are far more susceptible to falciparum malaria than are their negroid neighbors, and the establishment of settlements on elevated, well-drained surfaces reduces their exposure to malarial parasites (National Research Council 1981).

Many colonial military installations in the Sahel were similarly situated atop formerly fixed dunes. Severe environmental degradation occurred around such installations. Although the causes of this degradation vary, the primary contributors seem to have been perimeter clearance, the use of tree trunks in site preparation and building, the use of wood as fuel, and the damage inflicted on the local vegetation by herds of cattle, camels, goats, and sheep maintained by the garrisons (Toupet 1976).

These site preferences have led to the widespread destabilization of formerly fixed dunes through devegetation and physical disturbance by foot traffic, livestock, and, in recent years, vehicular traffic. This problem is naturally aggravated as settlements grow. Changing architectural traditions have further contributed to the problem. Less than 20 years ago, Boutilimit, Mauritania, was described as ". . . a city of tents" (Gerteiny 1967), a description that contrasts sharply with the mud-brick buildings of the city today. The construction of permanent buildings requires the use of much more wood for structural support than is required in the construction of traditional tents and huts. Moreover, in many areas of the Sahel the erection of permanent structures in mobile landscapes has greatly complicated matters, as the

FIGURE 9 Tamchaket, Mauritania. The establishment of settlements on fixed dunes has led to destabilization of the dunes through devegetation and physical disturbance. (J. Rowland Illick)

buildings themselves are responsible for the accumulation of sand that ultimately results in their destruction (National Research Council 1981).

The reactivation of Sahelian dunes through physical disturbances and the direct removal of vegetation to satisfy the building material, fuel, and fodder needs of local populations carries further environmental implications. It seriously affects the regenerative capacity of the vegetation as the drift sand generated by the dunes causes seedling losses through abrasion, burial, and desiccation.

The Gum Arabic Trade

The Dutch were evidently the first Europeans to recognize the commercial potential of the gum arabic produced in the Acacia senegal forests of the western Sahel. It was used largely for printing in the important Dutch textile industry. The gum exported to the Low Countries passed through Arguin, a trading center established by the Portuguese to the south of Cap Blanc (Cape Blanco) in 1448. Arguin had been taken over by the Spanish late in the sixteenth century and passed into Dutch hands in 1638. The French later became interested in the gum arabic trade and, in 1677, the Dutch ceded Arguin to the French following the Peace of Nimegue. Thirteen years later, the Dutch recovered Arguin and held it for 31 years before again losing it to the

French. During this period, the Dutch had established commercial ties with 'Ali Shandora of the Trarza region, which resulted in the founding of Marsa (later Portendik), a commercial outpost located on the coast some 40 km to the north of modern Nouakchott, Mauritania.

The French captured Portendik in 1723; it was subsequently regained by the Dutch, recaptured by the French in 1724, and taken by the English in 1762. By 1763 the English were in complete control of the Mauritanian gum arabic trade. Twenty years later, the Treaty of Versailles, which terminated Anglo-French rivalries in America, also returned control of the Mauritanian coastal zone south of Cap Blanc to the French. Renewed hostility between France and England again resulted in an English presence in the region. This presence was maintained until the peace settlement following Napoleon Bonaparte's defeat at Waterloo returned the region to France in 1816. Despite the apparent finality of this transfer, one finds reports of Moors selling gum arabic to the English in defiance of the French as late as 1834. In 1857, in exchange for the formal renunciation by the English of their gum trade at Portendik, the French ceded their remaining rights at Albreda on the Gambia (Crone 1937, Blake 1941-1942, Fage 1969, Church 1980).

This historical sketch illustrates the importance attached to gum arabic by the European powers. The intense demand for gum arabic resulted in increased competition and higher prices. As the exploitation of gum arabic became more profitable, production increased apace. The environmental consequences of increased production were evidently profound.

Gum arabic is a storage product of the *Acacia senegal*. The more stressed the tree, the greater the yield of gum. The tapping methods currently employed in the Trarza and Brakna to stress the trees and increase production also reduce the resistance of the trees to disease and drought. It is probable that similar methods were applied in the past. Trarza experienced severe droughts in the 1680s, from 1738-1756, and during the 1770s, 1790s, 1820s, and the 1830s (Nicholson 1979). Given the historical southward shift in gum production within the Trarza and the sequential decline in the importance of Arguin and Portendik, it would appear that destructive tapping techniques and the droughts of the seventeenth, eighteenth, and nineteenth centuries effectively destroyed the gum forests found inland from these important trading centers.

In the twentieth century, the well-known gum forests around Boutilimit, Togba, and elsewhere in Mauritania have disappeared (National Research Council 1981). The loss of the gum forests has had far-reaching implications for local economies as well as for environmental stability. In addition to producing gum arabic, the trees provide browse, support honey production, and are sources of tannin, wood, and charcoal. The hardwood is often used in the manufacture of such items as tool handles and weavers' shuttles, and a strong fiber can be obtained from the tree's long, flexible surface roots. Locally, the gum has a wide range of uses, extending from preparation of ink for use in Qur'anic schools, to a solution for stabilizing the interior walls of mud-brick buildings. The *A. senegal*

tree can be incorporated into dryland agroforestry systems to restore soil fertility and serve as a living fence as well as provide the products noted above (National Research Council 1981). The extensive root system of the Acacia senegal (Figure 10) maintains soil ecology and physical stability in sandy or otherwise well-drained tracts of the Sahel.

Agricultural Expansion

Rainfed Agriculture

The expansion of rainfed agriculture in the Sahel has been prompted by several events and circumstances: the cessation of slaving has encouraged a northward drift of agricultural populations into formerly hostile regions of the Sahel; normal population increase, which for agriculturalists occurs at a rate of 2.5-3.0 percent per year as compared to 1.5-2.0 percent for pastoralists (Le Houérou 1980), has brought additional land into use--often at the expense of fallow; in some regions, soil depletion forces agriculturalists continually to seek more fertile regions; and, increasingly, nomads have adopted the practice of combining farming with seasonal livestock movement. In many areas, expansion was facilitated by the unusually high rainfall of the 1950s.

The Republic of Mali witnessed an 80 percent increase in rainfed crop production between 1952 and 1975 (International Livestock Centre for Africa 1980); similarly significant increases are reported for Niger and for other countries of the Sahel. The expansion of rainfed agriculture results in a direct acceleration of soil erosion through the removal of vegetative cover and physical disturbance. Additional degradation occurs as trees and shrubs are cut to satisfy the construction and fuel requirements of the cultivators.

Sedimentation studies in the United States indicate that annual soil losses from forested areas are only a few hundredths of a ton per hectare, in contrast to 54 tons from land cultivated for maize production. Given the substantial amount of land withdrawn from production because of soil depletion in some Sahelian agricultural systems, it should be added that sediment loss for abandoned farmland in the studies cited was 450 tons per hectare (Thacher 1979, cf. Lowdermilk 1948). It should also be noted that agricultural expansion in the Sahel characteristically results in an indirect increase in the degradation of the surrounding rangelands since the conversion of the more productive forage areas to agricultural production forces pastoralists to "overgraze" the remaining land base (Thomas 1980). As Marchal (1982) has observed, Sahelian agriculture, "after having consumed space, preys upon it."

FIGURE 10 The extensive root system of the Acacia senegal contributes greatly to the maintenance of environmental stability in the Sahel. The deep taproot (severed in this photograph) extends down to the water table; the shallow lateral roots exploit light rain showers. (G.E. Wickens)

In many areas, agriculture development focusing on the cultivation of cash crops such as groundnuts has resulted in serious losses of soil structure and fertility, as well as a broad range of socioeconomic problems. The self-sufficiency of rural populations is often reduced as land and labor are devoted to cash crops. Rural subsistence is further impaired as crop yields decline and young men are forced to seek employment in urban centers in order to support their families. In many regions of the Sahel, the loss of young, vigorous farmworkers has resulted in those left on the land being physically incapable of cultivating areas sufficiently large to satisfy local needs (National Academy of Sciences 1980).

Irrigated Agriculture

In addition to an expansion of rainfed agriculture, ambitious irrigation schemes have been undertaken periodically in the principal basins of the Sahel. Prominent among them are the projects established in the Senegal River Valley, in the Interior Delta of the Niger, and in the Lake Chad basin.

The Great Depression in 1934 led to the creation of the Mission d'Etudes du Fleuve Sénégal to study and plan comprehensively the economic development of the Senegal River Valley. This project was replaced in 1938 by the Mission d'Aménagement du Sénégal. Initial attention was focused on cotton production until World War II disrupted the importation of the 60,000 tons of rice then consumed annually in Senegal. In 1945 it was decided to shift exclusively to the mechanical cultivation of rice on the uncultivated clay soils at the head of the Senegal Delta.

The earlier earthen barrages, built annually by the traditionalist farmers of the region, were replaced by a permanent barrage completed near Richard-Toll in 1948. Water was then pumped, at considerable cost, from behind the barrage into approximately 100 km of main canals to 5,402 ha of mechanically cultivated and artificially fertilized rice fields. In 1968, some 5,100 ha produced 10,200 tons of paddy--a very low yield (Church 1980).

As with all large irrigation schemes in the Sahel, the Richard-Toll Senegal Delta Irrigation Scheme encountered great physical and economic difficulties. Quelea, ducks, and other granivorous birds, as well as insects and rodents consumed large quantities of the rice grown; the control of wild rice became a serious problem; the soils became saline (see Pillsbury 1981); sheet erosion was caused by dry-season winds; and the costs of fertilizer and pumping became burdensome. Capital costs have been written off and the current costs are heavily subsidized. The scheme has made only a modest and very costly contribution to Senegal's rice needs (Church 1961, 1980; cf. Weiler and Tyner 1981).

Similar problems have been encountered in the project areas developed in the Niger Delta and the Lake Chad Basin. Presumably, knowledge and experience gained in the development of these costly and largely unsuccessful schemes will be taken into consideration in the current river-basin development efforts in Senegal and elsewhere in the Sahel.

The Proliferation of Cattle

It is a common assumption that the Sahel is a natural pastureland for cattle and that domesticated cattle have long sustained the populations of that region. This impression is often reinforced by the depiction of cattle in the rock art of the neighboring Saharan highlands (see, for example, Brentjes 1965, Lhote 1973).

It is true that cattle have long been associated with the Sahara and the Sahel. Wild cattle, including *Bos primigenius* and *B. ibericus*, were prominent among the animals that sustained the ancient hunting populations of these regions (Smith 1980). The archaeological record indicates the concept of domestication diffused into the area around 6000 B.P., and that the concept was evidently accepted and applied by populations of fisherfolk associated with the many lakes that existed in the central and southern Sahara at that time. The so-called Ténérian groups identified from the excavations at

Adrar Bous, Niger, would be representative of these early pastoralists (Smith 1976). The expansion of the cattle complex into the Sahel proper was apparently a direct result of the desiccation of the Sahara region.

The desiccation of the Sahara had an important impact on cattle because their water requirements are considerable. For example, they require four times as much water, at more frequent intervals, as camels under the same conditions. Also, unlike other animals in which the volume of urine is decreased and its concentration increased with higher temperatures, the increased intake of water by cattle results in decreased concentration and increased water loss through urination. Hence, the intake of water is greater than that required simply to compensate for increased losses. It appears that cattle drink not only to avoid dehydration but to cool the body with huge quantities of water (Schmidt-Neilsen 1964, cf. Nachtigal 1879).

Declining precipitation, a possible shift from a two-cycle rainy season to a single-cycle season (Toupet 1976), the effects of bush fires, deforestation, a reduction in groundwater recharge, and the growing impact of domesticated livestock eventually rendered the Sahel unsuitable for cattle. In response, the prehistoric cattle complexes of the Sahel gravitated southward into the savanna zone, where they are represented by such modern peoples as the cattle-holding Soninke.

The earliest historical records that describe the livestock inventories of Sahelian populations are those of medieval authors such as Ibn Hawqal and al-Muhallabi. These authors describe the Sahel as a region dominated by camel nomadism, and by peoples whose attachment to the camel carried almost religious overtones (Levtzion and Hopkins 1981).

A brief reintroduction of cattle into the Sahel occurred when, in 990, the Soninke-dominated empire of Gana (transcribed in Arabic as Ghana) expanded into the Sahel to assure their control over the trans-Saharan trade. Al-Bakri, writing early in the eleventh century, describes the dependence of the Soninke cattle on the wells that had been excavated during the mid-eighth century to support the trans-Saharan trade. His descriptions of the impoverished vegetation around wells and villages contrast vividly with those of al-Muhallabi written in the tenth century, before the expansion of Gana.

By 1055, Gana was forced to withdraw southward into the savanna zone, and descriptions of camel nomadism again dominated the writings of the medieval authors describing the Sahel.

Although the occasional presence of cattle in the western Sahel is documented in the writings of Ca' da Mosto (fl. 1455) and later authors, they are few in number and are largely associated with oasis-based Soninke cultivators. The absence of cattle reflects not only the limited carrying capacity of the region for cattle, but also the vulnerability of the herds and herders to the incursions of raiding tribes. In the western Sahel, the problem of raiding was particularly severe following the arrival of the Banu Hilal from North Africa late in the thirteenth century (Trimingham 1962). The problem persisted until the colonial pacification of the region early in the twentieth century.

It is possible that this relatively long period (thirteenth through nineteenth century) of political instability in the Sahel permitted a measure of ecological recovery. For example, an account of an expedition by Sultan Saboun against the state of Bagirmi in central Chad early in the nineteenth century describes ". . . the unoccupied lands situated between the boundaries of the Waday and the Bagirmi [as] covered with mature forests and dense, thorny undergrowth, which served as the refuge of lion, elephant, and rhinoceros" (Depierre and Gillet 1971). If a measure of recovery had occurred, it was short-lived.

The pacification of the Sahel permitted a northward expansion of agricultural populations early in the twentieth century. They took herds of cattle, goats, and sheep with them. The disenfranchised warrior classes were left with only herding and commerce as acceptable occupations, and economic considerations resulted in a rather abrupt numerical shift favoring cattle at the expense of camels, as the former were more marketable within the context of the new economic order. Furthermore, in Mauritania the policy of association--that is, working through traditional leaders--had strengthened the position of the religious leaders, the marabouts, at the expense of the warrior class, and the new wealth acquired by the marabouts was characteristically invested in herds of cattle (Chassey 1978).

Cattle dramatically increased in number following the pacification of the region. In addition to economic incentives, livestock maintenance and veterinary health programs were instituted throughout the Sahel. During much of this period of development, rainfall levels were unusually high, and therefore for planners and herders, perhaps deceptively high. According to Gallais (1979), the western Sahel as a whole had witnessed a five-fold increase in cattle during the 25 years preceding the 1968 drought (Table 2, Figure 11).

The relative lack of experience of many modern Sahelian populations in managing cattle, combined with a progressive loss of skilled herders to sedentarization and labor alternatives encouraged by development programs, has in many areas resulted in poor herd control. Poor management, in turn, has greatly increased the environmental impact of livestock. In addition, in many areas of the Sahel while herds of cattle were growing rapidly, other types of livestock that are better adapted to the region, more easily controlled, and less destructive to the environment declined in numbers (National Research Council 1981).

As indicated above, cattle are poorly adapted to Sahelian conditions; their conversion efficiency is poor, they require substantial quantities of water, and they are highly subject to stress. In response to declining precipitation and growing cattle populations, well-drilling programs were expanded throughout the Sahel. The vegetation around wells, as well as around seasonal pools and in other areas of intense pressure, has been both qualitatively and quantitatively modified (Bille 1976). Unlike camels and goats and most native herbivores, which are predominantly browsers, cattle are grazers. Cattle therefore increase pressure on perennial grasses and often eliminate them (Gaston and Dulieu 1976). Tree cover is also affected by cattle herds, as trees are used as sources of fuel and building material by herders, many species are used for emergency fodder, and

TABLE 2 Sahelian Cattle Populations

Country	Number of Cattle (in thousands)			
	1940	1968-1970	1974	1978
Chad	n.a.	4,630	3,250	3,600
Mali	1,174	5,300	3,640	3,800
Mauritania	850	2,100	1,175	1,200
Niger	754	4,200	2,200	2,850
Senegal	440	2,615	2,318	2,500
Upper Volta	491	2,900	2,300	2,600

SOURCE: Compiled from Gallais 1979.

FIGURE 11 Cattle are a principal cause of environmental degradation in the Sahel. The western Sahel witnessed a five-fold increase in cattle during the 25 years preceding the 1968 drought. (IFC/World Bank Photo by K. M. Ibrahim)

broad-hoofed cattle trample seedlings and compact soil. Three tree species have had particularly high mortality rates: Acacia senegal, Commiphora africana, and Guiera senegalensis (Poupon and Bille 1974). Hence, the qualitative aspect of vegetative degradation is reflected in shifts from perennial to annual grasses and the expansion of relatively unproductive trees and shrubs such as Calotropis procera at the expense of more useful species such as Acacia ehrenbergiana, A. senegal, and Balanites aegyptiaca (Bernus 1979).

As noted above, biomass production has also decreased. In the Tamesna region of Niger, for example, it is estimated that primary pasture production has dropped between 1,500 and 2,000 tons/ha to 360 kg/ha through overgrazing. Good fodder species such as Schoenefeldia gracilis disappeared and were replaced by short-cycle species requiring less water, such as Cenchrus spp. (Granier 1975). Equally significant declines in primary production have been recorded in the Senegalese Ferlo and other regions of the Sahel.

It has been estimated that the usable extent of the pastoral zone has been reduced by almost 25 percent since the onset of the 1968 drought. Nevertheless, in some instances these trends may be reversible. Schoenefeldia gracilis has reappeared in the Tamesna region. In the study in the Ferlo, total seed production was estimated at 30.6 kg/ha in 1970-1971. One-third of this production was consumed by animals; the rest was scattered by wind, water, and animals. Although many seeds were destroyed, 11 percent retained their powers of germination for at least 2 years. This indicates that, with proper management, recovery may be possible in many areas. If excessive livestock pressure is not relieved, however, seed production for many species ceases and regeneration cannot occur (Boudet 1972).

The reduction or elimination of vegetative cover, often in combination with soil compaction by livestock, triggers additional degradative sequences. For example, once the rainy season begins, raindrops striking the wet soil surface raise mud spatters, first sealing the surface and then mobilizing soil particles subject to transport by overland flow. This results both in reduced infiltration leading to depressed groundwater tables and soil erosion. In some areas of the Sahel, groundwater levels have fallen as much as 8 meters since the medieval period (Toupet 1977). As indicated elsewhere in this report (chapters 2 and 4, Appendix B), reduced vegetative cover might also reduce rainfall through biogeophysical feedback mechanisms regulated by such cover. A mat of vegetation, on the other hand, intercepts the raindrops and controls overland flow, as the water is forced to filter through a tangle of stems, grass blades, dead leaves, and root hairs. Meanwhile, infiltration in encouraged, and the rooting network serves to stabilize the soil (Butzer 1976).

Surface exposure and reduced organic content also disturb soil ecology through altered soil-water relationships and a greater amplitude in soil temperature. It is probable that this altered soil ecology would adversely affect critical microorganisms such as the rhizobial bacteria associated with Sahelian acacias and other leguminous genera (National Academy of Sciences 1979, National Research Council 1981). The rhizobia fix atmospheric nitrogen, increase plant

productivity, and reduce the impact of stress. As use pressure, depressed groundwater tables, and altered soil ecology directly eliminate certain plant species and frustrate regenerative processes in others, further losses occur though disruptions in plant dependencies and affinities.

Introduction of Advanced Firearms

Advanced firearms first entered the Sahel in connection with the slave trade. European traders commonly provided their Moorish associates with guns in payment for slaves. During his visit to West Africa around 1456, the Portuguese traveler Diego Gomes reported ". . . that there were caravals there which carried arms and swords to the Moors" in exchange for slaves (Blake 1941-1942). Writing in the 1790s, Mungo Park notes that the Moors obtained ". . . their fire-arms and ammunition . . . from the Europeans, in exchange for the Negro slaves which they obtain in their predatory excursions. Their chief commerce of this kind is with the French traders, on the Senegal River." James Riley, writing in 1817, recalled that "most of the Arabs are well armed with good double-barrelled French fowling pieces." By 1882, the African leader Samory Touré had purchased 4,000 repeating rifles from the British in Sierra Leone in order to check the French advance into the upper Niger region. By 1892 his forces possessed 8,000 such rifles (Gramont 1975).

Many medieval and modern authors have described the abundant wildlife of the Sahel (see, for example, Blake 1941-1942). The literature of Sahelian peoples such as the Moors and Kel Tamacheq frequently refer to camels, wildlife, and hunting but reflect virtually no interest in cattle, sheep, or goats. An appreciation of bush meat is revealed in the commercial importance of tishtar, jerked antelope flesh, in Mauritania (Trotignon 1975). Similarly, as recently as the late 1950s, wildfowl and game animals contributed more to the diet of the peoples of the Senegal River Valley than did beef (Cremoux 1963).

Given the appreciation of Sahelian populations for bush meat, it is not surprising that the introduction of improved firearms would result in a dramatic increase in hunting. Travelers' reports indicate that wildlife populations have declined steadily since the sixteenth century, and Bigourdan and Prunier (1937) indicate that the addax and oryx populations of the Mauritanian Sahel were already threatened by extinction before the conclusion of French pacification in the 1930s.

The destruction of wildlife populations in the Sahel has greatly aggravated the problem of devegetation in the region. Birds and browsing herbivores formerly played critical roles in the growth stimulation response (McNaughton 1976) and seed dispersal of Sahelian trees and shrubs, prominently including large-seeded legumes such as Acacia, Albizzia, Bauhinia, Cassia, Entada, Parkia, Prosopsis, Tetrapleura, and related genera (National Research Council 1981). In turn, habitat modification has eliminated additional wildlife species once important in seed dispersal (Huzayyin 1956) and has also reduced the quantities of seed available for dispersal.

Finally, changes have taken place in herding with the virtual eradication of wild carnivores in the pastoral zone. In the past, young herders were instructed to avoid forests and thickets in order to maintain herd control and avoid livestock losses to predators. The fear of such losses passed with the elimination of the large carnivores, and herds are now permitted to enter wooded areas. The extension of herding into these areas has resulted in the widespread removal of protective understory and seedlings. In consequence, wildlife habitat have been dramatically decreased, precipitation interception and groundwater recharge have been reduced, many wild plants and animals used by rural populations during periods of famine have been eliminated, and ecological processes have been seriously disrupted.

Wildlife losses are also significant, because the potential standing biomass of wildlife populations is much greater than that of livestock populations living under similar conditions. For example, studies done in East Africa indicate that acacia savanna carrying 19.6-28.0 kg/ha of domesticated cattle could carry from 65.5-157.6 kg/ha of wild ungulates. In contrast to domesticated livestock, wild animals occupy distinct and usually complementary ecological niches: wildlife eat vegetation that is often too coarse for most livestock, and wild animals use water more efficiently and are more tolerant of stress and disease. Hence, the wildlife of the Sahel could serve as important alternative sources of food during periods of need (Talbot 1963, Knight 1976).

In addition to the devastating impact of advanced firearms, Sahelian wildlife populations have been further reduced through direct competition with livestock and habitat modification associated with agricultural expansion.

The Development of Modern Transportation Networks

The major rivers of the Sahel, rails, and roads have opened new areas of settlement, brought new land into agricultural production, and facilitated the exploitation of forest products.

Towns and villages have been established along the modern transportation networks of the Sahel much as they were along the trade routes of the Sahel in the past, and for many of the same reasons. As in the past, these settlements have had predictable impacts on the environment as the surrounding forests are exploited for domestic building materials, fencing, browse, fuel, tannin, gum, cordage, medicinal substances, and other products to satisfy local needs. These networks also provide new economic opportunities, as local products can be more easily transported to distant markets. Hence, the human impact on the surrounding land is increased as local populations respond to these opportunities.

The major rivers of the Sahel have long been important arteries of transportation and commerce. The environmental impact of this movement increased substantially with the introduction of wood-burning steamships. On the Niger, the era of the steamship was initiated with

the arrival of the Quorrah and the Alburkah from England in 1832. By 1871, steamers from five companies regularly plied the river, and the Niger's banks were dotted with small trading posts and agricultural ventures (Gramont 1976). In addition to the deforestation along the banks of rivers resulting from the considerable fuel requirements of the steamers, further losses were incurred through the construction of buildings.

Writing early in the twentieth century, de Gironcourt noted the near-disappearance of doum palms (Hyphaene thebaica) along the banks of the Niger's northern bend; their trunks served as structural beams in administrative offices and other buildings. More recently, the riverine forests of the Sahel have been extensively exploited for fuelwood and charcoal production (Figure 12) (National Academy of Sciences 1979). These products are easily transported by boat to urban markets such as Saint-Louis on the Senegal and Niamey on the Niger.

The significance of the loss of riverine forests has not been fully appreciated in the Sahel. Field observations along the Senegal River made in 1979 and 1980 by the staff of the Advisory Committee on the Sahel have indicated that rates of erosion along the river have dramatically increased as the floodplain has been stripped of its protective vegetative cover, particularly the extensive stands of Acacia nilotica, so important as a source of charcoal (Figure 13) (National Academy of Sciences 1979). The rates of erosion on the floodplains of the Senegal will almost certainly result in levels of sedimentation and salinization far beyond those currently anticipated by agencies involved in the further development of the Senegal River Basin (National Academy of Sciences 1979, 1981a; cf. Organisation pour la Mise en Valeur du Fleuve Sénégal, n.d.).

Rail transportation in the Sahel was inaugurated with the opening of a line connecting Dakar and Saint-Louis in 1885. A link between the Senegal and Niger rivers was completed in 1904, and additional links connected Dakar with Kaolack (1911), Touba to Diourbel, and Linguère to Louga. The through-route from Dakar to Bamako and Koulikoro on the Niger was opened in 1923. Direct losses of vegetation were incurred in right-of-way clearance, bed preparation, and bridge construction, and in the considerable quantities of wood needed to fuel the steam engines employed on these lines; indirect losses occurred with agricultural expansion into the regions served by the rails. The most notable example of such agricultural expansion was the southward shift in groundnut production from the Senegal River Valley into the so-called Groundnut Basin of west-central Senegal. Senegal has become a world leader in groundnut production, but this expansion has also led to a high degree of economic vulnerability. The groundnuts are grown largely as a monoculture in an area of highly variable rainfall, and the basin has become degraded through intensive cultivation (Church 1980, National Academy of Sciences 1980).

Road building has also caused environmental degradation through physical disturbance, particularly in sandy soils, and through the derangement of drainage patterns. Indirect losses of vegetation have been incurred in many areas by the use of rights-of-way to trail cattle to urban markets and by agricultural expansion and the increased

FIGURE 12 Charcoal production in Acacia nilotica forests on the floodplain of the Senegal River near Dar al-Barka, Mauritania.

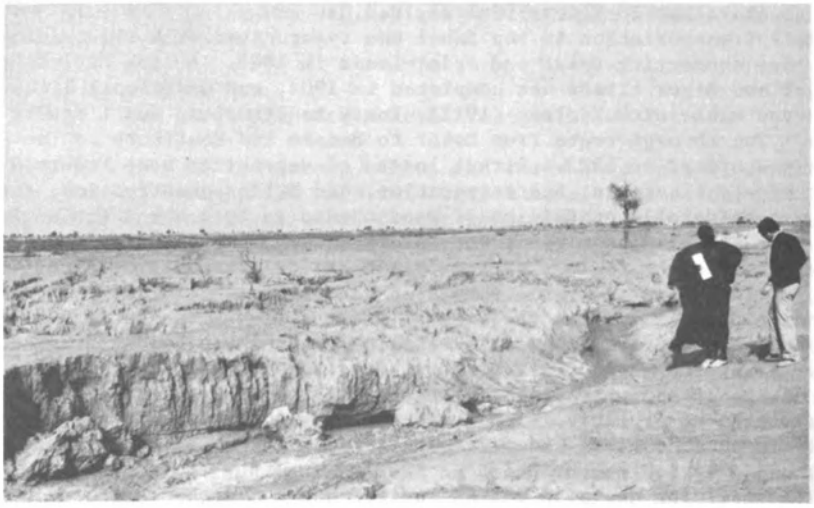


FIGURE 13 Severe erosion on the floodplain of the Senegal River near Tékane, Mauritania. The extensive stands of Acacia nilotica that formerly protected the soil have been destroyed through charcoal production.

exploitation of forest resources in areas served by roads. The impact of rural roads on woodlands can be easily appreciated as one sees the bundles of fuelwood and bags of charcoal stacked along these roads for transport to urban markets. The annual per capita consumption of fuelwood in the Sahel is 1.15 steres, or 0.317 cords. Given the current population trends of the region and the general lack of economically viable alternative sources of fuel, it is anticipated that forest losses will continue to outdistance dramatically the modest gains made by conventional fuelwood production and reafforestation projects in the foreseeable future.

Urbanization

The twentieth century has witnessed an unprecedented development of urban centers in the Sahel (Table 3). Nouakchott, the capital of Mauritania, grew from a village of 2,000 inhabitants in 1957 to a city of 134,000 in 1977. Niamey, the capital of Niger, grew from a village of 7,000 in 1945 to a city of 300,000 in 1979. Equally dramatic increases have been recorded elsewhere. Table 3 illustrates the rapid pace of urban growth in contrast to national growth in the Sahel.

In many instances new cities have been created. Examples are mining centers such as Zouérate and Nouadhibou in Mauritania, and Arlit in Niger. A further impetus to urban growth in the Sahel has been the creation of new administrative divisions, with their accompanying governmental offices, schools, health facilities, markets, and airports.

TABLE 3 Population Growth in the Sahel, 1970-1980

	Urban Population (in thousands)		Urban Growth	National Population (in thousands)		National Population Growth
	1970	1980	(%)	1970	1980	(%)
Cape Verde	16	19	n.a.	268	332	2.4
Chad	411	747	6.7	3,640	4,574	2.3
The Gambia	53	80	8.0	463	593	2.8
Mali	611	968	5.5	5,047	6,553	2.7
Mauritania	111	182	8.6	1,162	1,574	2.8
Niger	330	561	6.8	4,016	5,425	2.9
Senegal	1,024	1,537	4.0	3,925	5,591	2.6
Upper Volta	388	644	4.0	5,384	6,738	2.6

SOURCE: Compiled from Kurian 1982.

These centers have increased pressure directly on the resources of the surrounding countryside and, indirectly, on the more distant areas that provide food, fuel, fiber, and construction material for the urban dwellers. Delwaulle and Roederer (1973) have noted, for example, that there is little natural regeneration of vegetation within a radius of 15-20 km of Niamey, and that severe "desertification" is occurring within a radius of 40-50 km of the city.

Much of the degradation reflects the cities' substantial needs for building materials and fuel; some degradation results from an intensification of agricultural activity on already depleted soils in order to help satisfy urban demands for sorghum and other crops. Furthermore, considerable quantities of sand and dust are mobilized through the physical disturbances associated with urban construction activities, off-road traffic converging on the cities, and cultivation in the periurban fringe. This particulate matter often poses health problems, is frequently responsible for highway accidents, and increasingly results in the interruption of air traffic (National Research Council 1981).

CHAPTER 4

Environmental Rehabilitation: Discussion and Recommendations

The paleoenvironmental review and historical analysis presented in chapters 1 and 2 indicate that little climatic change has occurred in the Sahel for the last 2,500 years. The climate has been characterized as highly variable, with unevenly distributed rainfall and frequent drought. Acceptance of these characteristics is basic to the elaboration of successful environmental rehabilitation strategies in the Sahel region.

Chapter 3 of the report discusses a broad range of human activities that has dramatically altered the character and content of Sahelian ecosystems: bush fires, settlement on easily disturbed sites, the destructive exploitation of forest products, agricultural expansion, the proliferation of cattle, extensive wildlife losses, the development of modern transportation networks, urbanization, and other activities. Although the impact of these activities is by no means uniform throughout the region, for planning purposes it is important to realize that no area of the Sahel has escaped modification.

A basic understanding of the history of environmental change in the Sahel provides planners with a better grasp of the biological potential of the region and with important insights into ecosystem function and change. It is now clear that both the spatial extent of vegetative cover and biological diversity have been substantially reduced through time. Ecosystems in tropical arid and semiarid regions "renew" themselves only as long as sufficient species diversity is maintained to prevent the collapse of the system. Below a certain threshold, there is a dramatic "domino effect" to species loss within an ecosystem, leading to its collapse or radical simplification. Reduced vegetative ground cover results in increased soil erosion, reduced groundwater recharge, altered soil ecology, and a loss of those plant and animal species unable to adapt to these changing environmental conditions. It is now widely believed that reduced ground cover also results in a reduction of rainfall caused by biogeophysical feedback mechanisms regulated by vegetative cover, and reduced evapotranspiration of soil moisture associated with significant losses of vascular plants. It is believed by some that one- to two-thirds of all rainfall in the Sahel is derived from reevaporated soil moisture within the region (F. K. Hare, personal communication).

The restoration of biological diversity and ecosystem function is basic to environmental rehabilitation efforts and sustainable production in the Sahel. The ecosystem concept provides a scientifically acceptable framework within which rehabilitation efforts can be targeted and coordinated for maximum effect. Unless a realistic, ecologically sound framework for development activities is established, donors and Sahelian institutions alike will simply be involved in a costly and endless search for more and more basic data.

Declining biological diversity and productivity also threaten the adaptive and evolutionary capabilities of plant and animal species, reduce the viability of Sahelian agro-silvo-pastoral systems, and characteristically lead to economic, social, and political instability. It is important that donor agencies and officials in Sahelian governments as well as rural populations more fully understand the ecological implications of livelihood and development activities in the Sahel. It is also important to determine how Sahelian populations can best be made aware of the problems imposed by degradation and be involved in efforts to combat them. Consideration must also be given to further modifications of Sahelian economic and legal systems to encourage and guide ecologically sound economic activity in both the public and private sectors.

INSTITUTIONAL AND RESEARCH NEEDS

It is essential that information concerning environmental problems in the Sahel, and research efforts to resolve them, be systematically gathered, evaluated, and disseminated. The Sahel Institute was established within the framework of CILSS and the Club du Sahel to perform this function. Since its establishment, however, the Institute has frequently found it difficult to efficiently perform its responsibilities.

To improve this situation, it is recommended that:

- Sahelian governments and donors alike acknowledge the critical importance of information gathering and dissemination and research coordination in combating environmental degradation in the Sahel. Steps should be taken to strengthen the program and capabilities of the Sahel Institute to enable it to fulfill its mandate.

- Opportunities for staff development be provided to Sahel Institute officials. For senior staff members, this might take the form of administrative internships at similar institutions elsewhere, or the establishment of a consultative committee of senior scientists to help formulate, executive, and evaluate Institute programs. Junior staff members might benefit from working with postgraduate expatriates in peer relationships.

- Highly focused, process-oriented research efforts, such as the work of J.C. Bille and H. Poupon of ORSTOM (Office de la

Recherche Scientifique et Technique Outre-Mer) on ecology of the northern Ferlo in Senegal, be encouraged and supported.

- A regional project analogous to UNESCO's Integrated Project in Arid Lands (IPAL) in Kenya be established in the Sahel to conduct practical, long-term multidisciplinary research into the ecological and socioeconomic problems associated with environmental degradation. The project should be institutionally affiliated with the Sahel Institute.

Scientific exchanges and curriculum modifications should also be considered as important vehicles for stimulating awareness, focusing concern, and effectively addressing issues of environmental degradation. It is recommended that:

- A program of scientific exchanges be established which would permit leading non-Sahelian scientists to visit the Sahel to stimulate and focus scientific research, and would permit visits by Sahelian scientists to dryland research centers and reclamation projects in the United States and elsewhere for study and observation.

- More attention be given to effective ways of providing supplementary training to individuals in teaching and research positions, so that instruction and research is more directly relevant to the problems of the Sahel region.

PROJECT IDENTIFICATION AND IMPLEMENTATION

There is little agreement among development planners on appropriate approaches to project identification and implementation. It is therefore recommended that:

- The definition and identification of ecological provinces be a particularly high priority in future ecological research in the Sahel, as they constitute the basic physical units for analysis and rehabilitation. (These provinces will differ somewhat from the agrophysical units and other land use categories currently in use in the Sahel.)

- Simple, easily applied environmental energy flow models be developed and field tested in the Sahel. The use of such models would allow planners to identify breakdowns in ecosystem function and identify program activities that would help restore ecological processes. The use of such models is discussed in the National Research Council report, Environmental Degradation in Mauritania (1981).

- Case studies be systematically assembled that would enable project managers to benefit from earlier successes in environmental rehabilitation in the Sahel and avoid the pitfalls of past failures.

WATER RESOURCES AND SOIL CONSERVATION

As noted above, devegetation in the Sahel has greatly reduced groundwater recharge and has increased soil erosion. Recent hydrogeological research has indicated that groundwater levels in some areas of the Sahel are now 8 meters lower than they were during the medieval period. The reestablishment of adequate vegetative cover and biological diversity in Sahelian ecosystems will depend in large measure on parallel efforts to increase groundwater recharge and conservation.

It is recommended that:

- The problems and opportunities related to groundwater hydrology be more thoroughly and systematically explored. In many instances, such as in the Mauritanian Adrar, groundwater exploitation coupled with inadequate natural recharge has been highly destructive. In others, such as in the Bahr al-Ghazal of Chad, it would appear that groundwater resources could be more intensively utilized. Research into groundwater hydrology in the Sahel should build on the earlier studies undertaken by P. Elouard, J. L. Schneider, and others.

- Water conservation and groundwater recharge components be incorporated into all environmental rehabilitation projects undertaken in the Sahel. These projects might include such proven approaches as revegetation supported by water-harvesting techniques and the use of sand-filled storage dams to capture and hold runoff water that would otherwise be lost. Several approaches to water conservation and groundwater recharge are described in the National Academy of Sciences publication, More Water for Arid Lands (1974).

- Whenever feasible, domestic and agricultural water supply requirements be satisfied with nonmotorized, low-lift devices such as the traditional shaduf. Motorized pumps should only be installed where the long-term water supply is sufficient and possible negative consequences have been well studied.

River Basin Development and Irrigated Agriculture

The principal river basins of the Sahel are relatively dependable sources of water supply, even during periods of drought. The traditional systems of agriculture practiced along the margins of rivers and lakes throughout the Sahel represent a highly sophisticated

approach to sustainable agricultural production. Unfortunately, in many areas these systems will succumb to the regulation of river level fluctuation in modern river basin development schemes.

Few modern, donor-assisted irrigation projects in sub-Saharan Africa have demonstrated economic potential. Although many of the projects have been preceded by seemingly exhaustive studies, the studies are characteristically deficient in historical analysis and reveal little appreciation of the complex interrelationships among soil, water, vegetation, and other constituent elements of a river basin system. For example, in the case of the Senegal River Basin development project, little apparent importance has been attached to problems encountered by colonial irrigation projects in the basin during the nineteenth century or to the economic failure of the subsequent delta irrigation scheme. Furthermore, several classes of data that bear directly on the potential economic success and environmental soundness of the project have been inadequately assessed. These would include the rates and trends of soil erosion in the Futa Jalon highlands and the Mauritanian Chemama which, if not arrested, will result in unanticipatedly high levels of siltation and salinization and reduce the useful life and projected benefits of the project.

- The aggregate value of the sustainable resources that will be lost in modern river basin development schemes should be balanced against the apparently transitory benefits of the capital-intensive activities that will replace them. Long-term economic interests may be better served by building on indigenous strengths and adaptations rather than by superseding them.

There are additional reasons to be cautious when planning or implementing river basin development projects. First, the incidence of certain diseases, such as schistosomiasis and malaria, is likely to increase. Second, during the dry season, irrigated perimeters attract a considerable variety of crop predators and therefore require constant attention and protection. Third, farmers have to learn a complex system of new crops, new ways of handling cropping, mechanization, the management of unfamiliar water delivery systems, as well as other adjustments. Fourth, such projects are apt to result in the overutilization of the land surrounding the project area, particularly by foraging livestock. Finally, irrigation projects often bring about radical social changes. Family life is disrupted, traditional social controls are often lost, and crime, delinquency, emotional disorders, despair, and other indicators of social anomie, may suddenly increase (Bodley 1975).

In addition, the level of Western expertise in irrigated agriculture is often exaggerated. (Substantial tracts of agricultural land associated with irrigation projects in the American Southwest and southern Australia have been lost to production through mismanagement, salinization, alkalinization, and waterlogging.) Considerable caution should be used in applying Western experience in irrigated agriculture

to the arid and semiarid tropics where environmental factors are even less well understood, and required managerial skills are often limited.

MANAGEMENT, CONSERVATION, AND AUGMENTATION OF EXISTING BIOLOGICAL RESOURCES

The relatively high extinction rates of Sahelian flora and fauna, the traditional reliance of Sahelian societies on forests for the provision of food, fuel, and other products, as well as other ecological and economic considerations, require that far more attention be focused on the management and conservation of existing plant and animal resources in the region. Not only are introduced plants and animals generally less well adapted than their native counterparts, but the substitution costs are often unacceptably high.

Woodland and Grassland Resources

Since 1972, approximately $160 million has been spent on forestry projects in the Sahel. Most of the projects have focused on the establishment of plantations, often for the provision of fuelwood. Despite this level of effort, there has been a steady decline in fuelwood availability. This decline has been accompanied by the loss of many species locally valued for the many products they provide. Relatively few projects have dealt with the desirability of more effective management and use of existing natural forests. While donors spend substantial sums of money on plantation projects which often fail, the rehabilitation and conservation of natural forest stands costs very little and provides multiple benefits.

The limited success of plantation projects and social forestry activities in the Sahel is linked to the perception of their benefits to the people. Because of the terms of Sahelian public domain laws, such projects are viewed as de facto state-operated and therefore state-benefitting, activities and provide little incentive for emulation at the farm level. Farmers need practical, economic incentives to plant trees; legal uncertainties, conflicts related to traditional land tenure systems, or uncertainties about their ability to protect and maintain trees over 10-15 years will daunt the farmers' will to plant trees for future firewood needs. If, however, the trees can also produce, in a shorter period, cash benefits or forage, fruit, or other products, there will be much greater likelihood of "spontaneous" planting or replanting. Research is urgently needed to identify, through species trials, more productive multipurpose trees which can be adopted by farmers for their short-term economic benefit and for their general benefit, as well as that of the region, through environmental rehabilitation.

It is recommended that:

- Sahelian governments and regionally active donors cooperate in developing new multiple-use forest management strategies that

permit both the conservation and increased utilization of forest resources. Species trials to identify economically attractive, high-yielding, drought-resistant, multipurpose trees are an essential component for which additional resources must be allocated.

- Current efforts in the establishment of urban fuelwood plantations be continued to complement natural forest management. In addition to helping satisfy the fuel requirements of urban centers and relieving pressure on natural forests, such plantations serve as auxiliary habitat for wildlife, and, depending on location and need, can serve a variety of other conservation functions. Further attention should be devoted to species selection for urban plantations and, in some instances, to considerations of optimal land use. In some cases, for example, existing or proposed urban plantations are occupying, or will occupy, land that could be more profitably devoted to agriculture.

- Because the rapid growth of many Sahelian cities has been accompanied by the progressive deterioration of periurban environments, Sahelian governments and donor organizations recognize that urban fringes present an array of linked resource management problems which require coordinated action at the local level to ensure sustainable development, particularly to improve fuelwood availability and water supplies. Interest in urban fringe rehabilitation efforts should be communicated to the Commission on Environmental Planning of the International Union for Conservation of Nature and Natural Resources.

- Further research be undertaken on the impact of fire on Sahelian ecosystems and the possible use of fire as a tool in the management of Sahelian woodlands.

- Research be undertaken in large-scale environmental rehabilitation efforts that facilitate seed dispersal and generally reinforce natural regenerative processes. For example, *wadi*-head plantings would result in seed being washed into and through *wadi* systems, thereby increasing vegetative cover along *wadi* courses. As attested by studies in the American Southwest, such plantings can create extensive networks of vegetation available for further dispersal into adjacent areas. Projects should also be designed to better exploit livestock and wildlife movement, seasonally dominant northeasterly winds, and other environmental forces that promote seed dispersal and revegetation. By current project standards, such measures would be highly cost effective and could be complementary to other approaches to large-scale land rehabilitation, such as aerial seeding.

- Research be initiated to determine rates of extinction for various categories of Sahelian flora and fauna. Many often neglected species perform essential ecosystem functions; others have the potential to make important contributions to medicine, industry, agriculture, and commerce.

- A Sudano-Sahelian botanical research center be established for the conservation and study of native and exotic dryland flora. Research in appropriate silvicultural techniques should be undertaken. The application of innovative techniques, such as the use of tissue culture to rapidly multiply endangered plant species and accelerate programs of selection, should be incorporated into the center's program of research.

Agroforestry

Agroforestry is a new term for the old practice of growing woody plants with agricultural crops and/or livestock on the same land. In addition to being more stable and providing a broader range of economic products, agroforestry systems contribute significantly to the rehabilitation of local environments and are generally preferred by local farmers. Such systems allow more crops to be grown on smaller parcels of land, thus offsetting problems of land and labor scarcity. They provide insurance against crop failure through the differing susceptibilities of the various crops to drought, disease, predation, and other hazards, as well as throught the microclimatic amelioration and nutrient cycling provided by the trees and shrubs in the system. Further information on this topic can be found in a companion National Research Council report, Agroforestry in the West African Sahel (1983).

It is recommended that:

- Sahelian governments and international donors support the further development of agroforestry systems in the Sahel.

- Further efforts be devoted to the establishment of shelterbelts in the Sahel. In addition to the multiple benefits derived from such efforts, it is of some importance to know that shelterbelt programs have already been accepted and successfully undertaken by Sahelian populations. For further information regarding such projects, see Appendix A of this report and the National Research Council report, Environmental Degradation in Mauritania (1981).

- Browse reserves be established on marginal lands to promote conservation and support livestock production. Such reserves could also serve as emergency sources of food for human populations: many browse species bear fruit, leaves, gum, and other edible substances; some species can serve as sources of revenue through the sale of gum, honey, and other collected products.

- Efforts be made to more fully determine the economic value of currently underutilized native and naturalized plant species in the Sahel.

Several plant species already established in the Sahel could make important contributions to agriculture, medicine, and industry. For example, genetic infusions from the wild relatives and local cultivars of Sahelian crops such as sorghum could be of considerable importance in international crop improvement programs. Aloe barbadensis could be commercially exploited for use in pharmaceutical and cosmetic products; the fruit of Balanites aegyptiaca is said to be lethal to the snails which are the intermediary host of schistosomiasis and to the water flea that carries dracunculiasis (guinea-worm disease); Cissus quadrangularis has promising applications in pest control; Acacia seyal and Prosopis juliflora produce gums of commercial quality; Calotropis procera and Euphorbia spp., which can be grown on marginal lands, are promising sources of liquid hydrocarbons; Spirulina platensis, which is native to Lake Chad, is an edible alga rich in protein; several species produce vegetable oils which can be used as diesel fuel. In the Sahel these species are virtually untapped.

The economic value of genetic infusions for existing crops is widely underestimated. In the United States, for example, the value of regular genetic infusions to increase the productivity and adaptability of modern crops is estimated to be $700 million per year. Over-the-counter sale of drugs derived from plants and animals currently exceeds $40 billion a year worldwide (Myers and Ayensu 1983). Exploitation of these and other resources should include strategies that assure long-term use.

Animal Resources

The progressive loss of vegetation and wildlife in the northern Sahel has resulted in the compression of the zone and a general breakdown in ecosystem functions.

To remedy this situation, it is recommended that:

- Wildlife reserves be created or restored in areas of the Sahel in which significant numbers of endangered species of plants and animals exist or could be reestablished for in situ conservation. High priority should be given to the creation of a wildlife reserve in the borderlands of the Majabat al-Koubra in Mauritania, the creation of a similar reserve in the Aïr region of Niger, and the restoration of the Ouadi Rimé-Ouadi Achim Faunal Reserve in Chad. These reserves should serve multiple, nondisruptive social, economic, and environmental objectives. An important function of the reserves would be the protection or reintroduction of various wildlife species that have long served as important sources of food, that have in the past attracted numerous tourists and hunters to the region, and that play critical roles in the stimulation of vegetation and

seed dispersal. Determination of the habitat requirements for the species of the reserves will be of basic importance in establishing their boundaries.

- Further research be undertaken to determine the comparative productivity and hardiness of various forms of livestock and their compatibility with Sahelian ecosystems. Such research might also compare the advantages and disadvantages of domesticated livestock vis-à-vis selected, wild ungulates such as the addax and oryx. For example, existing research indicates that the standing biomass for cattle in the acacia savannas of Africa is from 19.6 to 28.0 kg/ha, while that for wild ungulates is from 65.5 to 157.6 kg/ha. Furthermore, various studies indicate that rural Sahelian populations generally prefer bush meat to the meat of domesticated livestock.

- Research be undertaken on the adaptability of the Asian water buffalo (Bubalus bubalis) to the riverine lowlands of the Sahel. Buffalo can subsist on coarse forage inadequate for the support of cattle and can feed on aquatic vegetation often unavailable to cattle. In addition to providing milk and cheese, buffalo produce beef of excellent quality and can provide traction as well. Basic information regarding the water buffalo can be found in the National Research Council report, The Water Buffalo: New Prospects for an Underutilized Animal (1981).

Marginal Lands

Marginal lands--those areas once productive but now so degraded that without attention and investment they will become unable to support vegetation and animal or human population--occupy an increasingly large proportion of the Sahel as the effects of environmental degradation spread. These areas present special problems for development activities where there are traditional religious or historical attachments that may run counter to contemporary economic realities. In many cases, however, these attributes may offer incentives for local participation in rehabilitation that are not present elsewhere, and may justify the use of scarce resources to revive the marginal area rather than comparatively less threatened areas.

It is recommended that:

- Demonstrations of sand dune stabilization and utilization be undertaken in selected areas throughout the Sahel to provide training for local populations in dune control. The demonstrations should include instructions in problems of wind-blown sand, provide field demonstrations of techniques in dune stabilization, consider the social aspects of successful dune stabilization efforts, and acquaint participants with

activities necessary to support dune stabilization projects--such as the establishment and management of nurseries. Trees and shrubs with secondary and tertiary products of economic value should be included. Special attention should be devoted to the production of films, filmstrips, simple manuals, and other aids to instruction in dune stabilization.

- Further consideration be given to the ecological significance and responsible utilization of Sahelian wetlands, such as extensive areas of the Interior Delta of the Niger River and the Lake Chad Basin. Many Sahelian wetlands are important in maintaining populations of endangered birds and animals. In some instances, as is the case with the Nile crocodile, village industries could be established which would both assure the survival of the species and permit the controlled and highly profitable exploitation of hides. The conservation and exploitation of crocodiles is the subject of a National Research Council report, Crocodiles as a Resource for the Tropics (1983).

A considerable amount of recent research into the reclamation and utilization of saline environments undertaken in the United States, Australia, Peru, and other countries would appear to be directly relevant to the problems of the Sahel.

- It is recommended that mechanisms be identified to assure the application of this research to the severe problems of salinization affecting the Fatik region of Senegal and other areas of the Sahel.

BIOLOGICAL RESOURCES FOR PROJECT IMPLEMENTATION

Microbiological Resources

A prominent factor affecting declining biological productivity and reduced stress tolerance in trees, shrubs, and crops in the Sahel is the widespread disruption of soil ecology, which often includes the absence of effective strains of critical microorganisms such as rhizobial bacteria, mycorrhizal fungi, and Frankia. Because these organisms are of critical importance in facilitating the availability and uptake of nitrogen, phosphorus, and other essential plant nutrients, their absence directly affects the success of many agricultural and forestry projects.

The Advisory Committee on the Sahel initiated the establishment of a regional microbiological resources center (MIRCEN) to make microbial inoculum available for use in agricultural and environmental rehabilitation projects. The center is directly affiliated with the Senegalese Agricultural Research Institute (ISRA), is associated with the international UNESCO/United Nations Environment Programme/International Cell

Research Organization MIRCEN network, and is engaged in research, training, and inoculum production and distribution.

It is recommended that:

- Development agencies active in the Sahel acquaint themselves with the programs and services offered by the MIRCEN by writing to: Director, West African MIRCEN, ISRA/CNRA, B.P. 53, Bambey, Senegal.

- Donors and regional organizations support the further development of the MIRCEN program. Although technical support is currently being received from ORSTOM, the Institut de Recherches Agronomiques Tropicales et des Cultures Vivrières, the U.S. Department of Agriculture, the AID-sponsored NifTAL Project at the University of Hawaii, and Agriculture Canada, direct financial support has thus far been received only from ISRA, the Foundation for Microbiology in New York, and UNESCO.

Germplasm for Trees, Shrubs, Grasses, and Drought-Tolerant Crops

Efforts to restore or increase the biological diversity and productivity of agricultural and environmental systems in the Sahel are dependent upon the availability of a broad range of high-quality plant germplasm.

It is recommended that:

- Systematic, coordinated species elimination trials be supported and expanded within the various ecological provinces of the Sahel region. Although the initial focus on such trials has largely been on trees, equal importance should be attached to shrubs, perennial grasses, and drought-tolerant crops such as amaranth and short-cycle maize. Whenever possible, these trials should be undertaken at forestry or agricultural schools and research centers. The information generated by these trials should be systematically evaluated, and the trial results should be made available to research institutions throughout the Sahel region. The Sahel Institute should be the lead organization involved in collection and disseminating trial data.

- It is proposed that a regional germplasm bank be established for the Sahel and West Africa as a whole, including the coastal states. The bank would be responsible for the conservation and documentation of seed, as well as for supplying seed in quantities sufficient for use in major forestry and environmental rehabilitation projects. It is suggested that the bank be associated with the West African MIRCEN so that seed shipments could be accompanied by rhizobial or other inocula if appropriate.

SOCIAL CONTEXT

It is almost axiomatic that project success is determined by the extent to which local populations understand the project and directly benefit from their involvement in it. Hence, close cooperation with local populations in developing projects is essential. As demonstrated in the AID-sponsored study, Gourmantche Agriculture (1979), and other similar studies, traditionalist farmers and herders possess a wealth of knowledge regarding the many social, economic, and environmental variables that best assure their well-being and contribute directly to successful project implementation. In part because of commonly held views of social development and progress, developers seldom take full advantage of this knowledge.

It is recommended that:

- A more concerted effort be made to reconcile traditional knowledge and modern scientific insight. One mechanism for doing so would be the establishment of agroforestry, or rural resource, centers--neutral ground on which the comparative advantages of traditional and modern approaches to environmental management and food production could be examined (Figure 14). Such centers could also provide the supplementary instruction necessary for local populations to manage nurseries for seedling production or other efforts related to environmental rehabilitation and improved crop production.

The failure of many environmental rehabilitation projects in the Sahel can be traced to indifferent or unresponsive central governments, inflexible forestry laws, weak local organizations, the decline of traditional authority, a lack of financial credit, insufficient specificity on the part of donor organizations, and poorly managed resources. Some of these problems could be avoided by more actively including regionally significant nongovernmental authorities in development planning, such as clerics associated with the Qadiriyya or Tijaniyya religious brotherhoods and the more recently formed Fadiliyya and Muridiyya orders. These individuals enjoy considerable popular authority and are apt to be highly supportive of projects that would benefit their followers.

Few, if any, large-scale environmental rehabilitation projects can be successfully implemented in the Sahel without greater control of foraging livestock. A serious obstacle to such control has been that herders, government officials, and donors have not cooperated in developing pastoral systems that are both ecologically sound and economically viable. Such cooperation has successfully taken place in Saudi Arabia and in Syria through the revival of the ancient hema system of range reserves--a system that incorporates conservation measures, such as range reserves and controlled grazing, with the establishment of herder cooperatives. In hema systems, cooperative rangelands are allocated, often on the basis of traditional claims, and grazing is prohibited except for the herds owned by the cooperative members. As evidence of the potential contributions of these systems

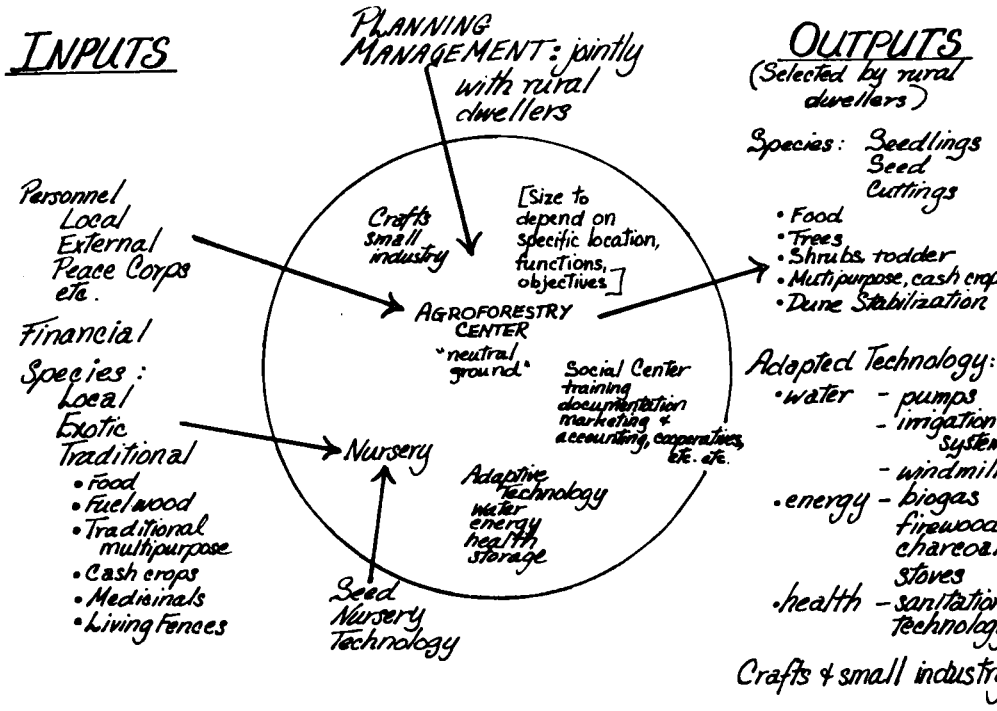


FIGURE 14 Cooperative planning with rural populations.

to environmental rehabilitation, hema cooperatives have been responsible for the revegetation of some 7 million hectares of rangeland in the Syrian steppes.

- It is recommended that the applications of the hema system to Sahelian problems and conditions be thoroughly explored in a regional seminar or workshop that includes appropriate Sahelian officials, appropriate traditional leaders, officials of development organizations concerned with livestock issues, and representatives of Middle Eastern hema cooperatives.

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APPENDIX A

Shelterbelt Establishment in the Drylands of West Africa

Robert Fishwick and Fred Weber

Shelterbelt establishment has emerged as a particularly promising component of environmental rehabilitation programs and more stable agricultural and livestock production in the Sahel. In addition to affording protection against wind and wind-blown sand and the provision of fuel, fodder, building materials, and various tertiary products such as gum and medicinals, the belts substantially increase wildlife habitat. This not only increases the availability of bush meat, but helps reestablish the role of wildlife in seed dispersal. Following are examples of shelterbelts that have been successfully established in the drylands of West Africa.

CAMEROON

The earliest record of the establishment of shelterbelts refers to the Diamare and Mayo-Danay districts of northern Cameroon. Between 1956 and 1960, 300-km belts of trees were planted around farms and along roadsides. The species used was *Cassia siamea* because it is not eaten by animals, and fencing was therefore not required. However, because of its shallow rooting system, it should be combined with other species in shelterbelts. The World Bank-assisted Rural Development Project No. 3031-CM is extending the system for another 750 km over a period of about 5 years. Additional species are being considered for inclusion in the project.

NIGERIA

The first shelterbelts were planted in 1963 and 1964 in the Gumel Emirate of Kano State by the Forestry Department in cooperation with the Agricultural Division. The belts consisted of 10 rows of trees spaced 3 m apart and were planted in strips 1.6 km long. These continuous fenced belts prevented people and livestock from crossing the countryside, and in 1965 the design was changed to circular groups of trees with diameters of 49 m, planted in lines in a staggered pattern. In 1969 and 1970, 3 separate sites were planted in Kazaure Emirate, Gumel Emirate, and Hadejia Emirate; the design was changed to

staggered rectangular blocks, which permitted people and livestock to cross the area. By 1978, when the program ceased in northern Nigeria because of the high cost of land and protection and the lack of funds, 1,034 ha of shelterbelt plantations over 365 km had been successfully established.

The original 1963 plantings consisted of 2 rows of Acacia nilotica on the windward side, then 6 rows of Azadirachta indica, then 2 rows of Acacia albida. The 1963 plantings in circular groups consisted of a central core of Azadirachta indica, with Acacia senegal on the windward side and Acacia albida on the leeward side. Later plantings in the more traditional design of 6 lines of trees consisted of Eucalyptus camaldulensis. Anacardium occidentale and Acacia nilotica have been planted around most governmental farm centers.

NIGER

Although not planted as shelterbelts, the practice of leaving 10-m wide bands of natural woodland between farmland, instituted in 1964, is an early example of the awareness of the value of protection from the wind by windbreaks. In 1975-1979, in the Majjia Valley of the Bouza District, 250 km of 2 rows of Azadirachta indica were established. More recently, Acacia nilotica, A. senegal, and A. tortilis have been planted by the American relief organization, CARE.

SENEGAL

Senegal has a long history of shelterbelt establishment, including plantings of Casuarina equisetifolia to protect the niayes (interdunal depressions in which vegetables are grown for the Saint-Louis and Dakar markets) of the Cayor coastlands. Anacardium occidentale (cashew) has been planted around many farm boundaries for a number of years. More recently, the German Forestry Mission has established shelterbelts of Balanites aegyptiaca and Acacia nilotica, subsp. adstringens, around Vidau Thingoly in the Fleuve. Additional shelterbelt projects are currently under way.

COSTS AND BENEFITS

The cost of the blocks planted and fenced in 1963 in northern Nigeria was approximately US $338/ha when daily labor was paid US $0.50 per day. Ninety percent of this was for fencing materials. The 6 lines of Eucalyptus planted in later years cost US $1,590/ha of which US $1,413 was for fencing materials.

The 250 km of 2 rows of Azadirachta indica established by CARE in Niger in 1975-1979 cost US $1 million, which equals US $400/ha for trees planted at 1-km lengths of shelterbelt plants for 10 ha of land. These lines were not fenced. The locally owned livestock were kept away from the planted trees by locally employed guards.

Because shelterbelts take between 8 and 12 percent of the farmland out of agricultural production, benefits from their protective role must be on the order of 15-20 percent increases in crop yields. Increases greatly in excess of this have been recorded in the Sahel.

In the Majjia Valley in Niger, for example, a 1-year study of the effects of the 2 rows of Azadirachta indica showed that millet yields in the protected fields were 123 percent of the yields outside the protected areas. This takes into account the loss of production caused by the proximity of the planted trees. At distances up to five times the height of the planted trees on the leeward side, yields were 156 percent greater than in the unprotected fields.

In the Kazaure Emirate rectangular block plantings of 1965, farmers interviewed in 1980 claimed that in the severe drought years of 1973-1974, surrounding villages without the shelterbelts experienced serious crop failures, whereas the protected fields had normal crops. An additional benefit reported by these farmers is that in normal years, only one sowing of the crops is required to the leeward of the shelterbelts. In the unprotected areas it is frequently necessary to sow seed two or three times each season because of blown surface sand burying or damaging the germinating seed.

An economic analysis of the value of shelterbelts to northern Nigeria's agricultural production undertaken by J. C. Nautiyal of the Food and Agriculture Organization in 1979, using 1973 costs and produce prices, demonstrated that if the land on which the trees were planted did not have to be purchased, the financial benefits from a 10 percent net increase in crop yields in normal years were positive, even without the value of the fuelwood from selective felling of the shelterbelt trees. The probability of drought every 5 or 6 years reducing overall crop yields and increasing prices accordingly, makes the total relative addition to agricultural values considerably higher than those used in the above model.

In 1980, the Forest Research Institute of Nigeria initiated an evaluation of the Eucalyptus shelterbelts established in the early 1970s. Groundnut and bean leaf production in the protected fields was double the average of the unprotected fields, but there was no significant increase in nut or bean production.

DESIGN OF SHELTERBELTS

The effectiveness of the shelterbelt depends on how impenetrable the wall of vegetation is.* A dense row of trees not only blocks the wind but also confines the effects of the wind close to the shelterbelt. A row of trees that provides less complete wind reduction also means that the effects of the wind are felt farther away. A vegetation density of 60 percent to 80 percent seems to work best in arid zones.

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*This section is drawn largely from: Fred R. Weber. 1977. Reforestation in Arid Lands. VITA Publications, Manual Series No. 37E. Volunteers in Technical Assistance, Mt. Rainier, Maryland, USA. Figures A-1 through A-3 are also from this publication.

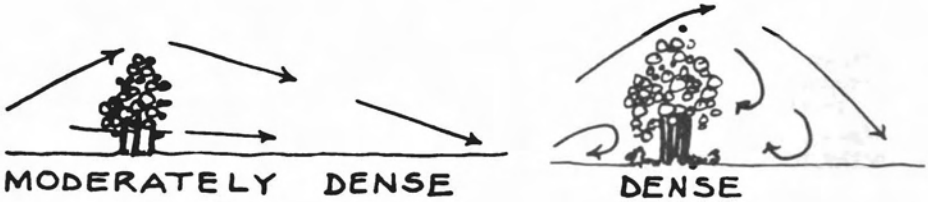

FIGURE A-1

Gaps or openings in shelterbelts should be avoided as much as possible. Wind rushes through gaps, concentrating its strength, so that its final effect can be very damaging (see Figure A-1).

A shelterbelt is generally wider and more dense than a windbreak. It can provide protection for downwind areas up to 20 times its height, provided it consists of several rows of plants of different heights. As shown in Figure A-2, large trees should be chosen for the center rows (A). Fast-growing species can be mixed with slower growing trees; the choices depend on local preference. The next two rows (B) are of smaller species. If possible, these trees should be chosen for their by-products. Rows C and D are auxiliary rows. These rows are planted with lower, bushier trees, shrubs, and grasses. A well-chosen "mix" of vegetation in the shelterbelt will not only provide protection from the wind but will also yield fruit, nuts, firewood, bark, resins, and possibly grass for grazing.

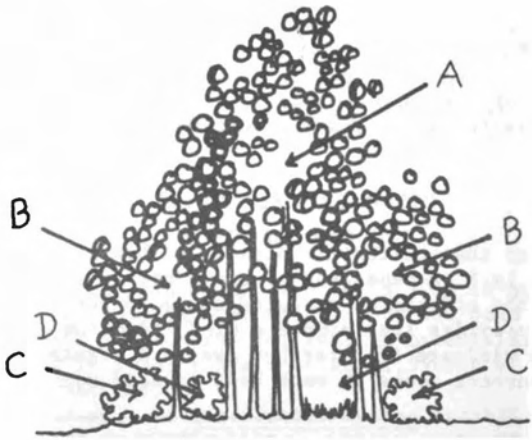

FIGURE A-2 Cross-section of a shelterbelt.

Shelterbelts can include carefully planned pathways and driveways for stock. Any opening should be at an oblique angle to allow the orderly movement of people or livestock without opening a gap for the wind. Other points to consider in the design of shelterbelts follow:

1. The selection of species for shelterbelts should follow the general guidelines for the different rainfall zones. Good selections can be made from species protected by law. Whenever possible, use species that local residents themselves have chosen and value.

2. The most efficient shelterbelts are those that combine low-growing bushes like Bauhinia, Combretacae, and Salvadora on the outside of the belt with rows of taller trees on the inside.

3. Frequently a combination of planting methods is highly practical when establishing shelterbelts. In other words, a combination of nursery transplants, live fencing, cuttings, and stumps can be planted (according to the time of year best for planting in the area).

4. An additional merit in a slightly wider belt is that it can be designed for multiple usage for selective choice of species for the middle portion, such as Tamarindus indica, Acacia senegal, or native fruit and medicinal species.

5. Preparation and protection of the site involved are important for shelterbelts. Keeping animals away from a long narrow strip of land is very difficult and much more costly than fencing a field of similar area but more rectangular in shape.

6. In complex situations, or where more extensive protection is desirable--for example, around towns or larger villages--it is most effective to stagger shelterbelts in a pattern of overlapping blocks as shown in Figure A-3.

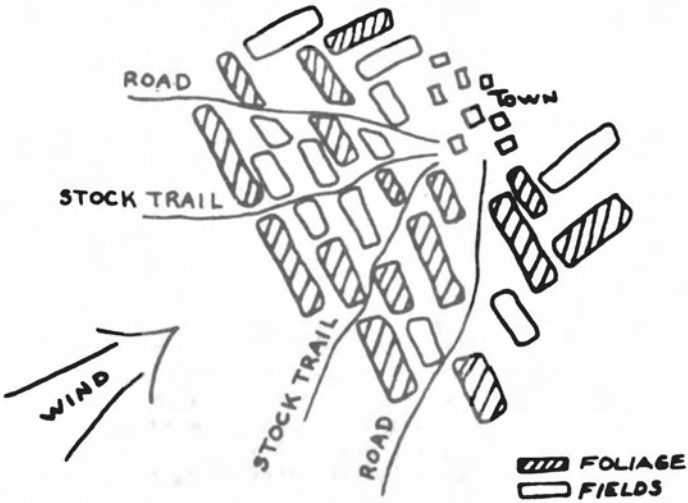

FIGURE A-3 Greater protection is afforded by staggering shelterbelts in a pattern of overlapping blocks.

7. Another planting pattern is to line farm fields with shelterbelts and plant trees such as *Acacia albida* in grids at intervals of 10 m inside the field. Further information on the beneficial integration of trees and shrubs in agricultural systems is contained in the companion NRC volume, *Agroforestry in the West African Sahel* (1983, National Academy Press, Washington, D.C., USA).

8. The selection of shelterbelt species should take into consideration the requirements of local crop predators in order to minimize crop losses.

APPENDIX B

The Climatology of Sub-Saharan Africa

Sharon Nicholson

The sub-Saharan region is characterized by low, highly variable rainfall and a landscape that undergoes a marked and abrupt change between wet and dry seasons within a year. The further south one goes from the Saharan margin, the greater the rainfall and the longer the rainy season. Rainfall gradients are steep--as much as 100 mm per 100 km in West Africa--passing from 100 mm in the northern region of the Sahelo-Saharan zone to over 1,600 mm in the Guinean zone. The duration of the rainy season also varies greatly, ranging from 1 month in the desert margin to more than 8 months in the Guinean coastal zone. Hence, the transition from desert to the humid tropics is abrupt.

In the semiarid sub-Saharan zones, rainfall is usually limited to the summer months (i.e., from May to October); aridity prevails during the cooler season and is most pronounced from December to February. An understanding of both the seasonality and the rapid transition from subtropical aridity to the humid tropics requires a look at the winds and general atmospheric circulation systems that affect the region, especially the subtropical high pressure zone and the inter-tropical convergence zone (ITCZ). The former is associated with aridity, the latter with rainfall; together these features form part of a major feature of the atmosphere's tropical circulation, a cell of vertical air motion called the Hadley circulation. This cell (Figure B-1) consists of rising air near the equator (near the ITCZ) and sinking motion in subtropical latitudes (the subtropical highs are at about 30° latitude).

The inter-tropical convergence zone (Figures B-2 and B-3), which globally represents the convergence of the northeasterly and southeasterly trade winds, marks over East Africa the transition between the dry northeasterly harmattan winds blowing over the Sahara and the moist southwesterly monsoon flow originating farther south over the tropical Atlantic. This convergence, accompanied by heavy cloudiness and generally intense rainfall, moves northward during the northern-hemisphere summer, bringing a short season of rainfall to the equatorward margins of the earth's low-latitude deserts. The length of the rainy season at a given latitude reflects the number of months in which the ITCZ dominates the local climatology; hence, the season progressively lengthens with southward distance from the Sahara. Later in the year it shifts to the southern hemisphere; a high pressure cell

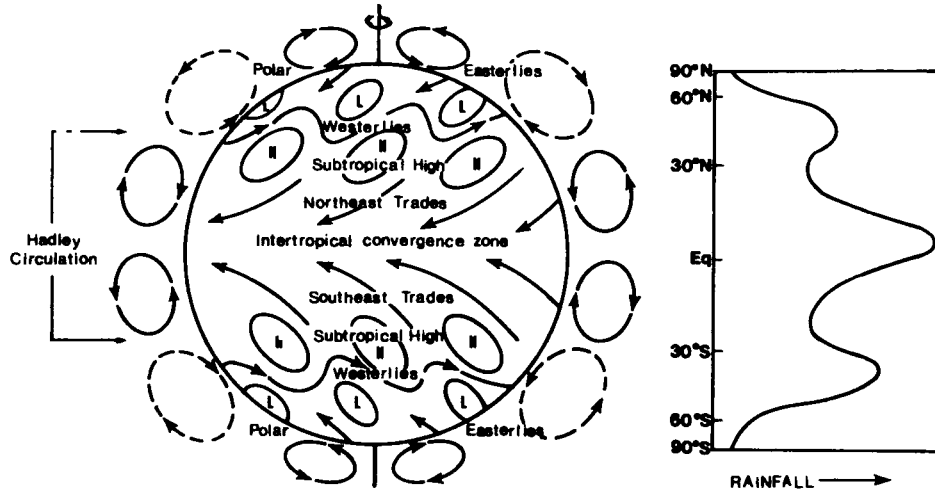

FIGURE B-1 Schematic diagram of global pressure and wind systems, rainfall, and the Hadley circulation. (Source: Nicholson 1982)

(Figure B-2) and the sinking motion associated with the poleward branch of the Hadley circulation prevail in the Sahara and along its Sahelian margins, ushering in the dry season.

Although the alternation of wet and dry seasons in the Sahel seems straightforward, an attempt to understand thoroughly the region's climate--and especially its climatic fluctuations--requires a departure from this simplistic scenario. The ITCZ represents a climatological mean; the zone is discontinuous in time and space, and it is composed of individual weather disturbances that move eastward across the continent at intervals of about 3-5 days. The most basic disturbance is a "cloud cluster", a super-cell covering hundreds of kilometers and including a number of smaller cells of intense rainfall. A second type of storm is the squall or squall cluster. These are rapidly moving cloud clusters that move westward at variable speeds; while cloud clusters average about 10 km/hr, squalls propagate at speeds up to five times that average. The origin of these systems underscores their large-scale nature. Most are associated with easterly waves and slight disturbances in the atmospheric pressure field. These waves appear to originate over eastern Africa and propagate westward as far as the Atlantic or the Caribbean, where they may spawn hurricanes. Climatic fluctuations may be associated with any factor that increases the size, intensity, or frequency of these disturbances.

Just as the movement of the ITCZ is not the only factor in sub-Saharan rainfall, its absence from the region and replacement by a high pressure regime most of the year is not the only cause of aridity. Other suggested factors governing the general aridity in the Saharan region include the nature of the balance of radiation in the region and the tropical easterly jet stream situated at 12 km above the surface. Thus, these elements may also be important factors governing climatic fluctuations in the Sahel.

CHARACTERISTICS OF THE RAINFALL REGIME

The potential for development in the semiarid sub-Saharan margins is limited not only by the small amount of rainfall but also by less commonly considered characteristics of the area's rainfall. These characteristics include extreme variability in time and space; the tendency for the number of below-normal years to exceed the number of wet ones; the occurrence of rainfall in the warm season, when evaporation is greatest; and the persistence of abnormal rainfall conditions such as drought or wet episodes over a multi-year period.

The maximum and minimum annual totals recorded at various sub-Saharan stations illustrate the extreme interannual variability of rainfall. The highest and lowest recorded annual totals are 219 mm and 7 mm at Akjoujt, Mauritania, in the Sahelo-Saharan zone; 691/141 at Saint-Louis, Senegal, in the Sahel proper; 960/120 at Dakar in the coastal Sudanian zone; and 1,844/750 at Bougouni, Mali, in the Sudano-Guinean zone. The coefficient of variation (CV) roughly defines the percent variation around the mean that is expected two-thirds of the time. It is 15-20 percent in the Sudano-Guinean zone, 20-30 percent in the Sudan, 30-50 percent in the Sahel proper, and as much as 100 percent in the Sahelo-Saharan desert fringe. Thus, the more arid the region, the greater the variability of rainfall; hence, the lower the "reliability" of the rains.

A related characteristic is variability in space--how well rainfall at any given point correlates with that in nearby areas. High spatial variability is a well-known characteristic of semiarid and arid regions (Sharon 1972, 1974, 1979; Jackson 1977). In Tanzania, for example, in regions with rainfall on the order of 1,000 mm per year, annual rainfall totals at stations only several kilometers apart may be uncorrelated; differences between nearby stations may be several hundred millimeters. These differences are not caused by local effects (e.g., topography) because the long-term averages at the station are the same; rather, this variability in space relates to the randomness of the convective rains that prevail in these areas. This characteristic becomes more extreme as shorter time scales (e.g., 1 month or individual storms) and more arid regions are considered. For the Sahel this means that in any given "normal" year--one in which the region as a whole is neither excessively dry nor wet--as many as 40 or even 50 percent of the individual stations experience below-average rainfall (Figure B-4).

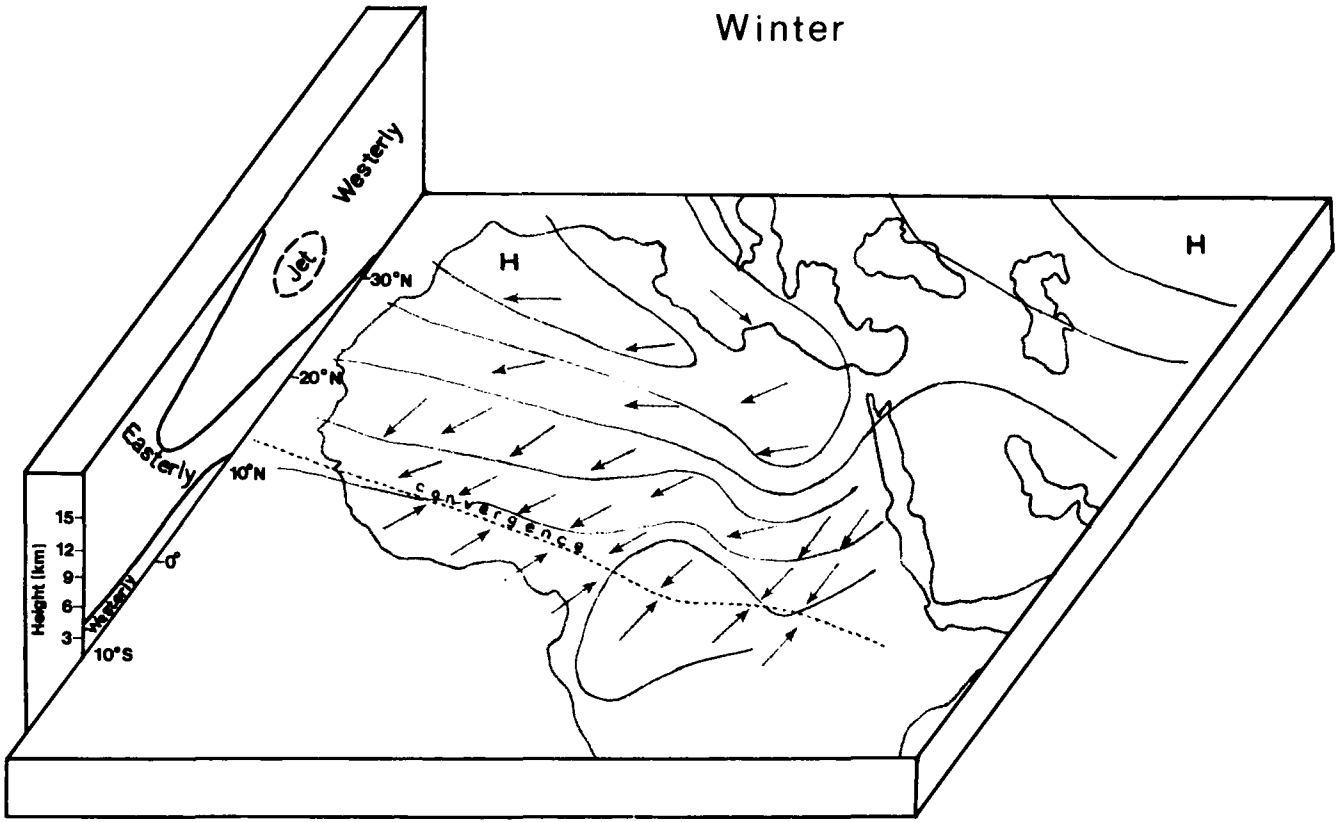

FIGURE B-2 Pressure and wind over Africa during January; vertical cross-section of winds aloft, including the jet streams.

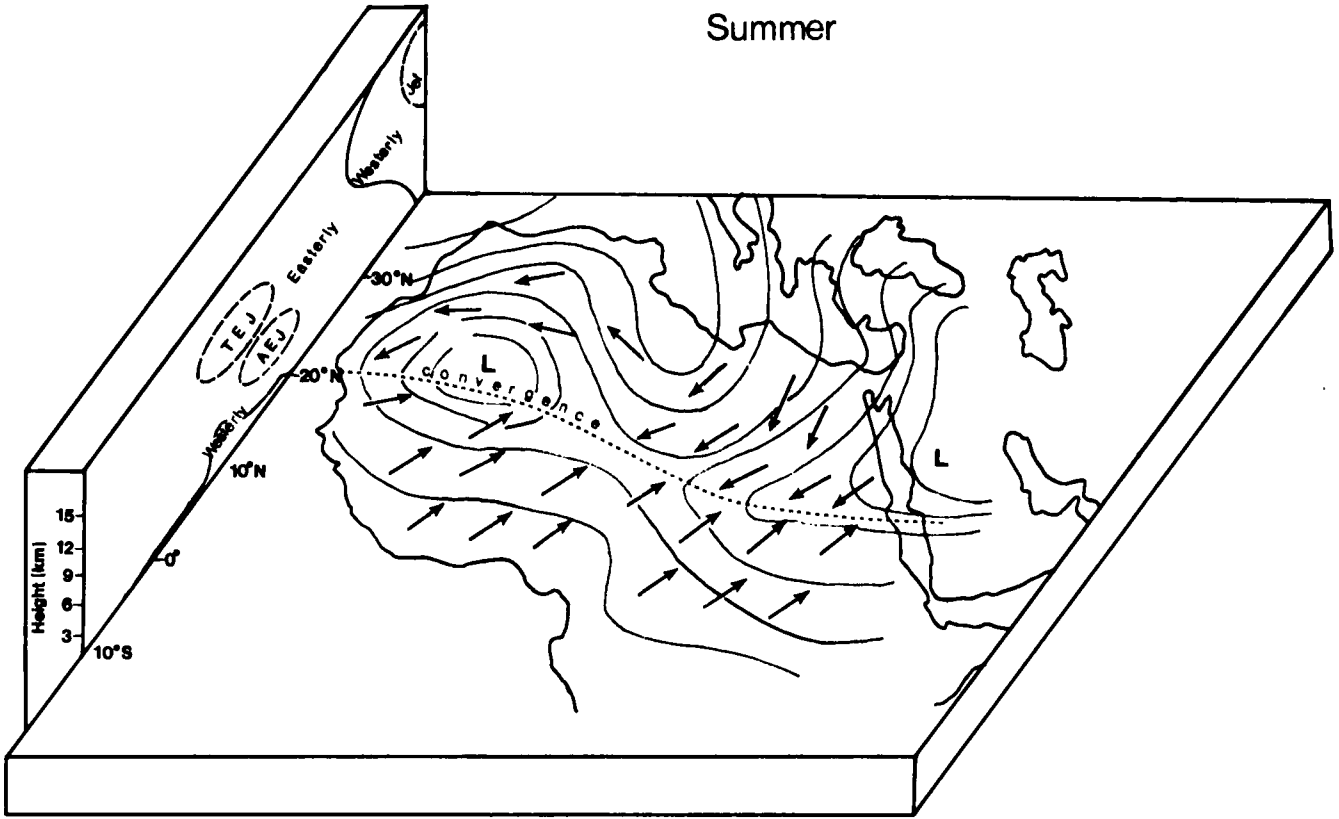

FIGURE B-3 Pressure and wind over Africa during July; vertical cross-section of winds aloft, including the jet streams (AEJ is the African easterly jet at 3 km above the surface; TEJ is the tropical easterly jet at 12 km).

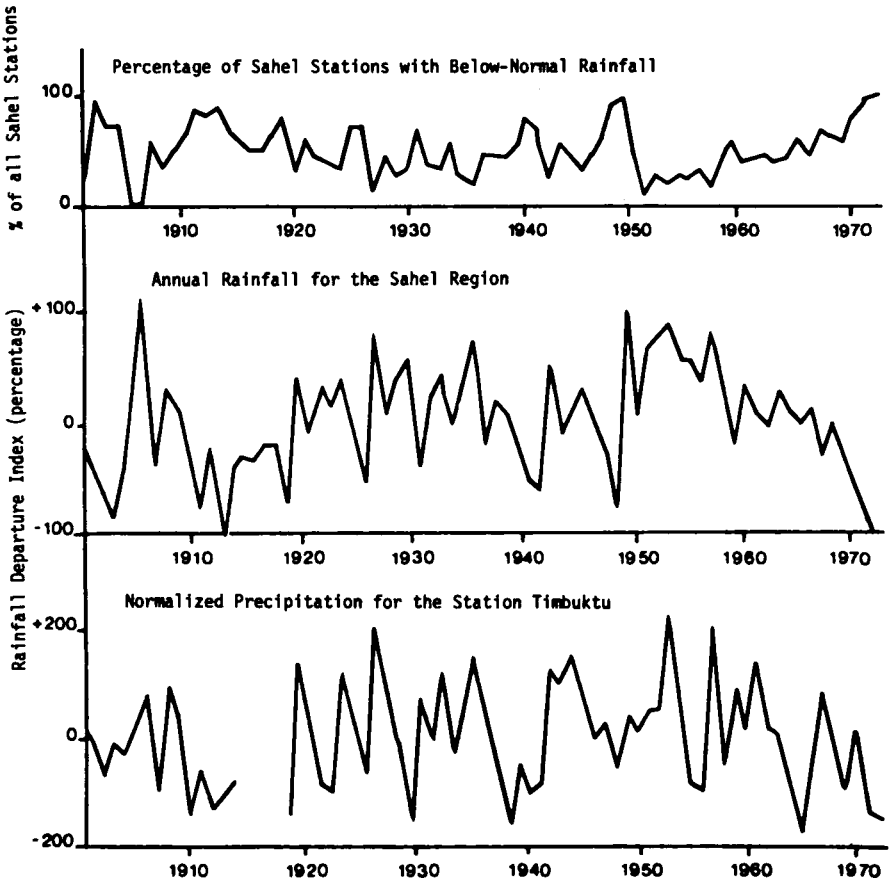

FIGURE B-4 Rainfall anomalies in the Sahel: the percentage of Sahel stations registering below-average annual totals (1901-1973) versus annual rainfall in the Sahel and at one station (Timbuktu).

The reason for this is clear when one considers the nature of the rainfall. Most rain is associated with large-scale weather systems (e.g., cloud clusters), but heavy rain is confined to smaller cells that make up a fairly small area of the total system. Thus, any individual storm leaves many areas dry. In the Sahel, where a few storms produce most of the rainfall, being randomly "hit" or "missed" by a major rainfall can markedly affect the rainfall totals at a given place.

The extreme variability of Sahelian rainfall clearly indicates that the concept of "mean" or "average" rainfall has little value for dry lands. This point is underscored by the typical frequencies at which various annual rainfall totals occur at a given location. In subhumid regions, subnormal years clearly dominate the distribution, and a few years of unusually high rainfall inflate the mean. The more arid the region and the shorter the time period considered, the more this distribution is skewed toward above-normal years. At Gao, Mali (mean annual rainfall is 244 mm), for example, August rainfall is below the mean in 23 of 35 years between 1941 and 1975; in only 4 years is rainfall within 10 percent of the August mean, while 19 of the 35 annual totals fall below the annual mean (Katz and Glantz 1977). In all cases, the mean exceeds both median and mode. At Niamey, in the wetter Sudanian zone (mean annual rainfall is 586 mm), 19 August totals and 18 annual totals fall below the 35-year mean. Mean rainfall clearly is not a good indicator of the environmental conditions to which livelihoods, life-styles, and agriculture must adapt.

Because most rainfall in the sub-Saharan region occurs during the warm months, and because of the region's subtropical location, much moisture is lost through evaporation. Indeed, in most of the region the net radiation received during the year is 2-20 times the amount required to evaporate the meager precipitation. Because of the showery nature of most Sahelian rainfall--intense rains of short duration with clear skies shortly thereafter--runoff and subsequent evaporation are high. Thus, compared to persistent drizzly precipitation or cold season rains that frequently occur in the middle latitudes, a relatively small proportion of these subtropical rains penetrates into the ground and becomes effective for plant growth.

High variability is an inherent characteristic of rainfall in dry regions. The critical factor, however, is not variability alone but in combination with the tendency for abnormal years to occur in succession. In most regions the inhabitants can readily withstand 1 or even 2 bad years. In the sub-Saharan regions, rainfall anomalies can persist for 8, 10, or even 15 years. This means, of course, a devastating drought if rainfall deficits persist. On the other hand, persistent years of above average rainfall can create a false sense of the true climatic conditions. In a wet decade in the Sahel, the pastoralists may advance northward into the delicate desert fringes, while agriculture is pushed northward beyond the true agronomic dry boundary. This, in fact, appears to have contributed to the disaster accompanying the recent drought that followed a decade (the 1950s) of extremely abundant rainfall.

UNDERSTANDING THE CAUSES OF SAHELIAN RAINFALL FLUCTUATIONS AS A MEANS OF FORECASTING

Various scientists (Bryson 1973; Lamb 1978a,b; Newell and Kidson 1979; Nicholson 1981b) have speculated about many possible causes of rainfall fluctuations in the Sahel, and numerous forecast schemes have been based on certain hypothesized factors (Bryson 1973, Winstanley 1973b,

Greenhut 1981). The suggested variables influencing Sahelian rainfall include the position of the inter-tropical convergence zone, sea-surface temperatures, moisture influx into the atmosphere above the Sahel, the strength and position of wind patterns and jet streams, and the strength of the tropical Hadley. These hypotheses will not be discussed fully here, but they are thoroughly described elsewhere (Nicholson 1982). Instead, remarks will concentrate on three relevant questions: (1) the assumed validity of the hypothesis relating variations in Sahel rainfall to a displacement of the ITCZ; (2) forecasting climate or rainfall fluctuations in the Sahel; and (3) the possibility that "biogeophysical feedback" influences the region--that is, that drought reinforces drought through the changes it produces in the land surface.

The most commonly suggested cause of the 1968-1973 drought is a southward displacement of major circulation features, especially the subtropical high and ITCZ (Bryson 1973; Winstanley 1973a,b; Greenhut 1977, 1981; Kraus 1977; Lamb 1978a,b). This is generally seen as a response to the expansion of the westerly wind belt (circumpolar vortex), which in turn forces the subtropical and tropical zones into lower latitudes. Thus, in the Sahel the aridifying influence of the subtropical high increases while the dominance of the ITCZ and related rains diminishes. Unfortunately, the role of the ITCZ has generally been assumed, and none of the above studies actually presents evidence that an anomalous displacement of this zone was, in fact, a significant factor in the recent Sahel drought.

There are, however, numerous studies that present evidence that this hypothesis is incorrect (Miles and Fowlard 1974; Tanaka et al. 1975; Krueger and Winston 1975; Bunting et al. 1976; Newell and Kidson 1979; Nicholson 1980a, 1981b; Stoeckenius 1981). The most relevant arguments follow. First, a southward displacement would require a decrease in the length of the rainy season at given latitudes during drought years and a southward displacement of the zone of maximum rainfall. The former occurs only in the region between 18°N and 20°N, a small part of the drought-stricken area of West Africa (Table B-1). Second, there is no consistent and significant difference in the latitude of maximum rainfall over West Africa during dry and wet years; in dry years it is further north than in numerous wet years. Finally, a mere displacement of the ITCZ could not explain the major configurations of rainfall patterns during drought years: the coupling of dry conditions both north and south of the Sahara and the tendency for rainfall to decrease synchronously over the entire continent. These characteristics are evident from (1) the four major geographical patterns of rainfall anomalies in West Africa (Figure B-5); (2) the rainfall departures occurring during the same years over the Sahel and southern Africa (Figure B-6); and (3) the marked similarity beween time series of rainfall departures in the Sahel and the Kalahari in the southern hemisphere (Figures B-7). The contradiction of this hypothesis is a critically important point because much nontechnical literature has simply accepted the ITCZ hypothesis as fact, and predictions have also been popularly based on this idea.

TABLE B-1 Comparison of the Length of the Rainy Season and the Number of Months with Heavy Rainfall in Wet, Normal, and Dry Years

	Latitude (°N)	Number of Months with 25 mm or More	Number of Months with 100 mm or More
Wet years	20	3	0
	18	4-5	1-2
	15	6-7	3
	13	7	5
	10	8-9	6-7
Mean or "normal" years	20	2	0
	18	3	0
	15	5	2
	13	7	4.5
	10	7	6
Dry years	20	0-1	0
	18	3-4	0
	15	5	1
	13	7	3.5-4
	10	7	6

SOURCE: Nicholson 1982.

Numerous forecast models (Bryson 1973; Winstanley 1973a,b; Ilesanmi 1971; Kraus 1977; Greenhut 1981; Faure and Gac 1981; Adedokun 1978) have been developed in an attempt to predict Sahelian rainfall. The results of these models, however, are highly speculative, and some derive from very tenuous, unproven relationships. This is especially true, as noted above, of models based on the ITCZ scenario. In other models, problems arise from faulty applications of statistical techniques. At present, no acceptable forecast scheme is available, and one must view skeptically any rainfall forecasts beyond one season.

To improve forecasts, models must be developed that rely on physical rather than statistical associations. A word of caution is in order on the current common use of the latter (e.g., Faure and Gac 1981). Most statistical approaches rely on the use of trends or cycles. Although these methods are useful in describing the past, they are of questionable value in predicting the future. Trends, in particular, cannot be extrapolated forward in time, as climatic fluctuations occur abruptly. The use of cycles (the so-called spectral methods) should also be avoided in forecasting. Furthermore, the detection of trends and cycles and their interpretation require a thorough and sophisticated knowledge of statistics. The common

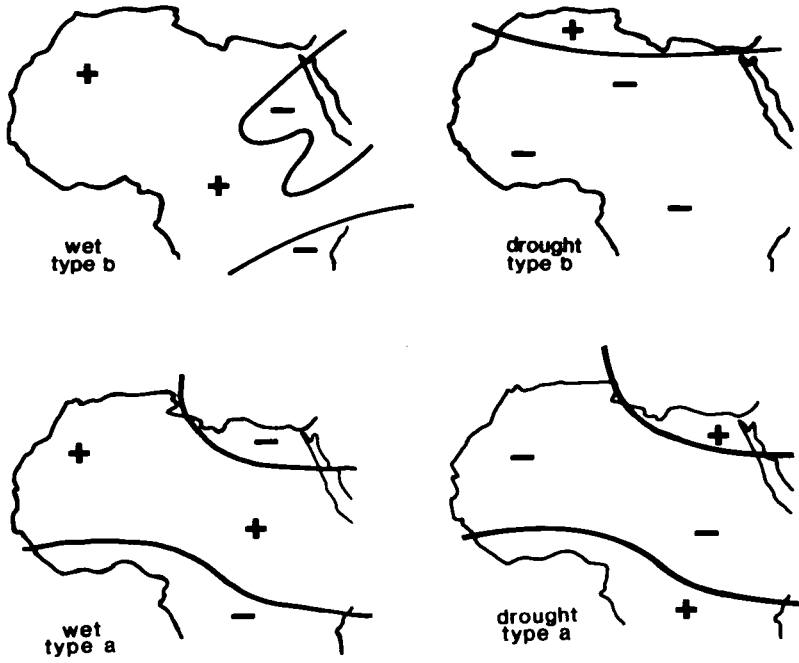

FIGURE B-5 Four frequently occurring patterns of rainfall fluctuations in West Africa (+ is abnormally wet, - is abnormally dry).

nontechnical approaches, such as those used by Faure and Gac--wherein a time series is "smoothed" by averaging and cycles are more or less detected visually--have little predictive value.

There are numerous reasons why "cycles" lack predictive value. First, as with trends, particular cycles may be present in a time series for some time, then abruptly disappear. Furthermore, exact periodicities are rare: a cycle of about 15 years may mean droughts at intervals of 12-18 years, hardly a basis for predicting a given event. In most cases, especially with fairly long cycles, the time series in which they are detected is so short that a cycle can repeat itself only a few times within the series. This can easily happen by chance or as a result of random events, and the presence of a particular cycle in a longer series cannot be inferred. Consider, as an example, the suggestion of a 30-year periodicity in Sahelian droughts. If this is based on rainfall data for the period 1900 to present, the "cycle" has

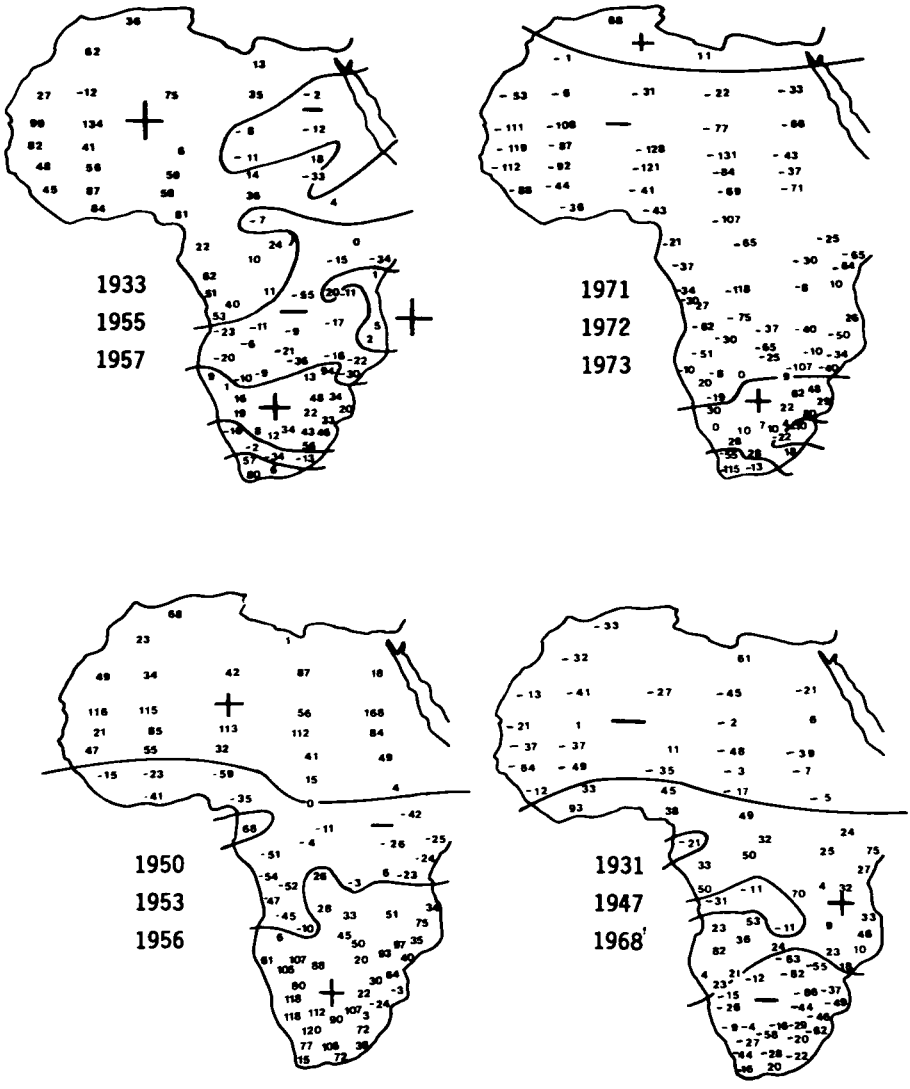

FIGURE B-6 Regional rainfall indices for 3-year sets representing the patterns in Figure B-5 (negative values are below normal, positive are above normal). (Source: Nicholson 1982)

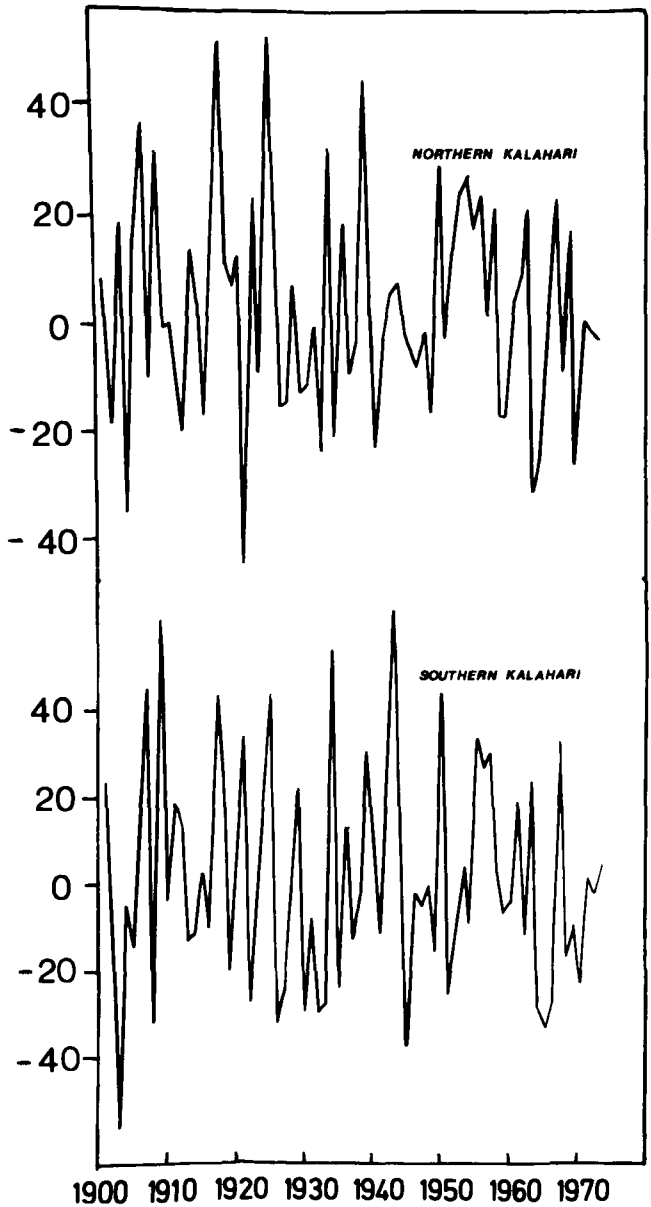

FIGURE B-7 Rainfall in the northern and southern Kalahari, 1901-1973 (expressed as a percentage above or below normal). (Source: Nicholson 1982)

occurred just twice--a result that can easily be achieved by purely random variations.

A final objection to using cycles to predict climate relates to a frequent misunderstanding about what they represent. Even if a particular cycle appears to be a real characteristic of some climatic series, it might explain only a small part of the variation of that series. All too often those who use this method fail to realize the difference between statistical significance (nonrandom, perhaps indicative of physical cause) and forecast value. Katz (1978) points this out about the statistically significant persistence in Sahelian rainfall. Consider the case in which spectral methods detect a 5-year cycle in rainfall. If a rigid significance test indicates that this tendency for fluctuations to repeat themselves every 5 years cannot be produced by chance alone, the researcher concludes that the rainfall series contains a real cycle of about 5 years. The problem comes if someone less familiar with the method concludes that a drought will occur every 5 years. The cycle can be shown to be significant (i.e., likely representing a real characteristic and not a series of random events) even when it accounts for only 10-15 percent of the rainfall variability. This accuracy, however, is generally insufficient for distinguishing between normal and subnormal years.

Models based on long-term mean climatologies or statistical correlations are misleading. For example, the association found by Ilesanmi (1971) between the subtropical high and Nigerian rainfall, which has been used in forecast schemes, is based on the seasonal patterns of both. The fact that they have a similar seasonal cycle does not mean that an abnormal position of the high for a given period is coupled with a similar anomaly in rainfall. It is equally unwise to use a pure statistical correlation--a proven similarity between two variables that implies neither cause and effect nor a physical relationship--to forecast one variable from another. Because of its simplicity this method is often and inappropriately applied to climatic forecasts. As commonly used (e.g., Winstanley 1973a,b), it is akin to using a farmer's almanac to predict weather.

Better approaches to forecasting Sahelian climatic or weather fluctuations include the teleconnections concept and physical models that relate rainfall to other atmospheric parameters, based on the equations of the dynamics of the atmosphere. The topic of teleconnections--or long-distance linkages--is at the forefront of current climatological research. We are seeing global climate anomalies that can be traced back to one or two basic physical phenomena. One example is the well-known El Nino (warmer ocean temperatures in certain areas coupled with increased rainfall in drier areas of the Pacific and surrounding coasts). It is now seen as part of a global pressure oscillation called the "Southern Oscillation," a phenomenon linked to climatic anomalies throughout the equatorial regions and extending into the higher latitudes of both hemispheres. By attempting to put the Sahel into such a global climatic context, we may have some hope of long-range forecasting if sequential relationships can be established. Furthermore, studies based on climatic dynamics rather than statistics have already produced good

results for shorter time scales (Krishnamurti el al. 1980) and will probably lead to better seasonal forecasting as well.

Biogeophysical Feedback

Jule Charney (1975) initially proposed the hypotheses of modification of Sahelian rainfall through processes termed "biogeophysical feedback"--the concept that drought is reinforced either through changes it evokes in the Sahelian land surface or through similar changes produced by human impact on the ecosystem. According to Charney, removal of vegetation increases surface albedo, which affects the atmospheric energy budget in such a way as to intensify the sinking motion which promotes aridity in the Sahel and Sahara.

Numerous scientists have picked up this theme and have proposed other ways through which such feedback could arise. Otterman (1974) suggests that a reduction of surface temperature takes place when soils with high albedo are bared through devegetation. Walker and Rowntree (1977) propose that the reduced amount of surface moisture during drought years acts to reinforce the conditions producing the drought. Schnell (1975) hypothesizes that a similar feedback effect occurs through the reduction of freezing nuclei when vegetation--a source of such nuclei--is destroyed. MacLeod (1976) suggests that dust over the Sahel can also have an aridifying influence on the region.

While the scientific community has been slow to accept the concept of biogeophysical feedback, in recent years numerical models have rapidly enhanced support for this hypothesis. What evidence do we actually have? First, most of the proposed mechanisms are physically sound. Furthermore, mathematical models have tested several hypotheses, and, despite different assumptions and varied surveyed mechanisms, the models universally conclude that changes in the Sahelian land surface can act to diminish rainfall. Finally, the known sensitivity of the tropical atmosphere to surface parameters renders these ideas quite plausible.

So far, there is no direct and conclusive observational evidence that such feedback operates in the Sahel, but some of the characteristics of the region's climate hint at this, including the extreme persistence observed in the Sahelian rainfall series (on the order of one or two decades (Table B-2)); the lack of such persistence in the Kalahari, its southern hemisphere analog; and the continued intensification and spread of the drought between 1968 and 1973. These observations provide some support for the idea that a positive feedback mechanism acts to prolong and intensify droughts south of the Sahara. Indeed, such feedback may be the only way of explaining the decadal persistence that characterizes Sahelian rainfall. In view of this, it is important to keep one point in mind: any of the changes in the Sahel that have been suggested as potential feedback mechansims (surface albedo, surface temperatures, reduced production of freezing nuclei, reduced surface moisture, dust) can also result from human activity alone or can intensify when overuse is coupled with extreme meteorological drought.

TABLE B-2 Frequencies of Runs of Years with Rainfall Above/Below the Median (Wet/Dry) in the Three Sahelian Zones (1901-1980) and the Kalahari of Southern Africa (1901-1973)

	Length of Run (Years)												Persistance Ratio
	1	2	3	4	5	6	7	8	9	10	...	15	
Sahelo-Sahara*	7	4	2	2	2	0	0	0	1	1		1	1.90
Sahel	9	6	3	3	1	0	0	1	0	1		1	1.62
Sudan	15	9	3	2	0	2	0	0	0	0		2	1.23
Northern Kalahari	27	8	6	3	0	0	0	0	0	0		0	0.84
Southern Kalahari	20	10	2	3	3	0	0	0	0	0		0	0.97
Random expectation													
N = 75 years	19.2	9.5	4.7	2.0	1.1	0.56	0.28	0.14	0.07	0.03		0.001	1.00
N = 80 years	20.5	10.1	5.0	2.5	1.2	0.60	0.30	0.14	0.07	0.03		0.001	1.00

*1906 to 1980

THE NATURE OF RECENT SUB-SAHARAN RAINFALL FLUCTUATIONS

A number of characteristics of African, and especially Sahelian, rainfall fluctuations become apparent from simple diagnostic analyses (Nicholson 1980a, 1981b), some of which have already been described. These analyses include time series of annual rainfall totals, spatial patterns of abnormal rainfall in extremely wet and extremely dry years, and the seasonality and intensity of rainfall in such years. The major conclusions are also supported by the historical data for the region (Table B-3).

- The recent Sahel drought is not unique; drought of this magnitude and extent is a recurrent feature of the region's climatology. The above is evident from analyses of both modern and historical records, as described in earlier sections. Drought occurred in the 1940s, though less severe and of shorter duration, and the 1910s were very similar to the period 1968-1973. Other episodes occurred in the mid-eighteenth century and early in the nineteenth century.

- An unusual feature of rainfall fluctuations in the region is their extreme persistence on the order of one or two decades. In most humid areas, dry and wet years are generally randomly interspersed. In semiarid regions, however, abnormal years tend to cluster together, so that dry (or wet) conditions endure over a multi-year period. In the Sahel this characteristic is extreme: wet or dry conditions may persist for one or two decades (Table B-2). As an example, the period 1960-1980 has been rather consistently dry, and extreme drought characterized at least half of the period. Similar episodes are evident also in the historical record of the region.

- The rainfall fluctuations occurring in the sub-Saharan lands are extreme in magnitude. Persistent periods with rainfall 30-50 percent above or below the mean are common in the more arid regions. In some areas, rainfall during the 1950s was about twice as great as during the period 1968-1973.

- Sahelian rainfall fluctuations are associated with preferred geographical patterns of rainfall variability; four basic patterns describe much of the variability of Sahelian rainfall (Figure B-5). Years that are abnormally wet or abnormally dry in the Sahel generally fall into one of the following four patterns of rainfall over West Africa (Nicholson 1980a, 1981b):

  -- Uniform drought in nearly all areas north of the equator
  -- Above average rainfall throughout most of that area
  -- Above average rainfall throughout the Saharan and sub-Saharan regions but abnormally dry conditions in the equatorial region below 10°N
  -- Drought throughout the Saharan and sub-Saharan regions but above average rainfall in the equatorial region below 10°N.

TABLE B-3 Characteristics of Rainfall Fluctuations in the Sahel and Elsewhere in Northern Africa

TEMPORAL FLUCTUATIONS

Droughts 1910s, 1940s, 1968-1973, 1976-1980
Wet 1950s
"Dry" 1960ff

PERSISTENCE

Abnormal conditions frequently persist 10-15 years or longer.

EXTREME MAGNITUDE OF VARIABILITY

Persistent periods with rainfall 30-50 percent above or below the regional mean are common.

LARGE-SCALE PATTERNS OF ANNUAL RAINFALL DEPARTURES

Most years can be represented by a small number of geographical patterns of above or below average rainfall.

These patterns indicate that conditions of abnormal rainfall are nearly continental in extent.

EXPANSION AND CONTRACTION OF ARID ZONE

This is a common characteristic of rainfall variability which is seen on modern paleohistorical time scales.

It indicates climatic interaction between tropical and extra-tropical areas.

LENGTH AND INTENSITY OF THE RAINY SEASON

The rainy season appears to be both longer and more intense during wet years; in dry years it is not shorter than normal but merely weaker.

SOURCE: Revised, from Nicholson 1982.

Departures tend to be uniformly negative or positive throughout the Sahel, Sudan, and Sahara and are generally of the same size both north and south of the desert. A less commonly occurring pattern includes drought in the eastern or western Sudano-Sahelian zone, but not throughout the zone.

- These patterns tend to be continental in extent; abnormal conditions in the Sahel tend to be coupled with abnormal conditions in the analogous semiarid regions of southern Africa. This characteristic is confirmed by numerous analyses and is illustrated by Figures B-6 and B-7, showing rainfall departures in southern Africa corresponding to anomalous years in the Sahel and rainfall fluctuations in the northern and southern Kalahari during the present century. The continental extent of rainfall anomalies is strongly apparent in the years 1950 and 1970 (Figure B-8).

- There is a pronounced tendency for rainfall fluctuations to manifest themselves as expansions and contractions of the Sahara, rather than a north-south displacement of the desert. This is true of the four major patterns of rainfall fluctuations (Figure B-5); in each case, rainfall departures of the same sign affect the northern and southern fringes of the Sahara simultaneously. This characteristic is evident also when monthly rainfall totals over West Africa are plotted as a function of latitude; the size of the "rainless" areas changes considerably in time, expanding during the years of Sahelian drought.

- In the semiarid, sub-Saharan regions, the length of the rainy season during drought years does not significantly differ from its normal duration except in the most northern extreme of the Sahel; instead it tends to be less intense than usual. During wetter years, the season tends to be both longer and more intense. This becomes evident by analyzing at various latitudes the number of months with rainfall in excess of 25 mm and the number of months in excess of 100 mm. These values are respectively used to define the duration and intensity of the rainy season. At 15°N, 0°W (approximately the position of Timbuktu), for example, the "normal" season is 5 months, with 2 of those months having more than 100 mm of rain (Table B-1). During the 6 drought years surveyed, the season is also 5 months, but rainfall exceeds 100 mm in only 1 month. During the 9 wet years surveyed, the season is 6 or 7 months, 3 of which exceed 100 mm. The only area in which the season appears to be shorter during drought years is the narrow Sahelo-Saharan zone between approximately 18°N and 20°N, a small part of the drought-stricken area.

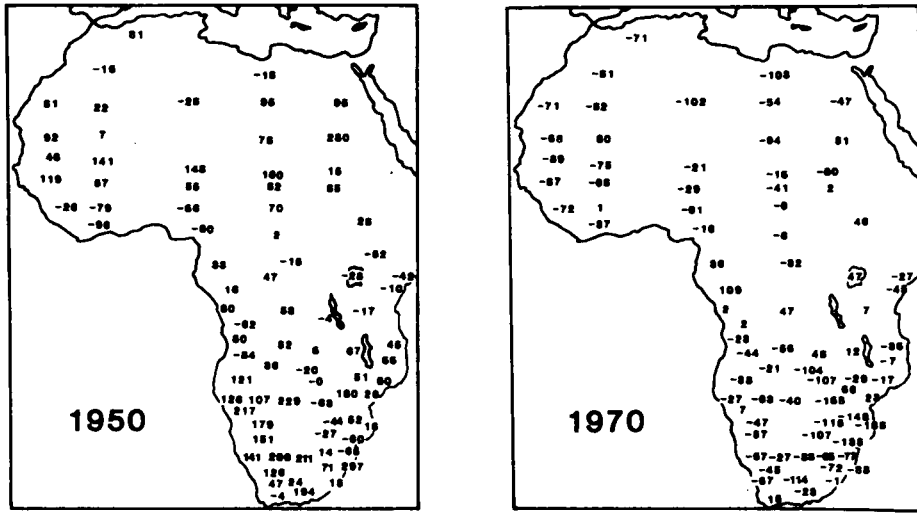

FIGURE B-8 Regional rainfall for 1950 and 1970 (percentage above or below normal). (Source: Nicholson 1982)

SUMMARY

In dealing with the Sahelian environment, climate must be treated as a variable, not a constant. Climatic fluctuations in the region are abrupt and extreme; rainfall in one decade may be nearly double that of the next. Both wet and dry episodes may persist on time scales of one to several decades, creating a false sense of "normal" conditions. Drought is an inherent characteristic of the Sahelian environment that recurs at inconstant intervals. While human impact can degrade the landscape, the most severe consequences--such as intense desertification--occur when human misuse is coupled with climatic variations. The search for simplistic solutions must stop, and the complexities of the region's climate must be realized. Sahelian rainfall cannot as yet be predicted on an annual or seasonal basis; long-range forecasts of drought or even drying trends cannot be substantiated.

From a climatic viewpoint, the best approach to development in the Sahel is one in which life-styles and support systems adapt to--and, when possible, make use of--the nature of the region's climate and fragile environment. The possibility that human activities in the Sahel can affect its climate cannot be ruled out. On the contrary,

there is much evidence that the landscape changes produced by a period of drought can "feed back" on the system and reinforce the drought. These changes include the vegetation cover, the reflectivity of the ground surface (due to removal of vegetation and changes of soil quality), and the storage of soil moisture. These changes can occur through human activity even in the absence of drought; but when agriculture and pastoralism are extended into marginal areas during wet years, the environment sustains greater damage when drought recurs. Conservative land use strategies, protection of the vegetation, and soil conservation minimize the risk and reduce the potential impact that human use of the system might have on climate through feedback processes. If, however, environmental degradation is of a magnitude large enough to actually have an impact on climate, the effect is likely to prolong and intensify major droughts. We are still striving to gain a complete understanding of Sahelian climate. Conclusive knowledge of the possible impact of mankind and environment on the region's climate requires continuous monitoring of the system.

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36. **Producer Gas: Another Fuel for Motor Transport.** 1983. During World War II Europe and Asia used wood, charcoal, and coal to fuel over a million gasoline and diesel vehicles. However, the technology has since been virtually forgotten. This report reviews producer gas and its modern potential.

38. **Supplement to Energy for Rural Development: Renewable Resources and Alternative Technologies for Developing Countries.** 1981. 240 pp. Updates the 1976 BOSTID publication and offers new material on direct and indirect uses of solar energy. Provides index to both volumes.

39. **Proceedings, International Workshop on Energy Survey Methodologies for Developing Countries.** 1980. 220 pp. Report of a 1980 workshop organized to examine past and ongoing energy survey efforts in developing countries. Includes reports from rural, urban, industry, and transportation working groups, excerpts from 12 background papers, and a directory of energy surveys for developing countries.

Technology Options for Developing Countries

8. **Ferrocement: Applications in Developing Countries.** 1973. 89 pp. Assesses state of the art and cites applications of particular interest to developing countries—boat building, construction, food and water storage facilities, etc.

14. **More Water for Arid Lands: Promising Technologies and Research Opportunities.** 1974. 153 pp. Outlines little-known but promising technologies to supply and conserve water in arid areas. (French language edition is available from BOSTID.)

21. **Making Aquatic Weeds Useful: Some Perspectives for Developing Countries.** 1976. 175 pp. Describes ways to exploit aquatic weeds for grazing, and by harvesting and processing for use as compost, animal feed, pulp, paper, and fuel. Also describes utilization for sewage and industrial wastewater treatment. Examines certain plants with potential for aquaculture.

28. **Microbial Processes: Promising Technologies for Developing Countries.** 1979. 198 pp. Discusses the potential importance of microbiology in developing countries in food and feed, plant nutrition, pest control, fuel and energy, waste treatment and utilization, and health.

31. **Food, Fuel, and Fertilizer for Organic Wastes.** 1981. 150 pp. Examines some of the opportunities for the productive utilization of organic wastes and residues commonly found in the poorer rural areas of the world.

34. **Priorities in Biotechnology Research for International Development: Proceedings of a Workshop.** 1982. 261 pp. Report of a 1982 workshop organized to examine opportunities for biotechnology research in developing countries. Includes general background papers and specific recommendations in six areas: 1) vaccines, 2) animal production, 3) monoclonal antibodies, 4) energy, 5) biological nitrogen fixation, and 6) plant cell and tissue culture.

Biological Resources

16. **Underexploited Tropical Plants with Promising Economic Value.** 1975. 187 pp. Describes 36 little-known tropical plants that, with research, could become important cash and food crops in the future. Includes cereals, roots and tubers, vegetables, fruits, oilseeds, forage plants, and others.

22. **Guayule: An Alternative Source of Natural Rubber.** 1977. 80 pp. Describes a little-known bush that grows wild in deserts of North America and produces a rubber virtually identical with that of the rubber tree. Recommends funding for guayule development.

25. **Tropical Legumes: Resources for the Future.** 1979. 331 pp. Describes plants of the family Leguminosae, including root crops, pulses, fruits, forages, timber and wood products, ornamentals, and others.

37. **The Winged Bean: A High Protein Crop for the Tropics.** (Second Edition). 1981. 59 pp. An update of BOSTID's 1975 report of this neglected tropical legume. Describes current knowledge of winged bean and its promise.

47. **Amaranth: Modern Prospects for an Ancient Crop.** 1983. Before the time of Cortez grain amaranths were staple foods of the Aztec and Inca. Today this extremely nutritious food has a bright future. The report also discusses vegetable amaranths.

Innovations in Tropical Reforestation

26. **Leucaena: Promising Forage and Tree Crop for the Tropics.** 1977. 118 pp. Describes *Leucaena leucocephala*, a little-known Mexican plant with vigorously growing, bushy types that produce nutritious forage and organic fertilizer as well as tree types that produce timber, firewood, and pulp and paper. The plant is also useful for revegetating hillslopes, providing firebreaks, and for shade and city beautification.

27. **Firewood Crops: Shrub and Tree Species for Energy Production.** 1980. 237 pp. Examines the selection of species suitable for deliberate cultivation as firewood crops in developing countries.

35. **Sowing Forests from the Air.** 1981. 64 pp. Describes experiences with establishing forests by sowing tree seed from aircraft. Suggests testing and development of the techniques for possible use where forest destructions now outpaces reforestation.

40. **Firewood Crops: Shrub and Tree Species for Energy Production.** Volume II. 1983. A continuation of BOSTID report number 27. Describes 27 species of woody plants that seem suitable candidates for fuelwood plantation in developing countries.

41. **Mangium and Other Fast-Growing Acacias for the Humid Tropics.** 1983. 63 pp. Highlights ten acacias species that are native to the tropical rain forest of Australasia. That they could become valuable forestry resources elsewhere is suggested by the exceptional performance of *Acacia mangium* in Malaysia.

42. **Calliandra: A Versatile Small Tree for the Humid Tropics.** 1983. 56 pp. This Latin American shrub is being widely planted by villagers and government agencies in Indonesia to provide firewood, prevent erosion, yield honey, and feed livestock.

43. **Casuarinas: Nitrogen-Fixing Trees for Adverse Sites.** 1983. These robust nitrogen-fixing Australasian trees could become valuable resources for planting on harsh, eroding land to provide fuel and other products. Eighteen species for tropical lowlands and highlands, temperate zones, and semiarid regions are highlighted.

Managing Tropical Animal Resources

32. **The Water Buffalo: New Prospects for an Underutilized Animal.** 1981. 118 pp. The water buffalo is performing notably well in recent trials in such unexpected places as the United States, Australia, and Brazil. Report discusses the animal's promise, particularly emphasizing its potential for use outside Asia.

44. **Butterfly Farming in Papua New Guinea.** 1983. 36 pp. Indigenous butterflies are being reared in Papua New Guinea villages in a formal government program that both provides a cash income in remote rural areas and contributes to the conservation of wildlife and tropical forests.

45. **Crocodiles as a Resource for the Tropics.** 1983. 60 pp. In most parts of the tropics crocodilian populations are being decimated, but programs in Papua New Guinea and a few other countries demonstrate that, with care, the animals can be raised for profit while the wild populations are being protected.

46. **Little-Known Asian Animals with a Promising Economic Future.** 1983. 133 pp. Describes banteng, madura, mithan, yak, kouprey, babirusa, Javan warty pig and other obscure, but possibly globally useful wild and domesticated animals that are indigenous to Asia.

General

29. **Postharvest Food Losses in Developing Countries.** 1978. 202 pp. Assesses potential and limitations of food-loss reduction efforts; summarizes existing work and information about losses of major food crops and fish; discusses economic and social factors involved; identifies major areas of need; and suggests policy and program options for developing countries and technical assistance agencies.

30. **U.S. Science and Technology for Development: Contributions to the UN Conference.** 1978. 226 pp. Serves the U.S. Department of State as a major background document for the U.S. national paper, 1979 United Nations Conference on Science and Technology for Development.

The following topics are now under study and will be the subjects of future BOSTID reports:

- **Leucaena: Promising Forage and Tree Crop for the Tropics** (Second Edition)
- **Jojoba**

For a complete list of publications, including those that are out of print and available only through NTIS, please write to BOSTID at the address above.

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