WORLD ATLAS OF DESERTIFICATIO

SECOND EDITION

World Atlas of Desertification

Second Edition

Co-ordinating Editors

Nick Middleton
University of Oxford

and

David Thomas
University of Sheffield

UNEP
For Life on Earth

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The lands in the arid, semiarid and dry subhumid climate belts (in tropical or temperate but not arctic zones), are referred to as the 'susceptible drylands'. (The hyperarid lands are deserts already and are therefore not included as susceptible drylands.) Since desertification, by definition, occurs in the arid, semiarid and dry subhumid zones, the lands in these zones are described as susceptible.

Desertification is land degradation in arid, semiarid and dry subhumid areas resulting from various factors, including climatic variations and human activities. This definition was negotiated and agreed at Rio and included in the United Nations Convention to Combat Desertification in Those Countries Experiencing Serious Drought and/or Desertification, particularly in Africa.

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Preface

Desertification directly affects, or puts at risk, the livelihoods of more than one billion people who are directly dependent on the land for their survival.

Desertification is the degradation of productive drylands, including the Savannas of Africa, the Great Plains and the Pampas of the Americas, the Steppes of Asia, the 'outback' of Australia and the margins of the Mediterranean. Desertification is occurring to such a degree that some lands can no longer sustain life.

Drylands have been central in the evolution of humankind. These are the lands that sustained our transition from hunting to pastoralism and agriculture. They still provide much of our grain and livestock and provide the habitat that supports most of the remaining big game animals. They also support a burgeoning human population, but with increasing insecurity as the available land per captia diminishes.

This *World Atlas of Desertification* presents an overview of these lands. It represents a substantial advance on the first edition. The text has been completely revised and there are two entirely new sections. Section 3 presents the latest assessment of Asia while Section 4 covers a range of issues including linkages with poverty, biodiversity and global warming, results of new studies in Kenya and the Aral Sea basin and a look at some recent success stories, as well as a reflection on the response of the USA to the Dust Bowl of the 1930s.

The atlas is designed for those working on desertification at the global, regional and national levels. It is intended to facilitate the work of governments at the Conference of the Parties of the Convention to Combat Desertification (CCD) and it is also aimed at a wider audience to be accessible through libraries, universities and schools. It provides a blend of data, images and text that enables the reader to gain a more comprehensive view of the global problem of desertification. The database provides part of UNEP's contribution to the work of the CCD's Committee on Science and Technology in furthering the assessment and dissemination of information on desertification.

UNEP's involvement with desertification spans more than 20 years. UNEP was entrusted with the co-ordination of the United Nations Plan of Action to Combat Desertification and tried to rally support for its implementation in the field. Much of UNEP's work focused on improving the definition and the knowledge and understanding of desertification.

It is very much to the credit of my distinguished predecessor Dr Mostafa Tolba that by the time of the Earth Summit in 1992 in Rio de Janeiro, a definition had finally been agreed, a more reliable global assessment had been carried out, and the need for an intergovernmental convention on desertification was acknowledged and demanded in Agenda 21. This treaty came into force on 26 December 1996.

The first edition of the atlas was prepared in time for the Earth Summit, to illustrate the global nature of this problem. In the Preface, Dr Tolba explained his hope 'that the information contained in this atlas, and arising from further research, will press home to politicians and policy makers the urgency of the need for action'.

The atlas was well received by many as a demonstration of the state of the art of assessing desertification. *The Holocene* called it 'by far the best illustrated source of information about the global extent and severity of desertification that has yet been published'.

Since the Earth Summit much new work on desertification and related issues has been done. This has included research and applied work on methods to increase carbon sequestration, to modify global warming, to improve sustainability at village level, to focus on the social dimensions of desertification, to reduce land degradation, to reduce destruction of forests especially for fuelwood use, to mitigate drought, to preserve biodiversity, and the negotiation of the most appropriate implementation methodology for the Convention to Combat Desertification

Through the publication of this second edition of the atlas, the continuing challenges are evident. Emphasis must be placed on the need to further improve the global assessment of desertification; to better determine the potential impact of global warming on desertification, and *vice versa*; to improve the prediction and mitigation of drought; to obtain a better understanding of the nature and dynamics of vegetation growth and its ecology in the drylands; and the need for much work on the social, economic and human dimensions of environmental management in the drylands and the interactions between physical degradation and social consequences.

Despite all the efforts, desertification continues apace. The link between desertification and poverty is direct and intimate. Existing land management practices in the drylands are not all sustainable and do have a global impact. To care for our people we must care for our land and protect the land that feeds us. I hope that this improved atlas will provide a useful tool in taking up this urgent challenge.

Elizabeth Dowdeswell
Executive Director
United Nations Environment Programme

Foreword

The United Nations Environment Programme is proud to present the second, revised and improved edition of the *World Atlas of Desertification*.

Desertification is land degradation occurring in the arid, semiarid and dry subhumid areas of the globe. These areas are referred to as 'the susceptible drylands' and they cover 40 per cent of the world's land surface. They are the focus of this atlas and of the United Nations Convention to Combat Desertification (CCD). New data show that they are the home of more than 1 billion people.

As the reprint of the first edition of the atlas sold out, UNEP and the publishers Arnold decided to prepare a second, much improved edition in time for the first Conference of the Parties of the CCD in September 1997. This volume is the result of that work. The first edition of the atlas was praised by many as an essential reference on the extent of desertification. But it was also criticised, partly because of the subjective nature of the database and particularly for the absence of references, explanations and sources. These shortcomings have been addressed in the revised edition to the maximum possible extent. A new, much more detailed database has been launched at the national level in Asia and this is demonstrated in Section 3. Section 4 is also completely new with up-to-date coverage of issues and studies on various topics. Although the database for Sections 1 and 2 is unchanged the accompanying text has been substantially revised to reflect new work.

Background

The first world map of desertification was produced by FAO/UNESCO/WMO in time for the United Nations Conference on Desertification held in 1977 in Nairobi. Most of the subsequent national, regional and global assessments of desertification undertaken by UNEP and others were based on the FAO/UNEP/ UNESCO (1983) 'provisional methodology' for the assessment and mapping of desertification. The 'provisional methodology' was later made use of by UNEP and its partners in the 1987–90 period to produce the first global assessment of human-induced soil degradation (GLASOD). This provided considerable information for the database of the first edition of this atlas.

One of the major problems in the 1970s and 1980s was that there was no consensus on how to define desertification. Without clear agreement on definition, there was no possibility of achieving an agreed assessment database. UNEP worked for 15 years to get desertification recognised as a significant global issue, to achieve international agreement on its definition, to improve the databases and to bring about a greater effort in implementing preventative measures.

In early 1990, UNEP brought together a team of international experts and international organisations to propose an internationally acceptable definition. Their definition, used for the first edition, was discussed, then slightly modified and adopted at the Earth Summit at Rio in 1992. The definition of desertification adopted by UNCED in Agenda 21 and embodied in the CCD is 'land degradation in arid, semiarid, and dry subhumid areas resulting from various factors including climatic variations and human activities'. The definition delimits the areas where desertification occurs and addresses its causes, emphasising climatic aspects (e.g. short-term droughts, long-term climate fluctuations), and human-induced land degradation, while not ruling out other factors.

The first edition of the *World Atlas of Desertification*, which was published in 1992 to coincide with the Earth Summit, displayed the existing state of knowledge of desertification and of its extent and possible solutions. It demonstrated that desertification is a major economic, social, and environmental problem affecting more than 110 countries in all regions of the world.

Agenda 21 included a chapter (12) on 'Managing Fragile Ecosystems: Combating Desertification and Drought'. This recommended, *inter alia*, better determination of the nature, extent and socio-economic impacts of desertification at local and national levels. It also recommended the establishment of an intergovernmental negotiating committee to prepare a convention to combat desertification.

The Convention to Combat Desertification was negotiated between May 1993 and 17 June, 1995. It was signed in Paris in October 1995 and subsequently by 115 countries and the European Union. After 50 countries had ratified the convention, it came into force on 26 December 1996. The first Conference of the Parties was scheduled for September 1997 in Rome.

The convention is innovative, emphasising the need for community-based action in the field. With regard to science, it provides for a Committee on Science and Technology (CST) made up of members appointed by governments. This committee is to focus on a global network approach to combat desertification; on the establishment of benchmarks and indicators to assess and monitor dryland degradation; on inventories of traditional and local technology, knowledge, know-how and practices; and on the establishment of research priorities.

Since the first edition of the atlas in 1992, efforts to improve the assessment and monitoring of desertification have continued. During the last 5 years, more than 110 nations have prepared national reports for the Earth Summit, for UNEP's Governing Council, the Commission on Sustainable Development, the UN General Assembly and for the meetings of the Intergovernmental Negotiating Committee for the Convention to Combat Desertification. These reports describe the extent of desertification in the countries; what steps are being taken or planned; and the continued worsening of the situation in many of the countries.

Although much of this information is of too general a nature to be incorporated into the atlas database, UNEP has continued to encourage and support the gathering and presentation of new and improved data on the drylands.

The assessment database

Several data sets are used in the compilation of the atlas. These include a global soils degradation database (GLASOD), a soils degradation database for continental Africa, a global climatic database and a more refined soils degradation database (ASSOD) that has been developed in Asia.

The basic indicator of desertification in this atlas is human-induced soil degradation. Data are available for the global land surface on the types, severity, causes and extent of human-induced soil degradation. These are supported by data on various other elements important in the drylands equation, such as climatic variability and vegetation degradation. The environment is highly dynamic in the dryland areas, hence it is often very difficult to separate natural processes of land degradation from those resulting from human activities.

The aridity zones (the arid, semiarid and dry subhumid areas where by definition, land degradation is desertification), are based on the relationship between precipitation and potential evapotranspiration, which forms an index of moisture deficit termed the Aridity Index. The maps of climate surfaces, including aridity zones, are derived from the data sets held at the Climatic Research Unit of the University of East Anglia, UK. The calculations carried out to determine the Aridity Index and aridity zones are described fully in the Introduction to this edition.

Although GLASOD was by necessity a somewhat subjective assessment it was extremely carefully prepared by leading experts in the field. It remains the only global database on the status of human-induced soil degradation, and no other data set comes as close to defining the extent of Desertification at the global scale.

In order to improve on GLASOD, a new approach has been launched by the International Soil Reference and Information Center, the Food and Agriculture Organization, the relevant international institutions and UNEP. This has commenced in South and South-east Asia. The results are described and displayed in Section 3. The GLASOD approach has been modified and refined to produce an Assessment of the Status of Human-induced Soil Degradation linking degradation with productivity.

The ASSOD survey was carried out through national institution members of the Asia Network on Problem Soils. Actual degradation assessments were made for 4450 mapping units (compared with 320 for GLASOD for the same area). The classifications include soil characteristics as well as terrain properties and represent a considerable advance in detail, accuracy and scale over GLASOD. ASSOD has so far involved 17 countries in South and South-East Asia. Seven of these (China, India, Myanmar, Nepal, Pakistan, Sri Lanka and Thailand) contain areas of susceptible drylands where desertification is an actual or potential problem. It is hoped that the ASSOD work will be extended to cover the rest of the globe as soon as possible.

Content

This edition of the atlas has a technical introduction and four sections. The Introduction provides the background and information needed to explain the technical basis of the atlas.

Section 1 presents the best available global assessment of desertification and related issues. The text which accompanies each map has been completely revised and updated with many new references reflecting work done since the first edition was published. A large part of Section 1 is devoted to relationships between climatic factors and desertification, particularly the variability of rainfall, which is an important aspect of dryland climates.

Section 2 presents the higher resolution GLASOD survey of human-induced soil degradation in Africa and related issues such as vegetation distribution. The revised text accompanying each map provides examples of the issues under consideration and the complexities of the interrelationship between degradation causes and effects.

Section 3, which is totally new, incorporates a number of methodological developments. In the ASSOD assessment of Asia, greater emphasis is given to generating assessments at country level rather than at regional level. Emphasis is also given to trends in degradation and to the impact of desertification on agricultural productivity.

Section 4 highlights, along with national and local databases and assessments, the interlinkages between desertification and other global environmental issues such as soil salinization, climate change, carbon sequestration, and biological diversity. The social dimensions of desertification, showing links between land degradation, human population and migration and socio-economics is an important part of this section.

The section also highlights success stories in combating desertification ranging from soil rehabilitation in north-western China to overcoming waterlogging and salinity in Western Australia and the continuing challenges of the Sahel. A new global initiative called the World Overview of Conservation Approaches and Technologies (WOCAT) is described here giving eastern and southern Africa as examples. The WOCAT case studies give information on severity of erosion, dominant soil and water conservation techniques and the impact of the conservation technologies on cropland and grazing areas.

The social impact continues

Today large areas of drylands are experiencing conditions comparable to the environmental disaster that occurred 60 years ago in the semiarid region of the United States of America. That experience was a pivotal event in the formation of dryland management practices which reversed the course of desertification in the western USA. However, in this area economic and political forces have encouraged new forms of unsustainable resource use in more recent times. The key to success in the battle against desertification is the availability of adequate financing with total commitment at the political level and at all levels of government and society to avoid a reccurrence. If the appropriate level of commitment and financing existed the problem could be overcome everywhere.

World drylands are high-risk environments. Erratic rainfall coupled with land degradation and inadequate technology and inputs results in fluctuating food production. The need for increased but sustainable food production is emerging as a major environmental concern in the drylands. The World Food Summit, in 1996, emphasised the importance of food security as a global issue.

The link between desertification and poverty is direct and intimate. Land degradation is an important reason for the steady decline in rural income resulting in a complex of demographic, economic and social changes. The process affects all those who depend on the land as a basic resource, whether for crops, livestock or fuelwood.

In order to increase the security of the millions at risk, Agenda 21 recommended implementation of urgent direct preventive measures in the drylands that are vulnerable but not yet affected (4.1 billion ha), and in those only slightly desertified drylands (430 million ha). It also recommended urgent implementation of direct corrective measures in moderately to extremely desertified drylands with a view to restoring and sustaining their productivity. These areas now amount to about 600 million ha.

There is now increasing understanding, helped by the CCD, that desertification is not just a physical issue but a life or death social issue. There is still much to be done to improve the data available on social and cultural patterns and on the economics of improved environmental management at the field level. Work has begun on better assessments of the costs of depleting soil and degrading land but much more effort is needed to draw attention to the economic consequences of degrading the land resource base.

Conclusions

The work of revising this atlas again draws attention to the remaining inadequacies of the information base and of the understanding and treatment of desertification. This highlights the need for increased attention to be given to the assessment and monitoring of change in dryland environments.

UNEP hopes that needs in this area will be recognised so that there will be increased support for improving the scientific assessment and monitoring of desertification and its alleviation, as well as rapid investigation of the social aspects of the issue. Combating desertification involves achieving sustainable management of the drylands environment so as to meet the needs of the population.

Among the more significant conclusions that have emerged during the preparation of this edition of the atlas are the needs:

- to continue with the new ASSOD approach towards completion of a new global assessment; if possible by the year 2002, 10 years on from Rio;
- to increase understanding of the social and human dimensions of desertification and on the interactions between physical degradation and social consequences;
- to improve the climatic surfaces and aridity index logarithms to better determine the potential impact of climatic variations on desertification and *vice versa*, and to improve the prediction and mitigation of drought;
- to obtain a better understanding of the nature and dynamics of vegetation growth and resilience in the susceptible drylands;
- to improve knowledge of on-site and off-site economic impacts and relationships of desertification;
- to improve the knowledge of the migration issue and its causes and effects;
- to broaden the approach to assessing and monitoring change in the susceptible drylands to incorporate additional characteristics including water, social and economic indicators.
- to draw more definitive conclusions about the issue of burning cropland and grasslands;
- to record, respect, evaluate and develop traditional knowledge and traditional practices;
- to carry out further research on carbon storage and on the feasibility of strategies to enhance carbon sequestration; and
- to encourage throughout the drylands the practice of sustainable management to ensure that the long-term needs of the land are respected at the same time as meeting immediate productivity goals.

W. Franklin G. Cardy
Executive Coordinator
Natural Resources and Director Land
United Nations Environment Programme

Acknowledgements and Abbreviations

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ABBREVIATIONS

ASSOD Assessment of the Status of Human-Induced Soil Degradation in South and Southeast Asia
CAC soil carbonate carbon
CCD UN Convention to Combat Desertification
CDE Centre for Development and Environment (Berne, Switzerland)
CESAR Centre for Environmental Studies and Resource Management
CILSS Permanent Inter-State Committee for Drought Control in the Sahel
CITES Convention on International Trade in Endangered Species of Wild Fauna and Flora
CPD Centres of Plant Diversity
CPR common property resource
CST Committee on Science and Technology (of the CCD)
DRU desertification response unit
EC electrical conductivity
ECOWAS Economic Community of West African States
ESP exchangeable sodium percentage
FAO Food and Agriculture Organization of the United Nations
GCM general circulation model
GDP gross domestic product
GEMS Global Environment Monitoring System
GIS geographic information system
GLASOD Global Assessment of Human-Induced Soil Degradation
GRASS grass cover for the recovery of arid and semiarid soils
GRID Global Resource Information Database
GVI Global Vegetation Index
ICIV Institut de la Carte Internationale de la Végétation
IGAD Intergovernmental Authority on Development (formerly IGADD Intergovernmental Authority on Drought and Development)
ISRIC International Soil Reference and Information Centre
MEDALUS Mediterranean Desertification and Land Use
NAFTA North American Free Trade Agreement
NCGIA National Center for Geographic Information and Analysis
NGO non-governmental organisation
OAR open access regime
ODI Overseas Development Institute (in UK)
PDES Plan de Développement Economique et Social (in Senegal)
PET potential evapotranspiration
SCARP Salinity Control and Reclamation Project (in Pakistan)
SEPASAL Survey of Economic Plants for Arid and Semi-Arid Lands
SOC soil organic carbon
SOTER World Soils and Terrain Digital Database
SWC soil and water conservation
TM Thematic Mapper
UNCED UN Conference on Environment and Development (the 'Earth Summit')
UNCOD United Nations Conference on Desertification
UNDP United Nations Development Programme
UNEP United Nations Environment Programme
UNESCO United Nations Educational, Scientific and Cultural Organization
UNSO UNDP Office to Combat Desertification and Drought
USDA United States Department of Agriculture
WMO World Meteorological Organization
WOCAT World Overview of Conservation Approaches and Technologies
WVI World Vision International
XIBPDR Xinjiang Institute of Biology, Pedology and Desert Research

Introduction

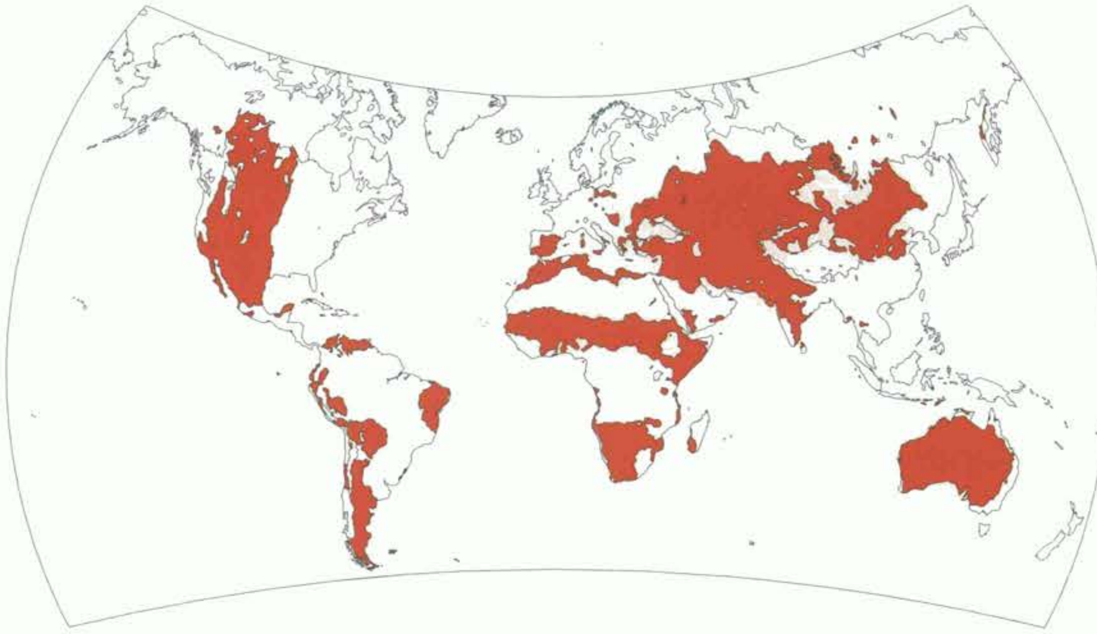
Desertification – the background

More than 6.1 billion ha, 47.2% of the Earth's land surface, is dryland. Nearly 1 billion ha of this area are naturally hyperarid deserts, with very low biological productivity. The remaining 5.1 billion ha are made up of arid, semiarid and dry subhumid areas, part of which have been degraded since the dawn of civilisation while other parts of these areas are still being degraded today. These lands are the habitat and source of livelihood for about a fifth of the world's population. They are areas experiencing pressures on the environment caused by human mismanagement, problems that are accentuated by the persistent menace of recurrent drought.

The term desertification was first coined in West Africa in 1949 by a French forester (Aubréville 1949) to describe the way in which it was perceived that the Sahara Desert was expanding to engulf desert-marginal savanna grasslands. The term was raised as a major environmental issue at the United Nations Conference on Human Environment, Stockholm 1972, at which the United Nations Environment Programme (UNEP) was established. Desertification reached a wider audience in the 1970s when international attention was focused on the plight of the drought-stricken Sahel zone of Africa, south of the Sahara. One outcome of this attention was the United Nations Conference on Desertification (UNCOD), held in Nairobi in 1977 (UN 1977a and b). A world map of land degradation by desertification and a number of case studies from all continents were prepared for the conference to illustrate the phenomenon (UNESCO 1977, 1980). These studies indicated that desertification was not just happening in Africa, but in drylands the world over. Following the conference, UNEP was charged with co-ordinating the implementation of the United Nations Plan of Action to Combat Desertification which was adopted by the conference and endorsed by the United Nations General Assembly.

In 1984 a Desertification Hazards Map was produced in a co-operative venture between UNEP, the Food and Agriculture Organization of the United Nations (FAO), the United Nations Educational, Scientific and Cultural Organisation (UNESCO) and the World Meteorological Organization (WMO). This was accompanied by a Provisional Methodology for the Assessment and Mapping of Desertification (UNEP 1984). At the same time, a revised definition of the problem was produced, one of more than a hundred such definitions that have been used both in scientific and political circles (Glantz and Orlovsky 1983). The lack of an agreed definition of desertification, an inevitable consequence of the issue's complexity, has been one aspect of a problem that has been characterised by controversy, conflicting opinions and differing interpretations (Hellden 1991, Thomas and Middleton 1994, Stiles 1995).

Susceptible drylands



Discussions in academic circles apart, the reason for interest in desertification is clear: degradation in drylands adversely affects the people who live there. To better address this issue, the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro requested the United Nations General Assembly to establish an intergovernmental committee to negotiate the Convention to Combat Desertification, which entered into force on 26 December 1996.

In order to solve a problem it is necessary to begin by defining the topic of investigation. With the problem defined, the researcher is able to plan the appropriate methods to study the problem, to discover where it occurs and what it looks like, how it works and what factors drive the processes, and thus to decide how best to solve it. Hence it is appropriate to begin this atlas with a definition of desertification.

This atlas uses the definition of desertification adopted by the Convention to Combat Desertification, which is: **Land degradation in arid, semiarid and dry subhumid areas resulting from various factors, including climatic variations and human activities. Land** in this context includes soil and local water resources, land surface and vegetation, including crops. **Degradation** implies reduction of resource potential by one or a combination of processes acting on the land. **Arid, semiarid and dry subhumid** climatic zones, defined in detail on pages 2–7, are collectively referred to as the 'susceptible drylands' (see Map). Hyperarid zones, the true deserts, are not considered to be prone to desertification because of their naturally very low biological productivity.

Sustainable land use

The concept of degradation is inseparable from that of sustainability (WCED 1987, Dowdeswell 1995). Expressed simply, a sustainable land use is one that is able to continue without degrading the land it is using. In this case the sustainability of a particular land use depends both on the properties of the resource and the way it is managed. The feature of a resource that dictates its sustainability under a particular use is its resilience, and it is important to note that the resilience of a resource will vary according to different land uses and indeed may vary from time to time, depending largely on natural seasonal and interannual variability and management practices and technologies.

A good way to measure the resilience of a particular unit of land is to look at its ability to recover after a disturbance. Such a disturbance may be climatic, for example a drought, or human-induced, such as vegetation clearance or soil tillage. The greater the ability of an area to recover within a particular time period, the greater its resilience. In essence, land degradation is the weakening of an area's resilience. One measure of land degradation in any particular area is the cost of rehabilitation.

It is important to emphasise that sustainable land use is a function of both the natural environment and human systems. Combating desertification therefore demands political, social, economic and educational approaches (Barraclough 1995) in addition to those approaches based largely in the physical sciences that have characterised much previous work in this area. This need for an integrated approach to sustainable environmental management in drylands is recognised and embodied in the Convention to Combat Desertification.

Variability in drylands

One difficulty of examining land degradation in dryland regions is their inherent variability. A definitive characteristic of drylands is their aridity which, put simply, means their lack of available moisture. An area can be said to be arid when its moisture inputs (precipitation) are exceeded by the moisture losses (evapotranspiration) plus any changes in storage (in rivers, groundwater, lakes and soil moisture). Various climatic and biological indexes have been devised to measure the aridity of drylands and these can be used to delimit dryland areas (see page 2). However, it is important to note that although drylands are usually deficient in moisture on an annual basis, the moisture inputs as precipitation are notoriously variable in both time and space (Williams and Balling 1996). The more arid dryland areas commonly receive all their 'average' annual precipitation in just a few days. The meterological systems responsible for rainfall in dryland regions are typically convective cells, formed in advected humid air masses, which means that rainfall falls in small specific zones.

The characteristics of dryland climate mean that these regions are highly dynamic on a timescale of weeks and months. Added to this is the variability of precipitation over longer timescales of years and decades. Droughts, in essence the absence of expected precipitation, are also characteristic of the dryland environment. A year, two years or several years may pass in which precipitation is well below average (Wilhite and Glantz 1985). Indigenous plants and animals have adapted their life cycles to cope with this inherent variability of the dryland ecosystem (Polis 1991, see also page 136). When the duration of below 'average' precipitation reaches the decadal scale, reference is often made to desiccation (Hare 1987). Beyond that, continued significant departures from a long-term average may enter the realm of climatic change (see pages 8–13).

Implications for the study of desertification

The implications of this environmental variability for the study of desertification are manifold. First, for the location of drylands themselves. In the pages of this atlas dryland areas are highlighted and given specific boundaries, but it is important to note that these boundaries are simply based upon average conditions and that true ground conditions vary greatly through variable timescales (Nicholson 1978, Hulme *et al.* 1992).

There are numerous implications for the human inhabitants of dryland regions (Mainguet 1995). The use to which land is put must be as dynamic as the environment and its resources if those resources are to be used sustainably. Fields that produce a good crop of millet for example during near-average rainfall years may have to be left fallow during a drought year, or be put to another use, if the land is not to be degraded. It is in areas where this flexible land use response does not occur that desertification takes place.

Perhaps the most serious implication of dryland variability in the present context is for the identification, monitoring and combating of desertification itself. Satellite imagery of vegetation greenness on the arid/hyperarid zone boundaries of drylands indicate that the natural variability in climate is reflected in a green vegetation dryland boundary that can fluctuate by up to 150 km from a wet year to a preceding dry year (Tucker *et al.* 1991). With such great natural fluctuations in the ground state of drylands, it is clearly necessary to monitor potential areas of desertification over a timescale of decades before it is possible safely to state that a particular region has suffered from land degradation in the form of desertification.

The need for data

Reliable identification of the locations and situations in which land degradation takes place is essential if viable remedies to the problem are to be reached. The actual reasons for unsustainable land use taking place in a particular area may well have their roots in social and economic conditions (Blaikie 1985). Unfortunately, accurate and reliable data on the extent and severity of desertification and the rate of its progress, based on actual ground surveys, are very scarce. The existing data are often controversial and open to doubts and criticisms (Thomas and Middleton 1994). Early attempts to assess the extent of desertification on the global scale, such as the world map prepared for UNCOD (UN 1977a), represent useful first steps towards the goal of solving the problem. But these first efforts had their own problems. Perhaps most importantly were the inconsistencies in the definitions used and the perception that desertification threatened all the world's drylands. However, when the prime motivation for studying desertification is to help relieve the problems faced by inhabitants in using dryland resources, it is clear that areas of hyperarid desert, which by definition have very sparse biological resources, should not be included in the areas of investigation. Very few people use these regions because of their lack of resources, and these areas can hardly become more desert-like. If an exception can prove a rule, then the very largely hyperarid country of Egypt is the major anomaly to this otherwise sound generalisation, since a reliable water supply allows permanent human occupation of the Nile Valley. Hence, for the purposes of this atlas, the regions deemed to be susceptible to desertification are those in the arid, semiarid and dry subhumid zones.

There may be grounds for criticising a global approach to the problem (e.g. Warren and Agnew 1988). The complex nature of desertification means that adequate assessment and consequent plans to counteract the problem can only be usefully carried out at the local scale, a central reason for the involvement of local populations and non-governmental organisations in approaches adopted by the Convention to Combat Desertification. None the less, a global perspective allows desertification to be evaluated relative to other global environmental issues. Furthermore, it is useful to develop a world-wide picture to identify 'hotspots' at the continental, national and local scales. For this reason this atlas is organised to start from a global perspective. Following the global section, appraisals of the problem at the continental level are presented for Africa (Section 2) and for South and South-East Asia (Section 3). Section 4 is designed to analyse in greater detail specific issues of particular importance to the study and resolution of desertification problems.

The thematic approach

The scarcity of detailed data on desertification and the many forms the problem can take has necessitated a fresh approach to assessing the problem. It is not realistic to produce a single map of world desertification. A more viable approach, first adopted in the previous edition of this atlas, is to map the many indicators of desertification and the factors that affect those indicators. Data sets for these indicators and variables are being compiled, but not all are currently available at the global scale. The basic indicator chosen for this atlas is human-induced soil degradation, and information is available on types, severity, causes and extent of human-induced soil degradation for the global land surface. These data are supplemented by various other data sets, principally on climate and vegetation.

The constraints of data availability mean that this atlas is not a definitive global statement. Human-induced soil degradation is an important indicator of desertification, but it is certainly not the only one (FAO/UNEP 1983). The degradation of vegetation is another important aspect of desertification. The loss of grassland resource potential due to excessive grazing of pastures, for example, may be as important on the world scale as soil degradation but, unfortunately, no adequate global database for vegetation degradation exists. There may be some overlap between vegetation degradation and soil degradation, such as in areas where vegetation cover has been lost, hence exposing soils to erosion, but there will also be areas where a degraded vegetation resource has no detectable impact on the soil resource, at least in the immediate term.

These deficiencies are highlighted in order to be clear about the basis of this volume. Nevertheless, this atlas represents a further step forward in the appreciation of desertification as a phenomenon and in the approach to its resolution. It builds on the foundation laid by the first edition by using new data and by highlighting emergent issues in the desertification debate. The methodology used to collect the data on human-induced soil degradation used in the first edition of this atlas, and presented here with more detailed analyses in Sections 1 and 2, has been further developed and applied to a continental sub-region in Section 3. These data are available in a computerised database and linked to geo-referenced mapping units by means of a geographic information system, or GIS. A GIS facilitates speedy analyses of the interactions of environmental variables, thus forming a bridge between monitoring and assessment, and environmental management. The system enables the user to visualise, model and quantify the interaction between many different parameters. These techniques have been used to produce the maps on the following pages.

Data sets

Several data sets have been used in the compilation of this atlas. Specific databases are discussed as they are introduced, but there are three which are central to the global and continental sections. These are a global soils degradation database, a global climatic database and a refined soils degradation database that has been used in South and South-East Asia.

The climatic database used to delineate drylands in this volume is the same as that used in the first edition of the atlas, and its development is explained in detail on pages 2–7. The data on soil degradation taken from the Global Assessment of Human-Induced Soil Degradation (GLASOD) are also the same as those used in the first edition. GLASOD is the result of a collaboration between UNEP and the International Soil Reference and Information Centre (ISRIC) in the Netherlands (Oldeman 1988). There are in fact two GLASOD databases, one of global, extent; the other, which is more detailed, is specific to Africa. The data contained in these databases are a compilation of existing information and of expert knowledge made available by more than 250 soil and environmental experts worldwide on the status of human-induced soil degradation in their specialist geographical regions. They contain information on the type of soil degradation, the degree, the area affected, and the major causes. It should be emphasised that these data refer only to *human-induced* soil degradation. More detailed appraisals of these data sets and their characteristics are given on pages 14–19 and 55–57. The GLASOD approach has been modified and refined to produce an Assessment of the Status of Human-Induced Soil Degradation in South and South-East Asia (ASSOD), a new GIS-based database (which is further explained on pages 77–79).

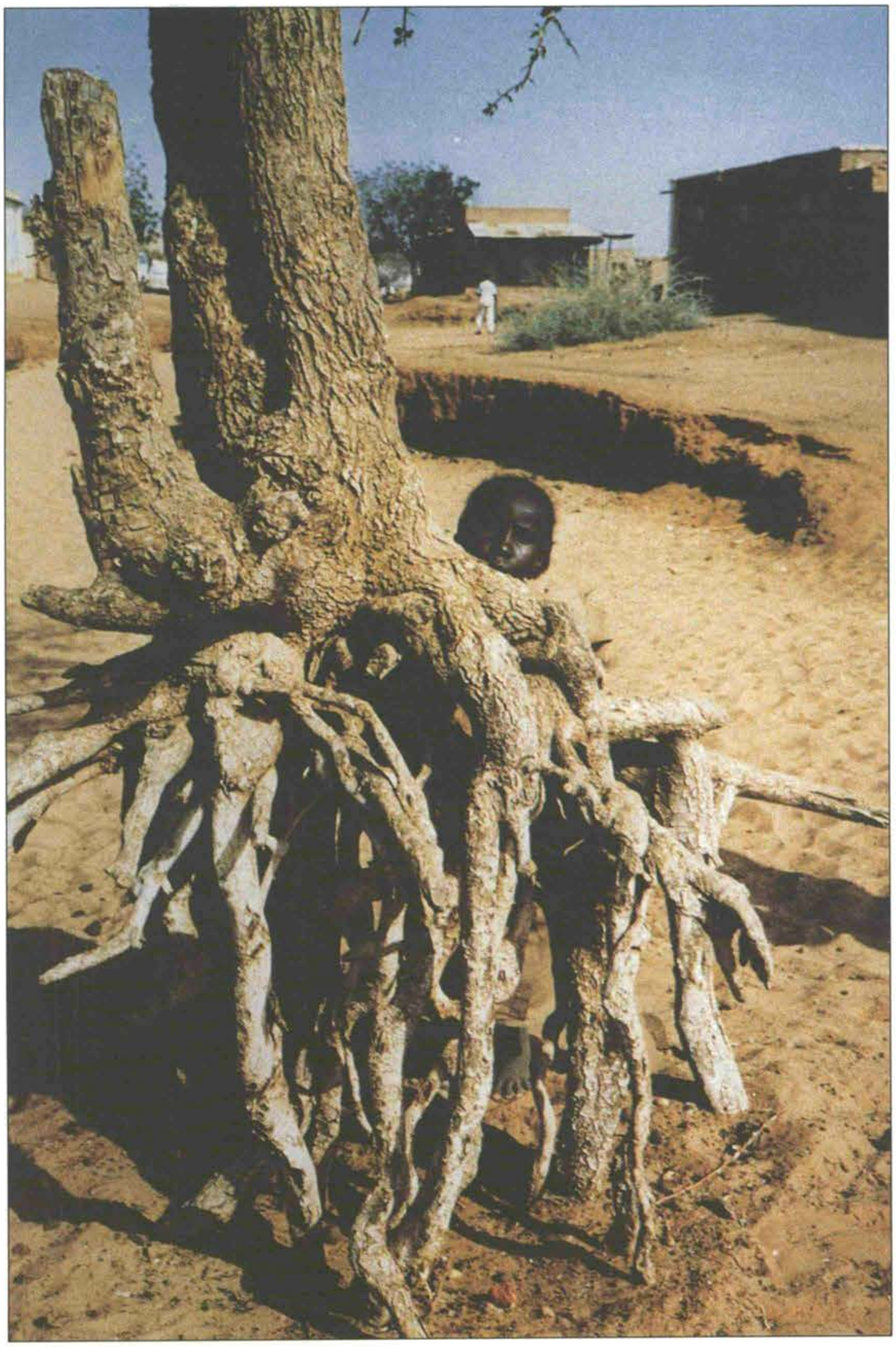
Using this atlas

It is important to note some of the limitations of the various methods for portraying the data contained in the databases outlined above. For the topics covered in this atlas at the global and continental scale, a world or continental map is accompanied by tables and diagrams. The world and continental maps are designed to give only a generalised impression of the distribution of phenomena concerned. The GLASOD and ASSOD databases contain information compiled for a series of polygon areas which are based upon physiographic land units. Although the limitations of producing a world map to be shown on the page of an atlas mean that an entire polygon is coloured according to a particular characteristic (red for every high degradation severity on page 15, for example) this does not necessarily mean that all the land within that unit possesses that characteristic. A map unit with an overall very high degradation severity may be characterised as such because moderate degradation processes occur in a very large part of the unit. Alternatively, the very high degradation severity may reflect extreme degrees of degradation that occur in a smaller part of the unit. However, the proportion of land within the unit that is severely damaged is recorded in the database, and the exact figure has been extracted to compile the tables and figures on the pages following the maps. Hence, areal data shown in tables and figures in the text are more accurate measures of the extent of the phenomena shown on the maps.

Part of a process

This second edition of the atlas represents a considerable advance on the first, both in its presentation and contents. As described above, however, it still can only be as good as the assessment data available. These data have been much improved and further assessments are currently under way.

This edition is designed to demonstrate the progress made, to provide in readily accessible form the state of the art, but also to emphasise and identify the work that still remains to be done to improve the state of knowledge of desertification.



UNEP/HUDA OSMAN ALL/TOPHAM

Global

1

Section 1 begins by outlining the methodology used to designate the aridity zones in the global, continental Africa and South and South-East Asia sections of this atlas. This is followed by an appraisal of climatic variability in drylands, an important characteristic of drylands which must be taken into account wherever the problems of desertification are studied. The remaining pages provide an overview of the problem by showing data on human-induced soil degradation at the global scale. More detailed assessments are presented in Sections 2 and 3.

Climatic Surfaces and Designation of Aridity Zones

At the global or regional scale, aridity zones can be defined by using a variety of approaches including drainage characteristics (de Martonne and Aufrère 1928), vegetation types (Shantz 1956) and by climatic characteristics (e.g. Penck 1894). Climatic approaches have the widest relevance, since climate influences many other environmental attributes and imparts important limitations on many human activities. Aridity can be simply defined as an overall moisture deficit in average climatic conditions (see, for example, Agnew and Anderson 1992). Various atmospheric and environmental factors contribute to the occurrence of aridity (see Williams and Balling 1996, Thomas 1997a), and these may vary in their occurrence and distribution through time (Hulme 1992, Balling 1994a). It is, therefore, important to outline the manner by which aridity zones have been defined and determined in this atlas, since these form the basis for the designation of regions in which desertification is examined in the subsequent sections.

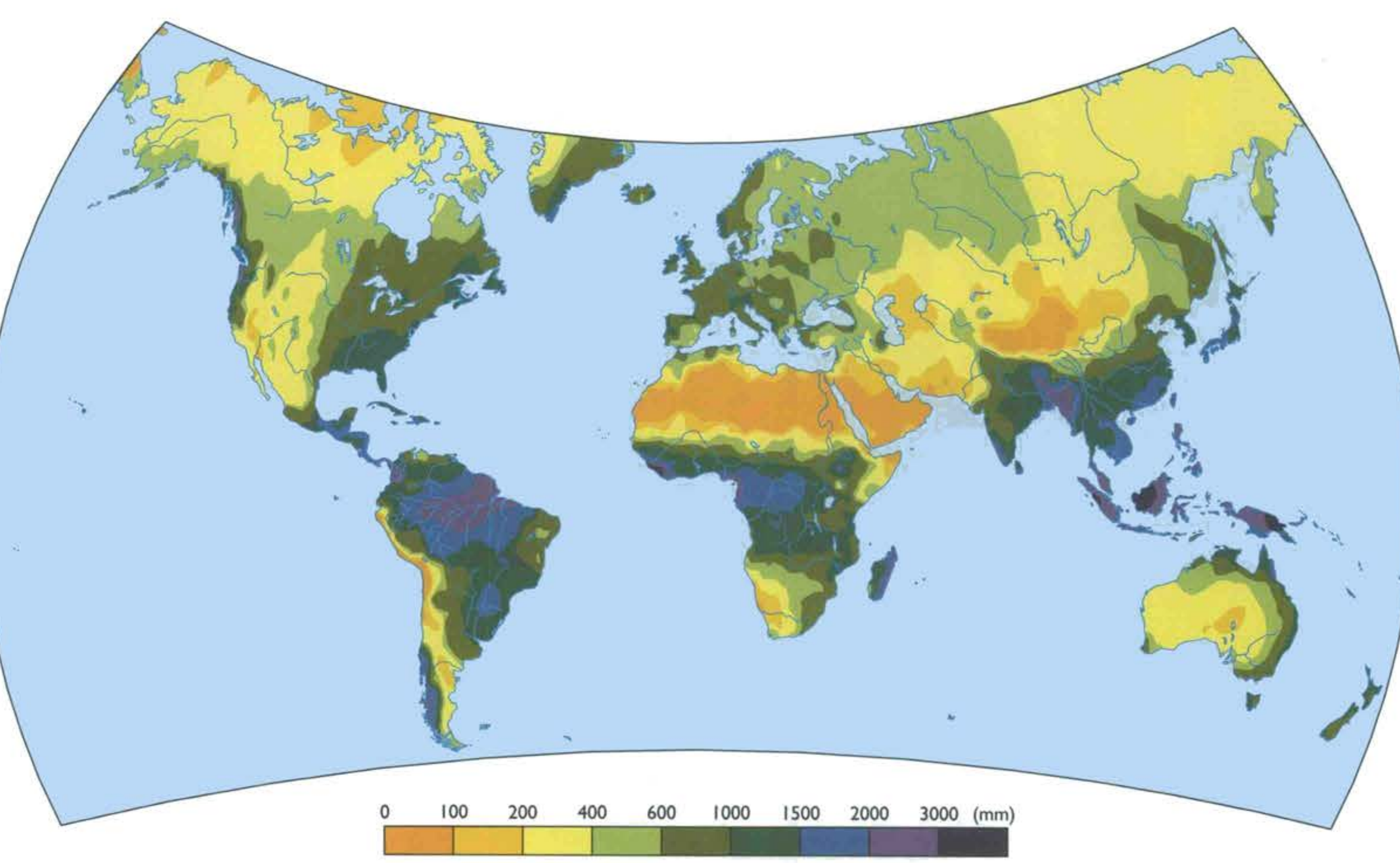
Aridity zones are based on an evaluation of the relationship between key climatic variables, creating an index of moisture deficit, termed the Aridity Index. To calculate index values it is necessary to compare incoming moisture totals with potential outgoing moisture (Kemp 1994). Although this is determined by the ratio of mean annual precipitation to mean annual atmospheric evaporative demand, usually expressed as potential evapotranspiration, there are a number of ways in which this index could be derived from climatic data (e.g. Meigs 1953, UN 1977a, Hulme 1996a, Le Houérou 1996). This makes it important to explain the way in which the Aridity Index used in this atlas has been determined, as well as outlining how it differs from other methods, for example that used for the FAO/UNESCO/WMO map of world arid regions (UNESCO 1977), produced for the 1977 survey of desertification (UN 1977a).

Data used in the determination of climate surfaces and aridity zones

The maps of climate surfaces, including aridity zones, were derived by the Climatic Research Unit (CRU), University of East Anglia, UK from their data sets of worldwide monthly mean precipitation and temperature values (Hulme and Marsh 1990). To produce maps of climate surfaces, data can either be interpreted on the basis of the total available data set, or for specifically designated time periods. When whole data sets are used, mean variable values are calculated for data from individual weather stations, regardless of the length of time for which data exist. This approach maximises the data potential, since it allows the full spatial and temporal ranges of data to contribute to the analysis. However, if this approach is taken other problems arise, particularly when comparisons are made between data from stations with different record lengths. This approach can lead to too much confidence being placed in values derived from data runs of only a few years, and is potentially a major difficulty for drylands, where marked climatic interannual variability is a normal feature (e.g. Le Houérou 1979, Agnew 1990).

An alternative approach to determining the extent and distribution of aridity zones uses

Map 1.1 Mean annual precipitation 1951–80



Source: CRU/UEA, UNEP/GRID

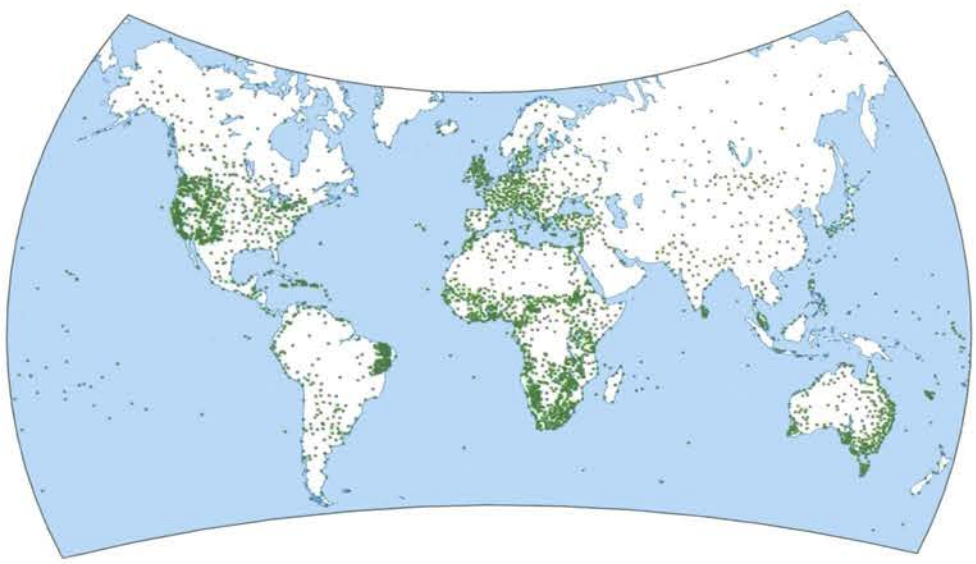
Approximate equatorial scale 1:195 million

data for specified time periods or 'timebands' (Hulme and Marsh 1990). A timeband approach is used in this study and offers a number of advantages over the use of temporally unrestricted data sets. First, it allows greater confidence to be placed in the compatibility of data from different locations. Second, it creates the possibility of producing sequential climate surface maps for a series of designated timebands, allowing changes in the location and extent of aridity zones to be identified and even predicted for the future (e.g. Hulme 1996a). In this study, stations with data for the timeband 1951–80 were used to produce surfaces of mean annual global precipitation (P) (Map 1.1) and temperature (T) as inputs to the calculation of the Aridity Index. Initially, 2769 station means were used as sources of P (Map 1.2) and 1834 for T (Map 1.3). Because of the lack of robustness of P data for extrapolating point data to area coverage, data from a further 989 stations were added for areas where the initial coverage was sparse, involving some relaxation in selection criteria. This enabled a grid of 0.5° (latitude and longitude) cells to be generated for the production of the climatic surfaces. While this might be considered to be a coarse grid, and although data are available for a higher resolution grid for some sub-areas, it generates the best overall global coverage that is currently available and is directly comparable with the grid used in the current generation of General Circulation Models (Hulme *et al.* 1992).

Determining evapotranspiration values

The calculation of the Aridity Index requires determination of the moisture loss or potential evapotranspiration (PET) values from the climatic surface data. PET can be determined in three ways, each having its own limitations and advantages. First, it can be established through direct measurement using lysimeters, evaporation pans or atmometers (Jackson 1989, Ward and Robinson 1990). At the global scale such an approach is impractical while the availability of existing data is poor, and in any case the equipment used in reported studies is not standardised and therefore not always directly comparable. Second, PET can be calculated using empirical formulae. The method of Penman (1948) is commonly cited, but its calculation requires a large body of directly measured meteorological data, including solar radiation, wind velocity, relative humidity and temperature. Its application at the global scale is therefore again constrained by data availability.

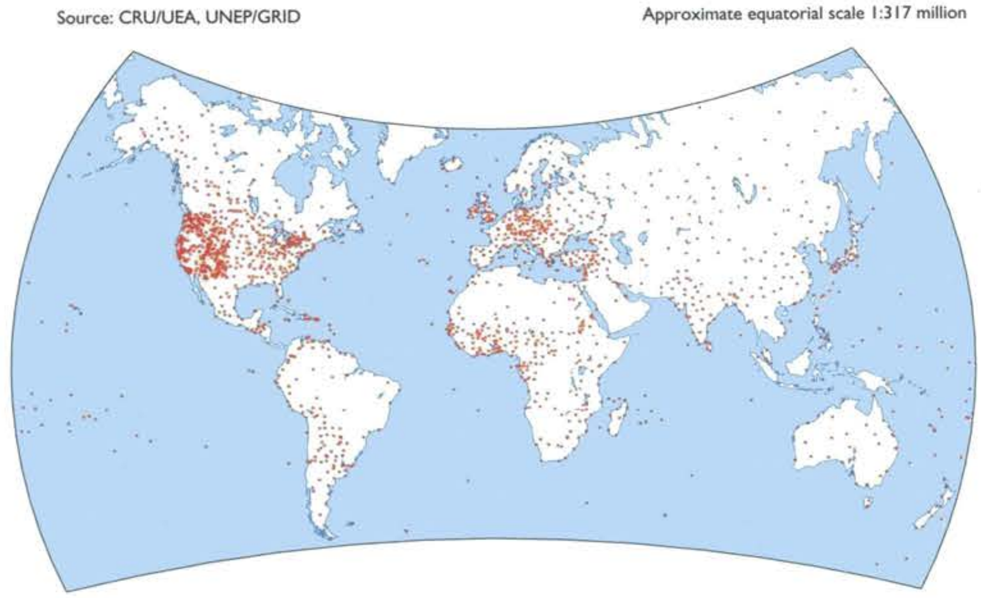
A more practical approach utilises knowledge and understanding of the empirical relationship between measured PET and values of more readily gained environmental variables (Thornthwaite 1948). This approach allows PET to be calculated from just two parameters: mean monthly temperature data and the



Source: CRU/UEA, UNEP/GRID

Approximate equatorial scale 1:317 million

Map 1.2 Precipitation stations (number of stations: 3758 1951–80)



Source: CRU/UEA, UNEP/GRID

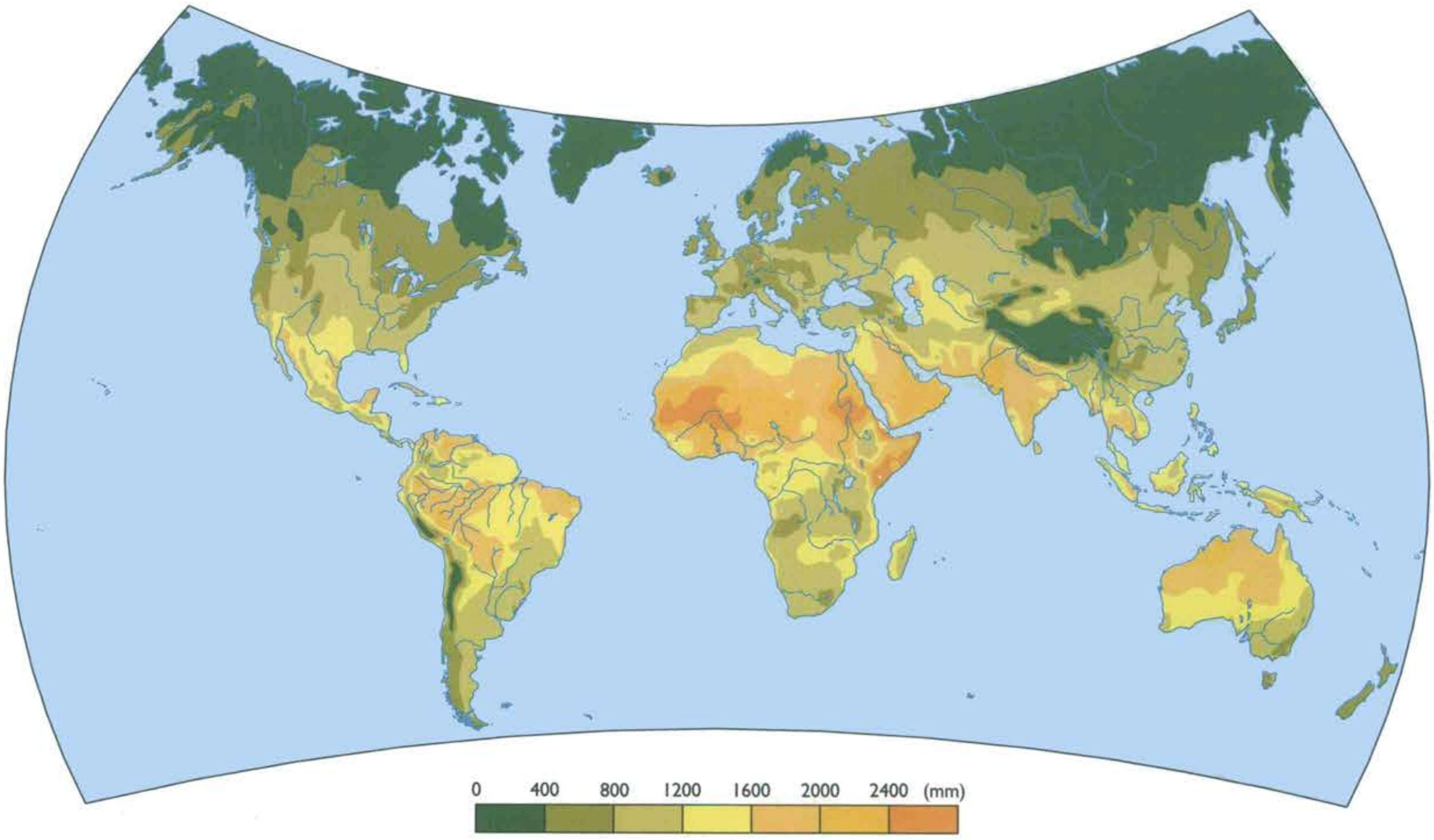
Approximate equatorial scale 1:317 million

Map 1.3 Temperature stations (number of stations: 1834 1951–80) average number of daylight hours by month. The Thornthwaite method has a practicality relevant to the scale of this study and was used by Meigs (1953) in the production of a map of world aridity for UNESCO. Though more sophisticated methods exist for calculating evapotranspiration rates for different crop types (e.g. Wright 1982), or for calculating the soil moisture deficit in relation to precipitation and evapotranspiration (e.g. Palutikof *et al.* 1982, Palutikof 1986), such approaches were not used here as once more they require the input of data that are not widely available.

A global Thornthwaite PET surface was calculated from the temperature surface data for a 0.5° resolution grid. The Thornthwaite method is known systematically to underestimate PET for dry conditions and to overestimate values for moister and cold environments (Mather and Ambroziak 1986, Hulme and Marsh 1990, McKenney and Rosenberg 1993). Consequently an empirical adjustment factor was applied to the data (Hulme and Marsh 1990) to bring the values closely in line with those of the Penman method. The global annual PET surface is shown on Map 1.4.

Figure 1.1 Pastoralists in arid areas are traditionally highly mobile. In Mongolia, herders live in tents, or *gers*, that can be quickly dismantled and moved to areas of fresh grazing (N Middleton)

Map 1.4 Mean annual potential evapotranspiration, 1951–80



Source: CRU/UEA, UNEP/GRID

Approximate equatorial scale 1:195 million

The Aridity Index

The Aridity Index (AI) was derived from the climatic surface maps and calculated, on a monthly basis, as the ratio P/PET. The monthly values were then averaged to provide both a map of mean annual potential moisture availability for the period 1951–80 and a global climatic classification based on potential moisture availability. AI values of <1.0 indicate an annual moisture deficit.

Aridity Index values were classified so that climatic zones could be delimited (Map 1.5). The classification of AI values was modified in a number of ways from that used in UNESCO (1977). The AI boundary between arid and hyperarid zones was increased from the value of 0.03 used in UNESCO (1977) to 0.05 (Hulme and Marsh 1990), as part of the adjustment for the Thornthwaite method underestimation of PET in very dry environments. The boundary between dry subhumid and humid was also changed because of the overestimation of values where conditions are moister. A separate designation of cold and mountain climates (not shown on Map 1.5) was introduced because cold environments present a different range of problems than those in warm dryland environments. As such these areas are excluded from the category of susceptible drylands in this degradation study, as the climate is too cold to allow a crop growing season.

Table 1.1 Aridity zones by region (million ha)

	Region						
Zone	*Africa*	*Asia*	*Australasia*	*Europe*	*North America*	*South America*	*Total*
Cold	0.0	1082.5	0.0	27.9	616.9	37.7	1765.0
Humid	1007.6	1224.3	218.9	622.9	838.5	1188.1	5100.4
Dry subhumid	268.7	352.7	51.3	183.5	231.5	207.0	1294.7
Semiarid	513.8	693.4	309.0	105.2	419.4	264.5	2305.3
Arid	503.5	625.7	303.0	11.0	81.5	44.5	1569.2
Hyperarid	672.0	277.3	0.0	0.0	3.1	25.7	978.1
Total	2965.6	4256.0	882.2	950.5	2190.9	1767.5	13 012.7

Types of aridity

Aridity may be defined in several ways, but most simply it represents a lack of moisture in average climatic conditions, caused by one of four climatic situations (Suzuki 1981, Thomas 1997a) which may interact in the case of individual dryland areas. These are

atmospheric stability, where, particularly in parts of the tropics and subtropics, anticyclonic subsidence results in zones of stable, moisture deficient, air;
continentality, where distance from oceans prevents the penetration of moisture-bearing winds into continental interiors;
topography, where mountain barriers create rain shadow zones; and
cold oceanic currents, which contribute to coastal desert zones by reducing sea-surface evaporation.

From place to place aridity varies in intensity, due to different levels of moisture deficit. The nomenclature used in this study reflects the terminology widely used in scientific literature since Thornthwaite (1948) and Meigs (1953). The extent and distribution of the different aridity zones determined in this study for the period 1951–80 are given in Map 1.5, Figure 1.2 and Table 1.1. It is inevitable that at the global scale each zone embraces a range of environmental characteristics. However, there are broad climatic and environmental attributes that can be used to provide a useful summary of each zone (e.g. Grove 1977):

Dry subhumid areas (0.50 P/PET < 0.65) have highly seasonal rainfall regimes with less than 25% interannual rainfall variability and agriculture is widely practised. UNESCO (1977) found such areas very susceptible to degradation, probably enhanced by the seasonality of rainfall, drought periods and the increasing intensity of human use. It is, therefore, appropriate to retain areas designated as dry subhumid in this survey and to regard them as part of the overall global arid realm. To this effect, dry subhumid areas are included in the definition of desertification.

Semiarid areas (0.20 P/PET < 0.50) have distinctly highly seasonal rainfall regimes and mean annual values up to 800 mm in summer rainfall areas and 500 mm in winter regimes. Interannual variability is nonetheless high (25–50%) so despite the apparent suitability for grazing of semiarid grasslands, this and sedentary agricultural activities are susceptible to seasonal and interannual moisture deficiency.

Arid areas (0.05 P/PET < 0.20) have mean annual precipitation values up to approximately 200 mm and interannual variability in the 50–100% range. Pastoralism is possible but without mobility (Figure 1.1) or the use of groundwater resources it is highly susceptible to climatic variability.

Hyperarid environments (P/PET < 0.05) have highly variable rainfall both interannually (up to 100%) and on a monthly basis such that there is no seasonal rainfall regime. In virtually all cases where data are available, year-long periods without rainfall have been recorded. These areas are the true deserts and as such offer very limited opportunities for human activities.

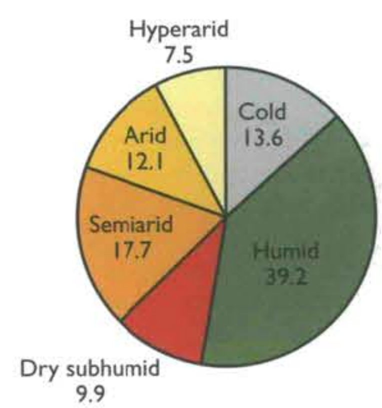


Figure 1.2 Global land area by aridity zone (%)

Problems of delineating dryland boundaries

Dryland boundaries are neither static nor abrupt (Tucker *et al.* 1985a, b and c, 1991, Hellden 1991). This is not surprising given the high interannual variability in mean rainfall and the occurrence of drought which may last for periods of several years at a time. Attempts to locate these climatically derived boundaries on the ground or identify them in terms of features such as soil type or natural vegetation are likely to fail (Thomas and Middleton 1994). Physical changes are likely to be gradual and they will be modified by human-induced processes such as grazing, deforestation and burning. Identification of climatic changes from shifts in boundaries therefore needs to proceed with caution given the dynamism that is inherent in dryland climatic regimes and the fact that drought can cause spectacular but temporary changes in natural vegetation (Tucker *et al.* 1991).

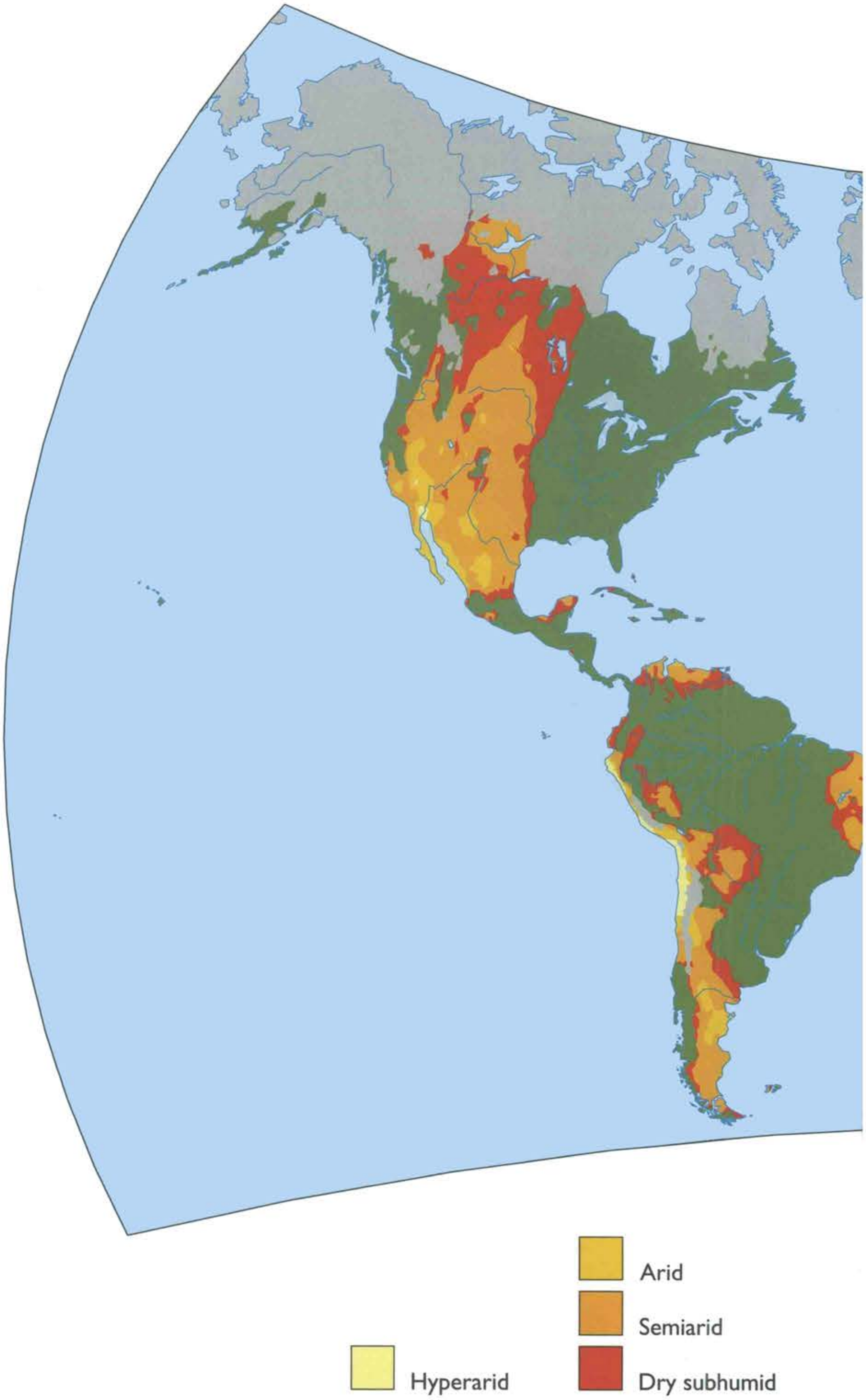
It should also be recognised that individual aridity zones do not represent homogeneous climates, either in the long term or during a particular timeband (Babaev *et al.* 1993). As already noted, specific P/PET ratios can be derived from a wide range of values for individual meteorological parameters.

Comparison with the 1977 UNESCO Map of Aridity

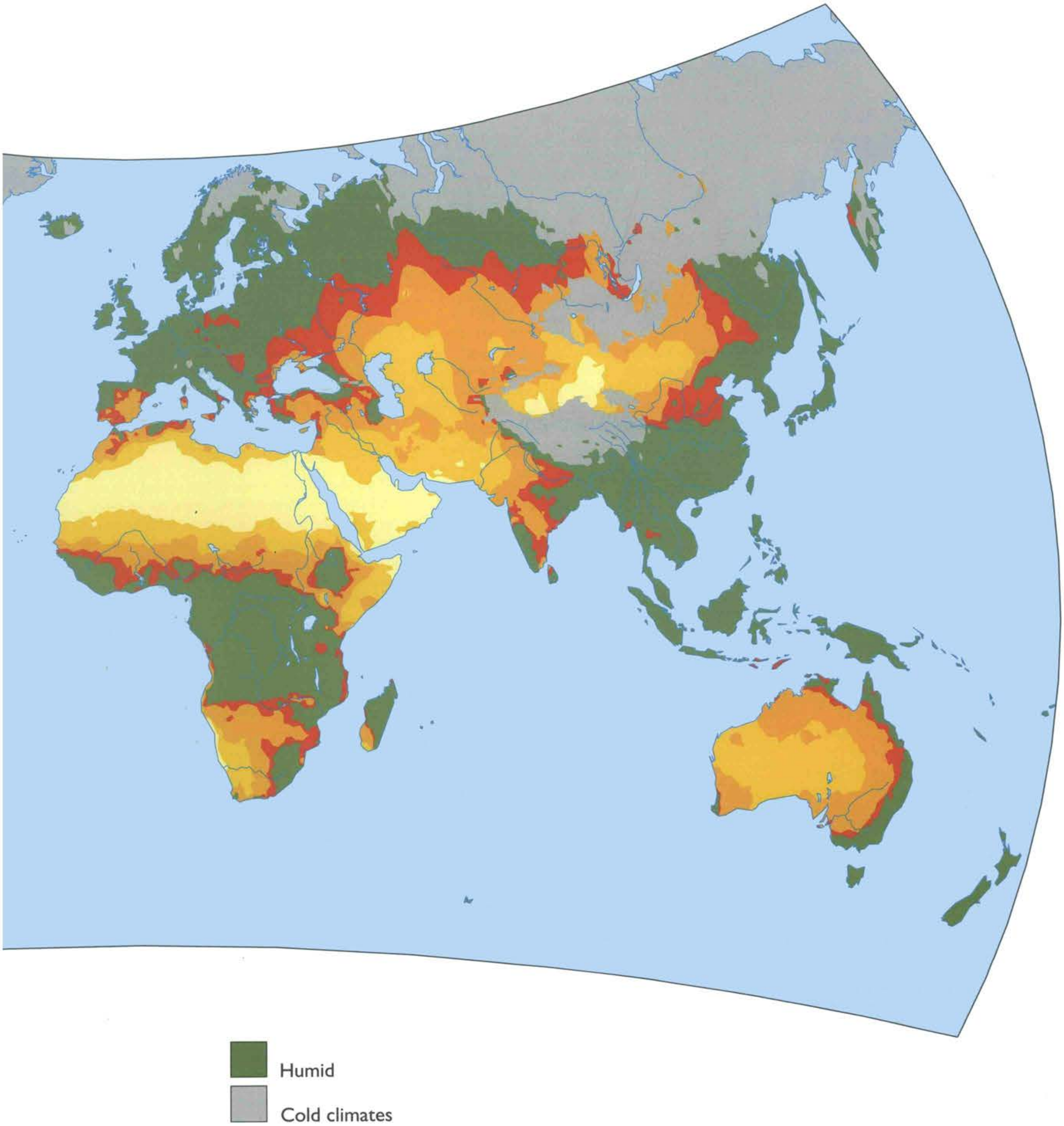
It is useful to identify how the map of world aridity zones differs from the widely used UNESCO (1977) map, which according to Heathcote (1983) is very similar to the map of Meigs (1953). Objective comparisons between UNESCO (1977) and Map 1.5 cannot be made, however, because of their different scientific bases. UNESCO (1977) only exists in paper form and was not derived from a geo-referenced data set that could be used as a basis for comparison (Hulme *et al.* 1992). The UNESCO map was, as far as it is known, derived from a timeless database, details of which are unclear, and certainly does not identify the range of time periods covered by different station data sets. For areas where the spatial coverage of meteorological stations was limited, local experts were consulted to suggest or adjust the boundaries between aridity zones. Finally, the calculation of PET values in the UNESCO study employed the Penman (1948) method, requiring a wider range of meteorological data inputs. Although the PET values in the study for this atlas, calculated using the Thornthwaite (1948) method, were empirically adjusted to better fit Penman values, there may still be statistical divergence in some areas of the Aridity Index values (Hulme and Marsh 1990).

Overall, it is believed that the utility of the map in this study is greater than UNESCO (1977). The use of timeband climatological data for the calculation of the Aridity Index will permit future comparisons with maps for other designated time periods, as Hulme (1992) has done for African precipitation surfaces and Hulme *et al.* (1992) for aridity surfaces. As the 1961–90 surface was unavailable with global coverage, this edition of the atlas retains the previously used surface for the period 1951–80. Additionally, the use of an empirically based method to calculate PET may be more pragmatic than using the Penman method at the global scale, not just because of the problems of generating the necessary data input but because it utilises fewer meteorological data and therefore reduces errors inherited from primary data collection.

Map 1.5 Aridity zones



Source: CRU/UEA, UNEP/GRID



Approximate equatorial scale 1:104 million

Climatic Variability and Change in Drylands

Introduction

The study of desertification is complicated by the natural environmental variability that occurs in dryland areas (Thomas and Middleton 1994). Accurate identification of the causes of desertification at any particular location, and thus suitable strategies for its treatment, can only be made by paying close attention both to the human use and possible mismanagement of natural resources and also to the way in which dryland ecosystems and their resources respond to natural climatic variations. This is especially important given the definition of desertification used here, which is that adopted in Agenda 21 and embodied in the Convention to Combat Desertification (CCD) (UN 1994). This incorporates the three separate elements of short term drought, long term climate fluctuations and land degradation caused by human actions (Cardy 1993). While this atlas concentrates on human-induced soil degradation, it is important to understand the dynamic nature of some of the natural elements in the dryland equation. This is particularly vital given that climatic variability not only impacts directly on ecosystems, but indirectly through influencing human actions and activities, including land use opportunities and migration (Olsson 1983, 1993, Cardy 1993, Norse 1994). As Agnew and Warren (1996) note, variability is not simply a series of changes but a series of impacts on communities. Because aridity zones are climatically defined, changes in climate that alter the extent of aridity zones will implicitly impact on the scale and extent of desertification problems (Hulme *et al.* 1993).

The inherent natural dynamism of dryland ecosystems is very largely governed by the variability in climatic parameters that characterise such regions (Agnew and Anderson 1992). Chief amongst these is precipitation, the input of moisture into drylands. While many dryland areas receive important inputs of moisture from dew (Evernari 1985), and some others from fog, for example in western Namibia (Seely 1978), rainfall is still the key source of moisture in most of the world's dryland regions, however sporadic and unreliable its occurrence may be. It is not sufficient to consider rainfall inputs alone, however, since the effectiveness of rainfall, which is the amount available for plant growth or other uses, is also dependent on outputs. The main output route, evapotranspiration (ET), is influenced by parameters such as plant cover and type, wind speeds, and perhaps most importantly, temperature.

It is also valuable to consider the timescales over which climatic fluctuations in drylands occur, since their recognition and identification influences the strategies for survival that societies have to adopt (Warren and Khogali 1992, Thomas and Middleton 1994, Williams and Balling 1996). In this section, therefore, the relationships between climate change and desertification will be considered, and the scales of climate change and variability will be explained. Following this, a closer examination of the variability of rainfall and temperature in the world's drylands, serves as a contextual background to the considerations of dryland degradation that follow.

Interactions between climate change and desertification

In their book *Interactions between climate and desertification*, produced for WMO and UNEP, Williams and Balling (1996) note that desertification can affect climate as well as climate affecting desertification. Climatic change induced at the global scale by human actions, notably the emission of greenhouse gases, will impact on the extent of drylands and the nature of climatic regimes within them. Specifically in drylands, human actions can alter the nature of the land surface, which in turn may modify the energy balance in the lower atmosphere and the occurrence of rainfall. Both these changes are considered further under the section on climate change.

Climate changes, regardless of their cause, can impact on desertification processes and human activities that lead to land degradation. Any changes of climate in the future are likely to be relevant to issues of desertification and land degradation, particularly if the balance between moisture gain and moisture loss through evapotranspiration is altered. Such changes will alter the extent and distribution of drylands and may intensify, or even perhaps reduce, problems of moisture availability and drought occurrence, by changes in climatic variability. Even if absolute changes in moisture availability are limited, changes in the seasonality of climate can have significant impacts on the distribution of vegetation communities, on soil moisture availability, and on the potential for specific human, especially agricultural, activities. Desertification may even be triggered or exacerbated in productive areas by pressures brought to bear in other locations. The occurrence of a prolonged drought, or an increase in aridity in one area, will inevitably increase the pressures to cultivate and produce more food in other areas.

Climatic change

There is considerable well-established evidence that demonstrates the occurrence of marked global climatic changes at the millennia and greater time scales (e.g. Williams *et al.* 1993, Kadomura 1994), and it is well attested that such changes have affected arid zones, leading to both their expansion and contraction in the past (Thomas 1997b). These long-term changes, driven principally by external forcing mechanisms, particularly changes in earth–sun relationships, have had important effects on the development of landscapes, soils and animal and plant distributions in drylands. These changes must, however, be contrasted with climate changes and variations that occur within the scale of human lifespans and which have a more direct and immediate effect on society–environment relationships.

While it is clear that many factors control and influence climate at global, regional and local scales, with many of these factors currently only poorly understood, it is widely agreed that human actions themselves have an important impact on climate (Williams and Balling 1996). What remain uncertain are the likely magnitudes of human-induced climate changes, and their impacts on areas susceptible to desertification.

At the global scale, it is widely accepted that the build up of radiatively active gases, the so-called 'greenhouse gases' in the atmosphere, particularly carbon dioxide (CO_2), methane (CH_4) and chlorofluorocarbons (CFCs), is contributing to global warming (IPCC 1990). Dryland areas are globally important stores of carbon (Adams *et al.* 1990), and land degradation in these areas is contributing perhaps 5 to 10% of total greenhouse gas accumulation (Williams and Balling 1996). It is therefore important to increase our understanding of the patterns of carbon storage in drylands and to aim to adapt and improve land management systems to reduce the flux of carbon to the atmosphere.

At regional and local scales, it has long been suggested that human-induced soil and vegetation changes in drylands may modify rainfall amounts (Otterman 1974, Charney 1975). In this 'biophysical feedback model' it is hypothesised that vegetation reduction both lowers the contributions plants make to atmospheric moisture by evapotranspiration, and increases surface albedo and thereby atmospheric stability through reduced lower atmosphere warming. While there have been numerous studies to investigate this phenomenon and the principles involved (e.g. Charney *et al.* 1975, Walker and Rowntree 1977, Sud and Molod 1988, Le Houérou 1993), the possible contribution it makes to climate changes in drylands remains debated (Schlesinger *et al.* 1990, Williams and Balling 1996). Overall, climate change is clearly an important issue related in a number of ways and at a range of temporal and spatial scales to desertification. The complex interactions that are likely to exist between its different components, and how these relate to desertification processes (Figure 1.3) are clearly vital areas for further investigation.

Climatic variability

Climatic variability refers to the year to year variability of individual climatic parameters around longer-term mean values, and is inherent in dryland areas (Le Houérou 1996). Climatic variability can occur whether longer-term climate is stable or is changing – for example, year to year rainfall values may fluctuate around an overall trend towards wetter or drier conditions. Balling (1994b) has shown that for the dryland areas of North America, between 1890 and 1990, there were annual variations in temperature anomalies around an overall warming trend of 0.86°C (Figure 1.4).

Climatic variability may be linked to variations in climate forcing mechanisms. Cycles of change in solar output, identified by sun spot changes (Meadows 1975), operate at scales of 11, 60, 80 and 180 years, and are believed to impact on climate variability (Seitz *et al.* 1989, Warren *et al.* 1996). Links between sea-surface temperature and atmospheric circulation changes, particularly the 'El Ninõ Southern Oscillation' (ENSO) event (Lockwood 1984), are thought to have particularly significant impacts on climate in low latitude regions. Though a complete understanding of the specific impact of such links on climate remains to be ascertained (Hidore and Oliver 1993), the occurrence of marked droughts and periods of significantly enhanced rainfall in some arid areas have been related to ENSO cycles, which have 3–7 year periodicities (Warren *et al.* 1996).

Rainfall variability is an important aspect of dryland climates, and is described under each aridity zone (page 5). While aridity results from low average moisture availability, human activities can be compromised further by the uncertainty that exists about rainfall occurring in any particular location in any one season or year. Despite the identification of quasi-cyclical trends in rainfall variability in some dryland regions (e.g. Tyson 1986), the unpredictability of year-to-year (or interannual) variations of rainfall in drylands makes planning for agricultural activities difficult. Interannual rainfall variations have great relevance to issues of land degradation, and the failure of rains in one location can increase the pressures on neighbouring lands that have been better watered. Significantly, periods of better rainfall may contribute to desertification as well, by increasing the pressure of cultivation which then creates difficulties during subsequent drier periods. Gonzalez Loyarte (1996) has noted this effect in semiarid and dry subhumid areas of Argentina.

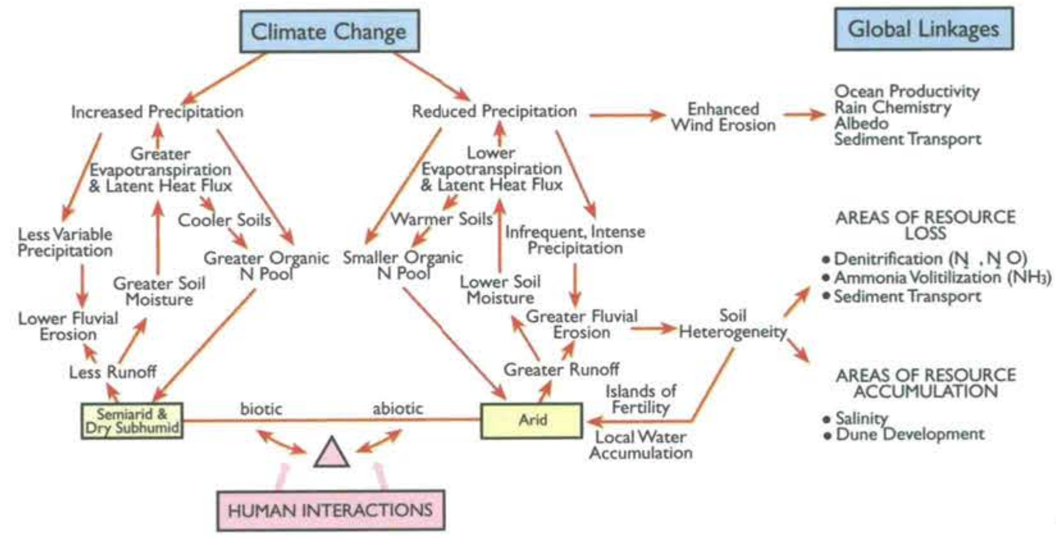


Figure 1.3 Possible linkages between climate change, environmental change and human activities during desertification (based on Schlesinger *et al.* 1990)

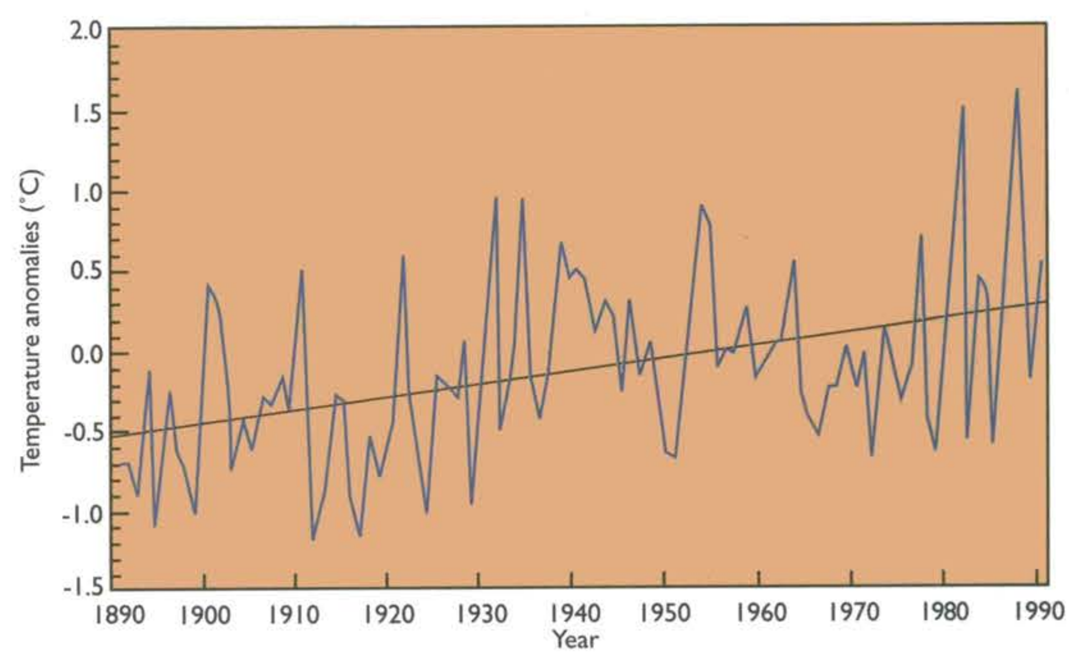


Figure 1.4 Temperature anomalies for the drylands of Mexico, the United States and Canada for the period 1891–1990. The linear trend line reveals a statistically significant warming (after Balling 1994b)

Marked rainfall deficiency below average conditions in any one year is commonly referred to as drought, but this is a very imprecise term (Kemp 1994) that has been defined in many different ways (WMO 1975). It is particularly important to distinguish between *agricultural drought,* which is expressed in terms of the moisture requirements of crops, and *meteorological drought,* which refers to a moisture deficit in relation to mean precipitation. Wilhite and Glantz (1985) catalogue a range of definitions that have been used in different studies, and to some extent the appropriateness of any definition relates to the purpose for which it is intended. A further complication is that it is becoming increasingly common to distinguish *drought,* considered to be a period of below average rainfall lasting for a year or so, from a period of *desiccation*, which is a decadal scale reduction in moisture availability (Hare 1987).

The nature of the climate systems that bring rainfall to drylands, particularly the occurrence of convective rainfall cells and the seasonal movements of the Inter-Tropical Convergence Zone (ITCZ) in low latitudes, contributes to rainfall uncertainty (e.g. Hastenrath and Heller 1977). As well as temporal variability, these systems contribute to spatial variability in rainfall. In Niger, for example, Agnew (1992) has shown that during the 10-year period commencing in 1967 some areas of the country experienced 10 drought years, while others less than 200 km away had 2 or less. This variability at the country level demonstrates just how difficult it is to produce reliable global summaries of drought. Hulme (1992) has also shown that is also possible to identify variability within the seasonality of rainfall in some African drylands.

Examples of rainfall variability in dryland areas

The nature, characteristics and variability of rainfall anomalies in the susceptible drylands can be investigated by recourse to four examples, based on data supplied by the CRU. Other analyses and comparisons of rainfall trends in dryland areas include those of Hulme (1996a) for nine different global dryland areas, and Nicholson (1989) and Hulme (1992) for Africa. Figures 1.5 to 1.8 show time series graphs of annual rainfall for dryland regions in three different continents: the Sahel region of Africa, which extends from the Atlantic coast to 35°E; the north-eastern region of Brazil, from the equator to 10°S; northern China, from 100°E to the China Sea and from 35°N to the borders of Mongolia and Russia; and the whole of Pakistan. The areas are shown on Map 1.6.

To construct each graph, data from each area have been handled as follows. For each station that contributes to a graph, the annual rainfall series has been normalised by subtracting the long-term mean from each value. The difference was then divided by the long-term standard deviation. The mean and standard deviations used were derived from the 1951–80 data, which corresponds to the time series used for calculating Aridity Indices (page 5). Normalising the data series in this way enhances comparability, since mean values become close to zero and standard deviations close to one, for each data set. The spatial mean rainfall anomalies have been calculated by averaging the values for all stations in each area with data. While the number of stations with data throughout each period in each of the three areas is not constant, the time series are the best available. As they represent a spatial average for each area they reliably reflect the annual rainfall anomalies in each area in question. The same approach has been used by Hulme (1992) in an analysis of rainfall variations in different areas of Africa. The smooth curves fitted in each of Figures 1.5–1.8 are 10-point Gaussian filters fitted through the data, which suppress variations of less than a decade. Thus the curves give a reliable indication of trends in rainfall anomalies.

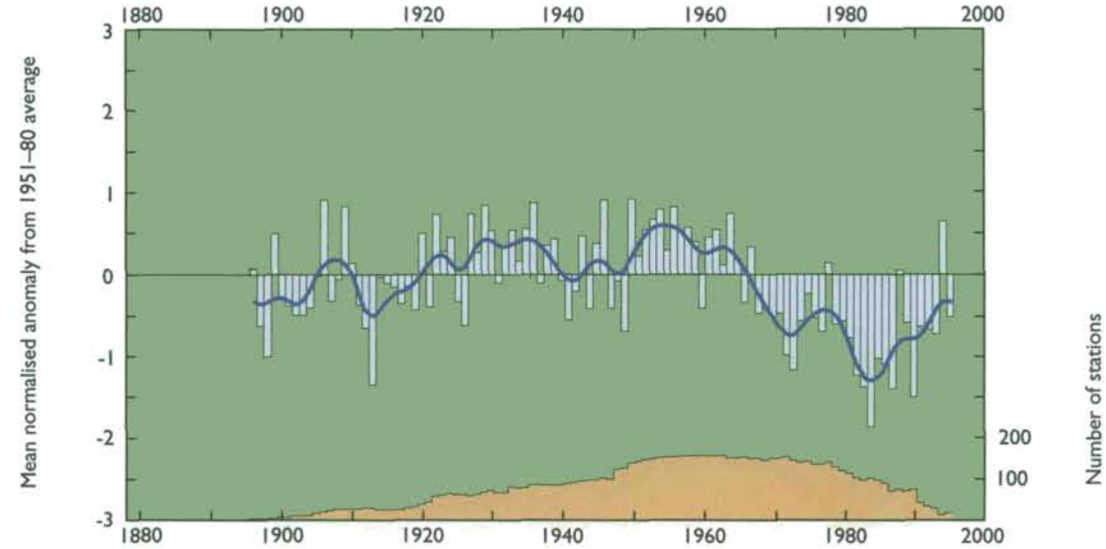


Figure 1.5 Sahel annual rainfall, 1896–1995 (1951–80 mean = 524 mm). Source: CRU/UEA

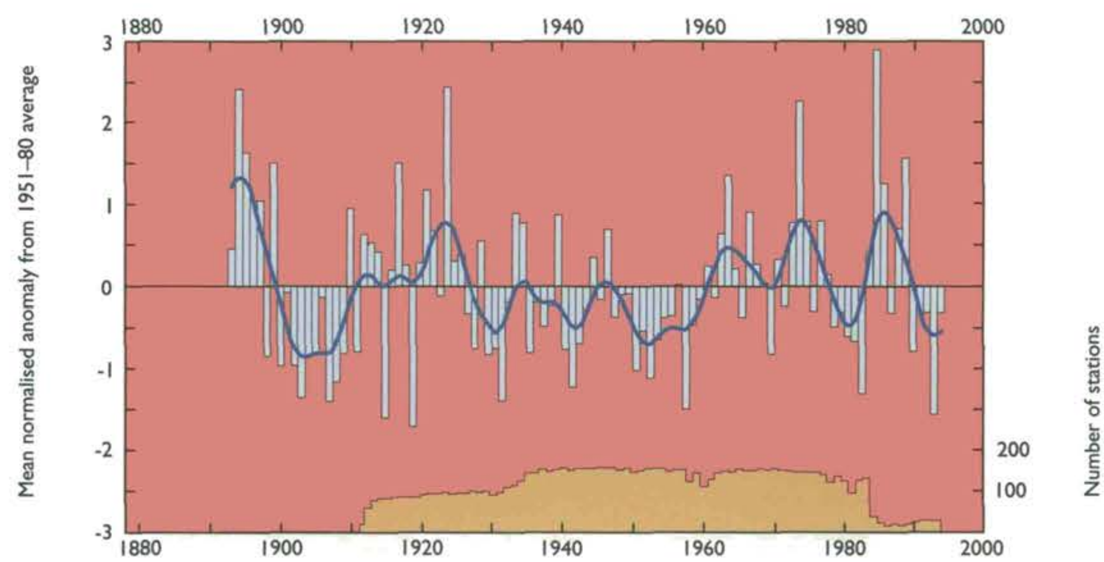


Figure 1.6 North-eastern Brazil annual rainfall, 1893–1995 (1951–80 mean = 829 mm). Source: CRU/UEA

All four graphs (Figures 1.5–1.8) demonstrate how dryland regions experience prolonged periods of above and below mean rainfall, as well as individual years of marked rainfall excess and deficit (drought). In the Sahel, (Figure 1.5), 1898 and 1913 were particularly marked drought years. The 1930s and 1950s were prolonged periods of above-average rainfall across the whole region, during which livestock populations markedly increased (Warren and Khogali 1992). The rainfall deficit periods around 1900, preceding the early 1920s and 1940–42 have been suggested by Lamb and Peppler (1991) to relate to marked ENSO activity, but overall the Sahel displays a poorer relationship between ENSO events and drought occurrence than many dryland areas (Williams and Balling 1996). Extended drought conditions, contributing to a period of desiccation, have occurred in the Sahel since the late 1960s. Across the region as a whole, only 1978, 1988 and 1994 experienced above average conditions during this period. If the tri-decades 1931–1960 and 1961–1990 are compared, the rainfall decline has been of the magnitude of 20–40% (Hulme and Kelly 1993) and exceeds the duration of events that might normally be

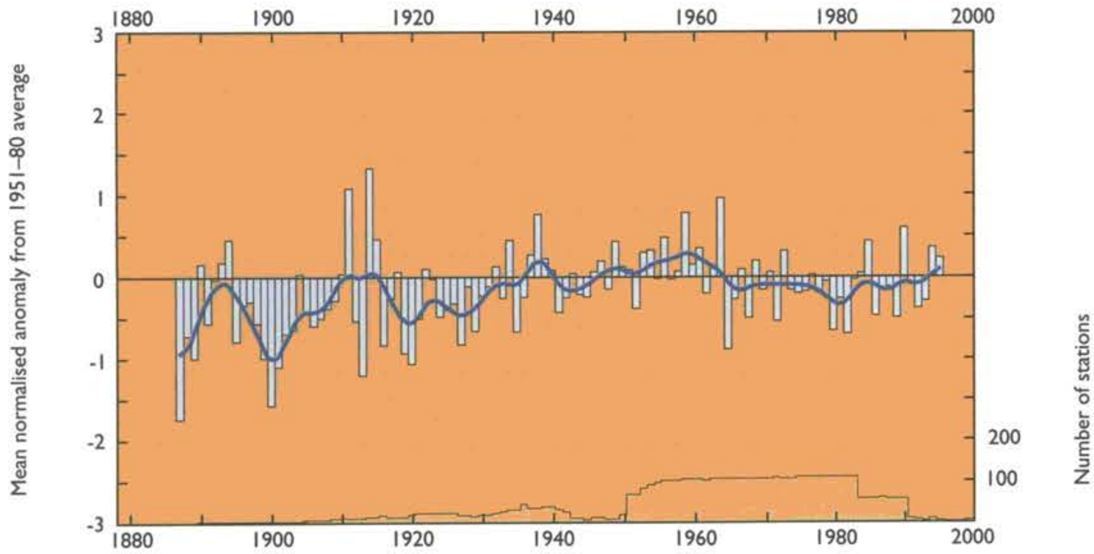


Figure 1.7 Northern China annual rainfall, 1887–1995 (1951–80 mean = 491 mm). Source: CRU/UEA

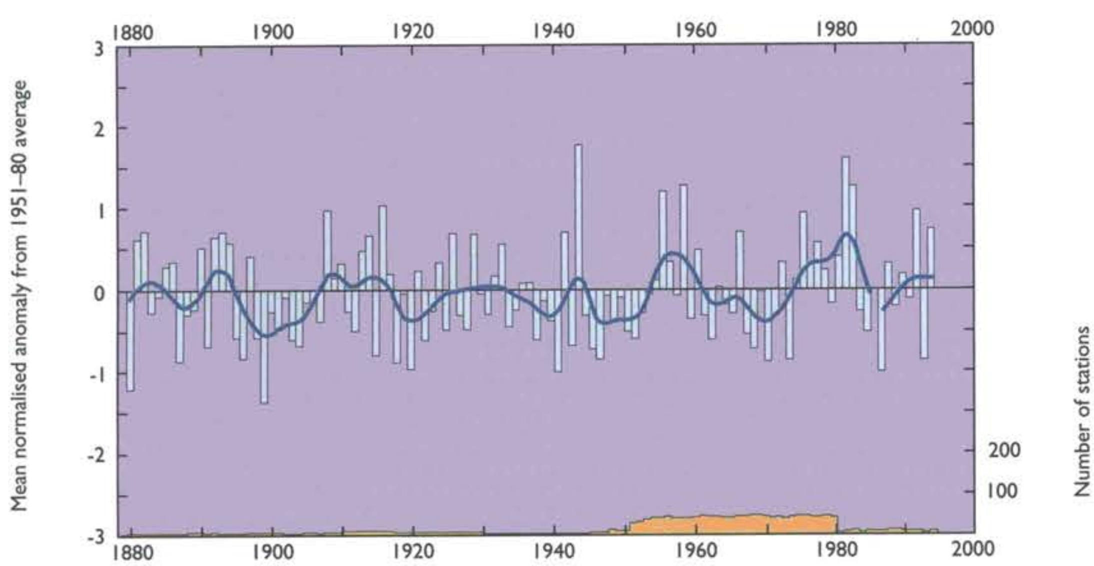
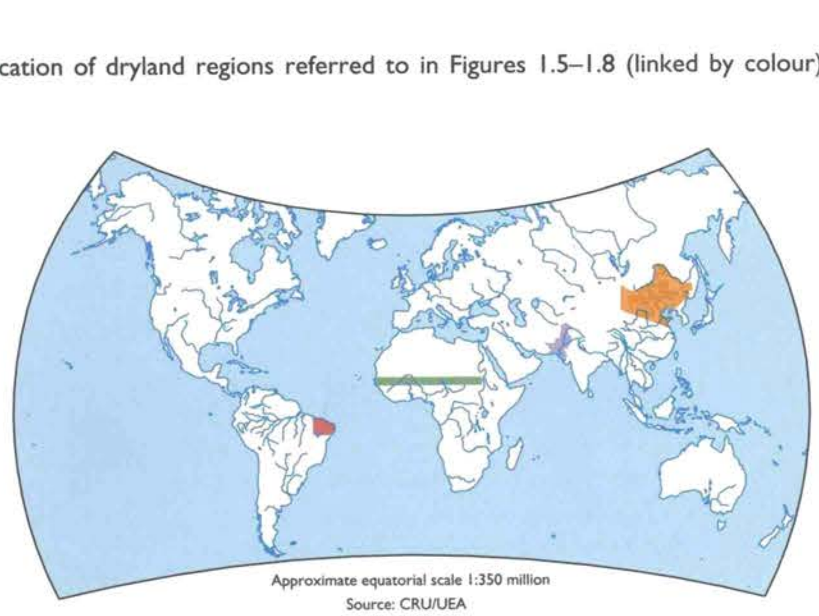


Figure 1.8 Pakistan annual rainfall, 1880–1994 (1951–80 mean = 435 mm). Source: CRU/UEA

Map 1.6 Location of dryland regions referred to in Figures 1.5–1.8 (linked by colour)



expected to be associated with ENSO events (Le Houérou 1996). There is perhaps some evidence that the 1990s have not been quite as dry as the 1980s, but there is no clear sign of a return to the wetter decades of the mid-century. There is debate about whether the recent desiccation period represents the onset of a marked climatic change. Examination of historical and sedimentary records, however shows that this recent episode of desiccation is not unique, since equivalent or even longer periods of moisture deficit have occurred in the Sahel on several occasions during the last 500 years (Nicholson 1978) and even the last millennium (Maley 1989). Despite doubts regarding the longer term significance of the current long period of rainfall deficiency in the Sahel, and despite sub-regional variations within the overall picture of Sahelian rainfall deficiency (e.g. Agnew 1992), it is probably sensible to regard the rainfall conditions of the last 30 years as a more appropriate basis for current planning decisions than a longer-term mean value.

Figure 1.6 shows that in the north-eastern region of Brazil dramatic variations in rainfall anomalies occur over short periods. For example, 1917 was an extremely wet year, but 1915 and 1919 experienced severe and extreme droughts, and in the mid-1980s years of high positive rainfall anomalies were closely juxtaposed to a severe deficit in 1983. As well as short-term variations, Figure 1.6 also shows that NE Brazil experiences marked runs of years with rainfall above and below mean values. Care should however be exercised in extrapolating region-wide impacts of these trends on human activities, since the region is also noted for the very high spatial variability of its rainfall (Harzallah *et al.* 1996). This is because a wide range of climatic systems impact on the region (Hastenrath and Heller 1977, Chu 1983). In the drier parts of the region there is nonetheless a very strong correlation between rainfall departures from the mean and sea-surface temperature anomalies (SSTA) linked to ENSO (Rao *et al.* 1986, Ropelewski and Halpert 1987), with droughts commonly occurring in El Ninõ years (Kemp 1994). The years of extreme rainfall and drought commented on above are particularly well associated with SSTA (Harzallah *et al.* 1996, Roucou *et al.* 1996), suggesting that improvements in understanding the causes and periodicities of SSTA could provide an important predictor of future droughts and floods in this region.

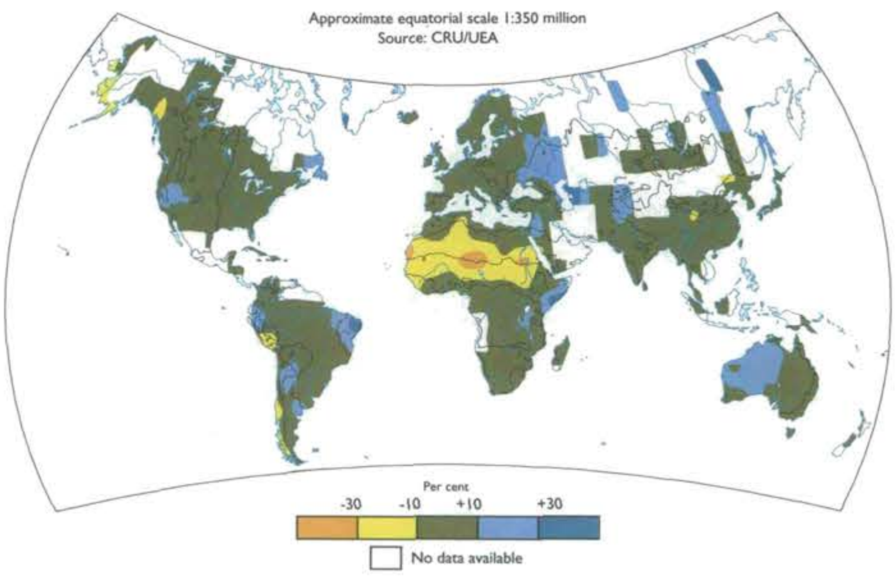
Comparison of the curves in Figures 1.5 and 1.6 indicates that certain times of extreme rainfall anomaly in NE Brazil correspond inversely to those in the Sahel. This inverse relationship may be not be coincidental since teleconnections – the tendency for variations in climate in one part of the world to be linked to or to precede changes in other areas – may be an important factor in explaining aspects of climatic variations in dryland areas (Glantz *et al.* 1991). One of the mechanisms that links NE Brazilian and Sahelian rainfall (sometimes inversely) seems to be found in the thermohaline circulation of the Atlantic Ocean.

The rainfall graph for northern China (Figure 1.7) also shows high year on year variations, such as those from 1913 to 1914 and 1965 to 1966, as well as prolonged periods of above and below average rainfall, notably the period of desiccation spanning the turn of the 19th to 20th century and throughout the 1920s. There is some evidence to link drought in northern China with ENSO events (Williams and Balling 1996), and the availability of old historical records for the desert areas of China does show that runs of drought years have been a feature of the region's climate during the last 300 years (Yan *et al.* 1992).

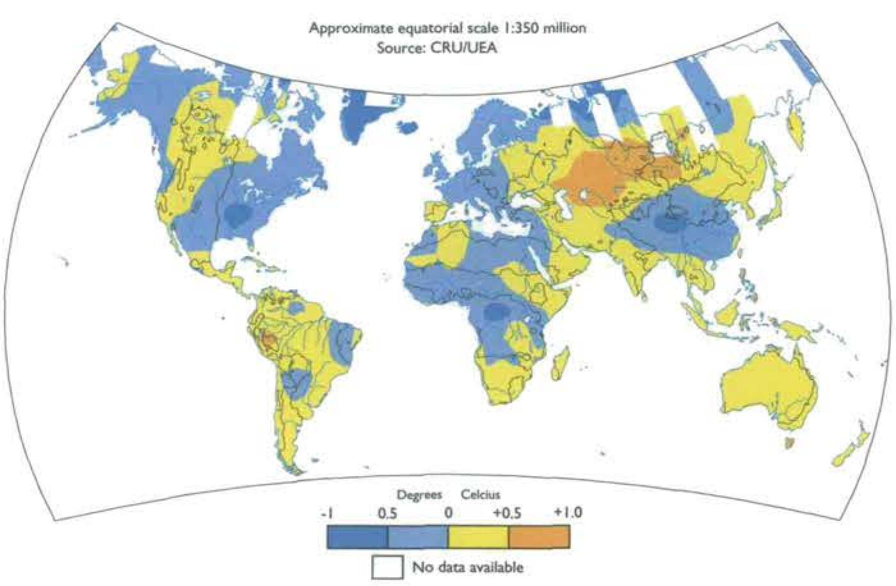
The Pakistan rainfall time series (Figure 1.8) is based on data from rather fewer stations than the other regions. A maximum of about 50 stations contribute data compared to more than 100 for the other areas. Prior to 1940 the series is based on only 5 stations. With this note of caution borne in mind, the series nevertheless gives little indication of any long-term trends in rainfall in Pakistan as a whole. Again variability can be high from year to year; for example in 1941–44 and 1992–94. The 1900s and 1945–55 were long dry periods, while 1975–85 was a relatively wet period.

It is particularly the years of rainfall deficiency that have relevance to the study of desertification and dryland development. The four case studies presented here demonstrate that such years are common both as shorter-term periods of drought and more extended periods of desiccation. It must not be forgotten that as well as overall rainfall deficiency, the timing of rainfall events is highly important to human activities. The focus here has been on meteorological drought, but the severity of the impact of drought to some extent depends on the types of land use being practised and varieties of crops being grown in an area. A certain level of rainfall deficiency at a particular time of year may mean the critical loss of a sorghum crop for example, but be more advantageous for yields of millet in a neighbouring field. Understanding the causes of drought and linkages with controlling factors is undoubtedly important for future attempts to forecast its occurrence, but the ability to predict may differ markedly from area to area depending on how strongly linkages with causal mechanisms and teleconnections can be established (Nicholls and Katz 1991).

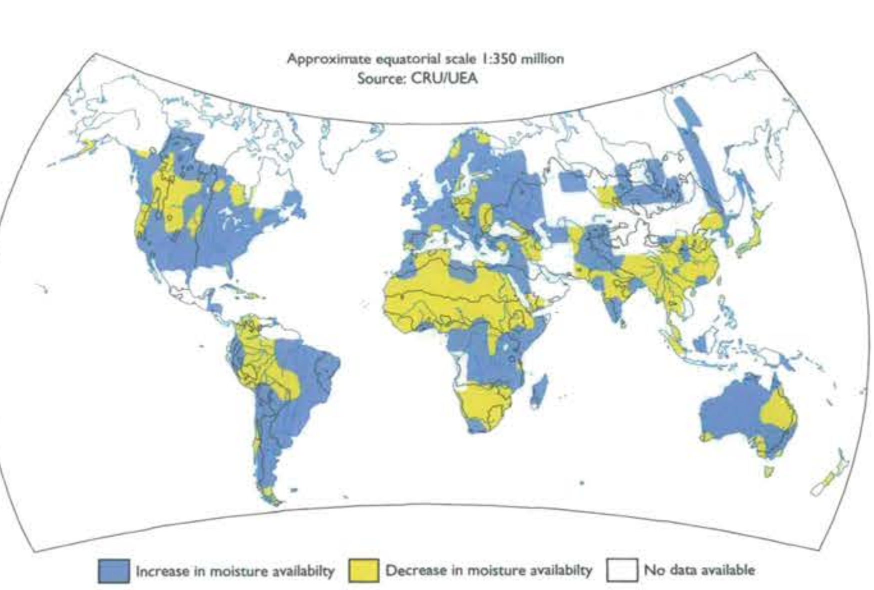
Map 1.7 Mean annual precipitation change from 1930–59 to 1960–89



Map 1.8 Mean annual temperature change from 1930–59 to 1960–89



Map 1.9 Mean annual Aridity Index change from 1930–59 to 1960–89



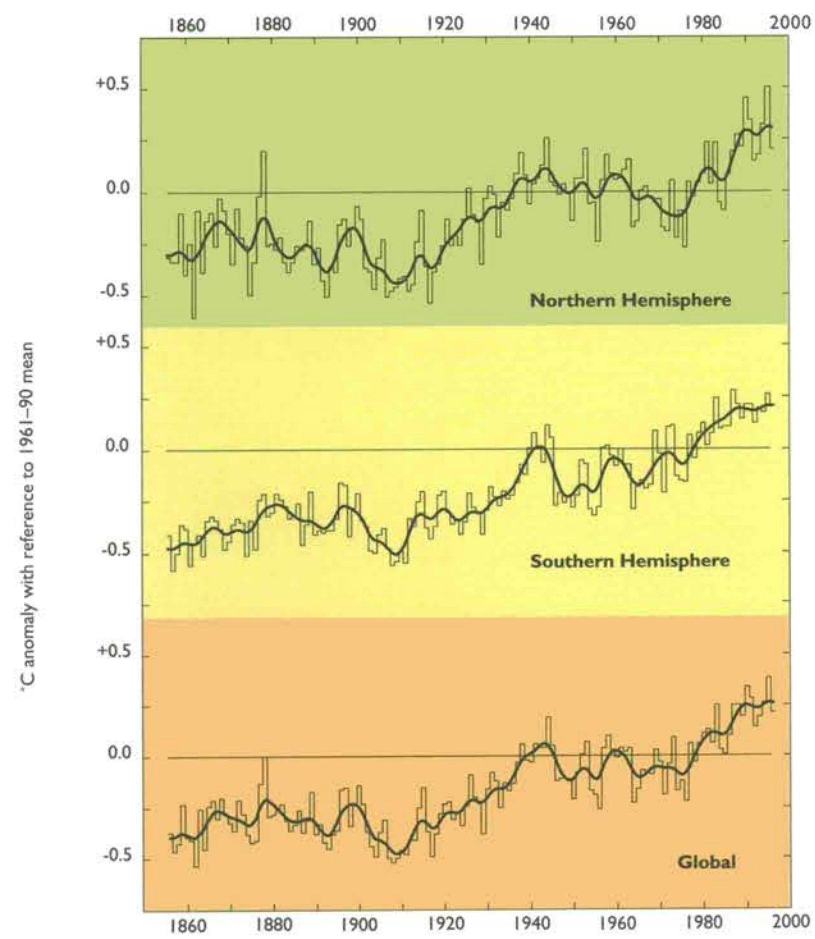


Figure 1.9 Hemisphere and global warming trends. Source: CRU/UEA

Changes in climatic surfaces, 1930–59 to 1960–89

The variability of dryland climates makes it likely that the extent of different dryland zones will vary over time. Maps 1.7, 1.8 and 1.9 give a spatial perspective on this variability, showing changes in the global climatic surfaces for precipitation, temperature and the Aridity Index between two 30-year periods, 1930–59 and 1960–89. The surfaces were constructed in the same manner as described on pages 3–5, with the values of change presented in Map 1.9 being one approach to identifying the fluctuations in the area of drylands that have occurred (Hulme *et al.* 1992).

The rainfall graphs for the Sahel and NE Brazil (Figures 1.5 and 1.6) are confirmed in Map 1.7 which shows these regions respectively to have been drier and wetter in the 1960–89 period. Most of the Sahel west of Ethiopia has been considerably drier, with an annual precipitation decline between 10 and 30%. In southern Somalia by contrast, where the principal controls on climate are different, annual precipitation has increased by over 30% in recent decades. Similar increases have occurred in NE Brazil and in the Middle Asian region east of the Caspian Sea. Lesser but none the less significant increases have occurred in western Australia and parts of the south-west USA.

Mean annual temperature changes between the two 30-year periods are shown in Map 1.8. Increases of up to 0.5°C have occurred in the dryland areas of southern Africa, parts of the Sahara and the eastern Sahel, SE Europe, southern Asia including India, northern China and Australia. In contrast, a reduction in mean annual temperatures occurred in the Tibetan and Kunlun Mountain drylands.

Map 1.9 shows changes in Aridity Index values between the two periods and as such represents the composite impact of precipitation and temperature changes. Parts of northern Mexico and NE Brazil have experienced enhanced moisture availability in the later period. Most striking, however, is the decrease in moisture availability in the Sahel from Ethiopia westwards and in parts of the Maghreb region. Southern African drylands also experienced declining moisture availability, for although precipitation was little changed, temperatures increased. Hulme *et al.* (1992) carried out a similar analysis of Aridity Index changes for nearly identical 30-year periods. They have estimated that in Africa from 1931–60 and 1961–90 63% of the continent experienced a decline in Aridity Index values (that is, areas getting more arid), with around 7% of the continent's land area being reclassified into a drier aridity zone. Changes were concentrated north of the equator, and resulted in the extent of hyperarid areas increasing by 50 million ha and the overall extent of humid areas declining by 26 million ha (Hulme *et al.* 1992).

Global warming

It was noted on page 8 that human actions are now widely believed to be contributing to climate change at the global level: indeed, Hulme (1996b) indicates that there is little doubt that the world is warming under this influence (Figure 1.9). Doubts do exist though about the nature, timing, and distribution of the regional consequences of global warming. This situation arises due to the complexity of influences on, and linkages between, the climates of individual regions as well as the combination of climatic variables that can be influenced by change. For example, it is not just overall annual temperature and precipitation values that may alter, but other more complicated variables such as the seasonal distribution of changes, the timing of the onset of rainfall periods, and the intensity of rainfall events.

Various routes are being followed to try to establish the levels of changes in temperature and precipitation that might be expected to occur during the next century. The main method being used is numerical modelling using General Circulation Models (GCMs), where various scenarios of the impact of enhanced atmospheric greenhouse gas concentrations on climate can be examined (e.g. IPCC 1990, 1995), and predictions based on short-term observational data and longer-term proxy records (Williams and Balling 1996).

Most outputs from models predict that during the next century year-round temperatures in drylands will increase during all seasons, but there is considerable variance between models concerning future precipitation trends in dryland areas (Williams and Balling 1996). It can, however, be instructive to view possible trends in the context of observed 20th century climatic patterns in drylands. Using a gridded database similar to that used in constructing the climatic surfaces on pages 3–5, Hulme (1996a) has shown that in all the world's dryland areas, there have been overall warming trends. In most dryland areas, at the annual and decadal levels, warmer years have been associated with drier conditions. The only exceptions to this are the drylands of Patagonia and in Middle Asia, where warmer conditions have been associated with enhanced rainfall. The problems faced by climatic modellers in predicting future trends are well demonstrated by the fact that the warmer–drier relationship has only been statistically significant in the Maghreb countries, the Sahel and southern Africa (Hulme 1996b). Nevertheless, the warning for inhabitants of drylands is clear: global warming is likely to further reduce the already limited availability of moisture. This serious implication, along with other more detailed and localised effects, must be taken into account in all efforts to solve desertification problems into the 21st century, and emphasises the need for stronger action to be taken.

Soil Degradation

Introduction

Soil is an integral part of most terrestrial ecosystems and serves a fundamental function in supporting human communities, primarily through its importance as a medium in which crops and other plants grow. Soil degradation, therefore, is an environmental issue of crucial concern to all societies (Barrow 1991, Blaikie and Brookfield 1987). Its occurrence is generally agreed to be widespread and its effects threaten the sustainability of human life (UNEP 1982, WCED 1987). Identifying the geographical distribution of soil degradation and quantifying the areas affected is therefore a task of great importance. The GLASOD project was formulated as the first step towards an appraisal of soil degradation worldwide, with the immediate objective of

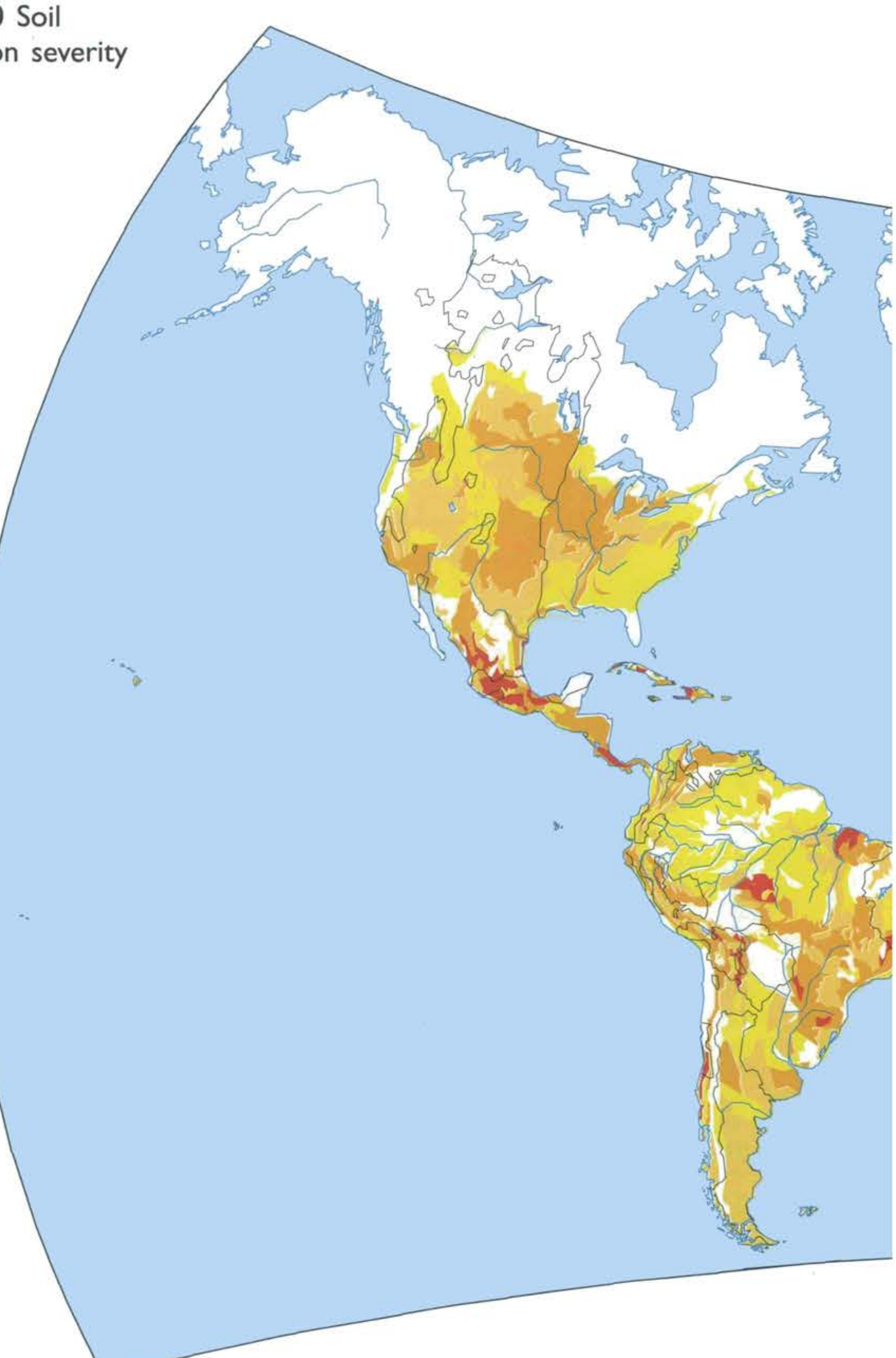
> Strengthening the awareness of decision makers and policy makers on the dangers resulting from inappropriate land and soil management to the global well being, and leading to a basis for the establishment of priorities for action programmes (Oldeman 1988: 1).

The most direct way to create awareness is a visual representation in map form, and the map of soil degradation severity on the global scale (Map 1.10) embodies both the degree of degradation and its spatial occurrence within individual mapping units. It therefore provides both a comparative framework for the overall degradation problem throughout the world's drylands, and an overview before the specific types of degradation are considered in the maps that follow.

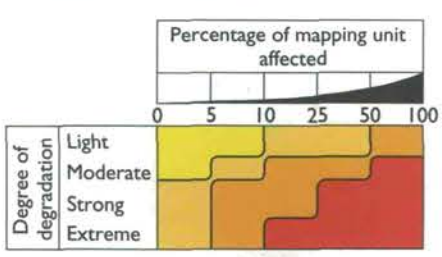
Methodology

GLASOD defines soil degradation as 'human-induced phenomena which lower the current and/or future capacity of the soil to support human life.' Two principal categories of human-induced soil degradation processes are recognised (Table 1.2). The first deals with degradation by displacement of soil material, principally by water erosion and wind erosion. The second deals with internal soil deterioration by physical and chemical processes. Soil erosion processes are recognised to cause degradation both on-site and off-site, while degradation by deterioration only includes *in situ* effects on land that has been abandoned or forced into less-intensive uses. This latter category does not include cyclic fluctuations of soil conditions of relatively stable agricultural systems, in which the soil is actively managed to maintain its productivity, nor does it include gradual changes in the chemical composition as a result of soil-forming processes. Particular areas may of course suffer degradation from more than one type of

Map 1.10 Soil degradation severity



Approximate equatorial scale 1:104 million
Source: UNEP/ISRIC



The different levels of severity were obtained by the combination of degree of degradation and the percentage of the area affected

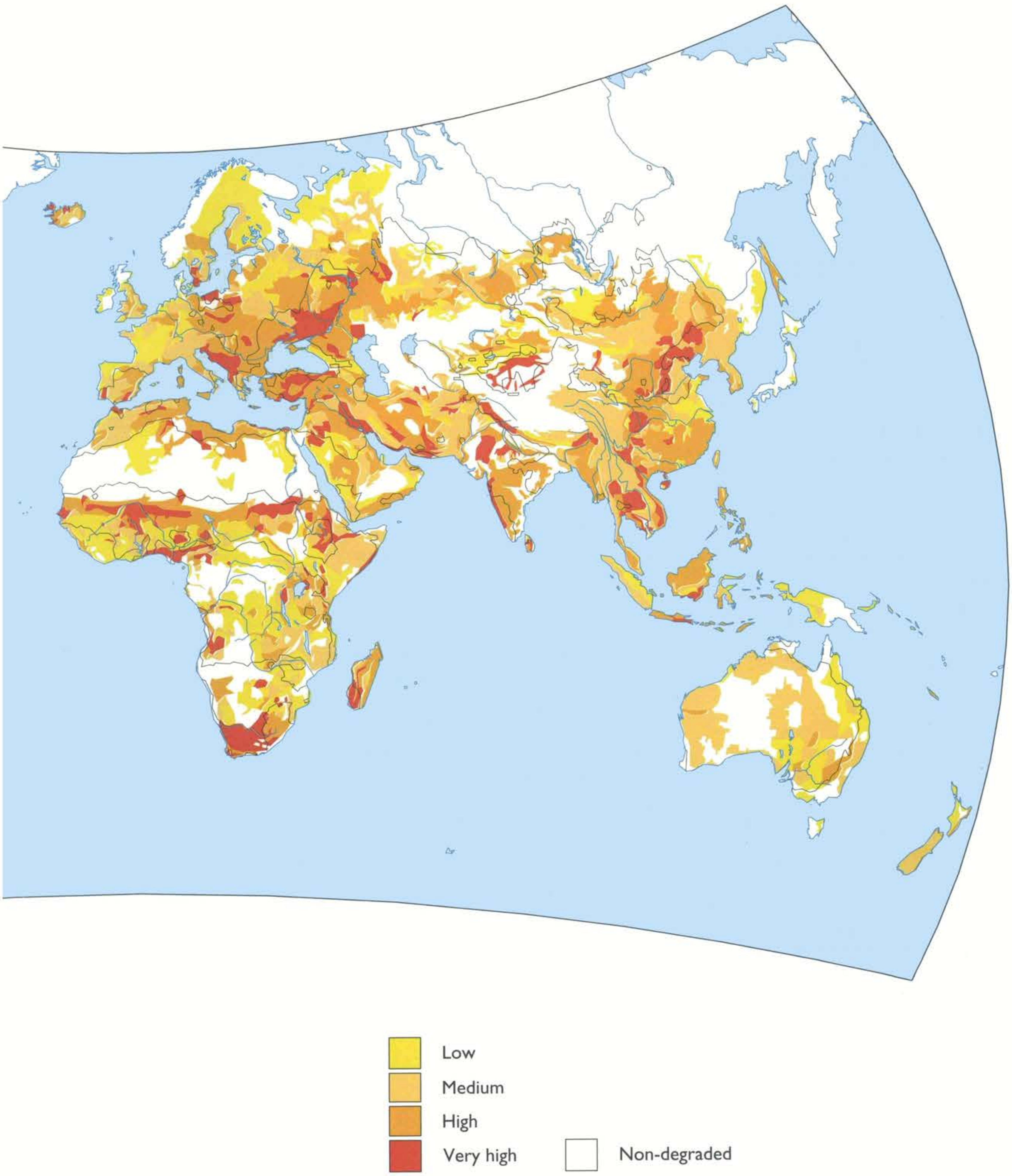

Low
Medium
High
Very high
Non-degraded

Table 1.2 Summary of GLASOD soil degradation types (Oldeman 1988)

Degradation type	*Description*
Soil displacement	
WATER EROSION	
On-site	
• Loss of topsoil	uniform loss by surface wash and sheet erosion
• Terrain deformation	irregular displacement characterised by major rills, gullies or mass movement
Off-site	
• Sedimentation	of harbours, lakes, reservoirs and burial of coral, shellfish beds or seaweed
• Flooding	including by riverbed filling, riverbank erosion, excessive siltation of basin land
WIND EROSION	
On-site	
• Loss of topsoil	uniform displacement by deflation
• Terrain deformation	uneven displacement characterised by major deflation hollows, hummocks or dunes
Off-site	
• Overblowing	encroachment on structures such as roads and buildings, sand blasting of vegetation
Internal soil deterioration	
CHEMICAL DETERIORATION	
• Loss of nutrients	often leading to reduced production (e.g. accelerated acidification of soils in the humid tropics)
• Pollution and acidification from bio-industrial sources	excessive addition of chemicals (e.g. organic manure, acid rain)
• Salinization	caused by activities such as irrigation
• Discontinuation of flood-induced fertility	resulting from any conservation method that controls flooding and leads to discontinuation of natural replenishment of nutrients by flooding
• Gleysation	as a result of waterlogging
• Other chemical problems	such as catclay formation upon drainage of some coastal swamps; negative chemical changes and development of toxicities in paddy fields
PHYSICAL DETERIORATION	
• Sealing and crusting of topsoil	
• Compaction	by heavy machinery on a soil with weak structural stability or on soils in which humus is depleted
• Deterioration of soil structure	due to dispersion of soil material by Na (and Mg) salts in the subsoil (sodication)
• Waterlogging	human-induced soil hydromorphism; flooding and submergence (excluding paddy fields)
• Aridification	human-induced changes of the soil moisture regime towards an aridic regime (e.g. by lowering of the local base groundwater level by changing grassland to wheat cultivation) but excluding deep groundwater depletion
• Subsidence of organic soils	by drainage, oxidation

process. Soil compacted by the use of heavy agricultural machinery, for example, is often characterised by enhanced runoff rates and increased soil erosion by water (see page 40).

Although soil degradation is affected by a range of human-induced and natural processes (Figure 1.10), it is important to stress that it is by definition a social problem. While purely environmental processes such as leaching and erosion occur with or without human interference, the description of these processes as 'degradation' implies social criteria relating land to its current or possible future uses (Blaikie 1985, Blaikie and Brookfield 1987). The GLASOD database and maps indicate areas of soil degradation caused by human misuse, such as soil erosion enhanced above natural rates by the clearance of vegetation for use as fuel. The causes of degradation are noted

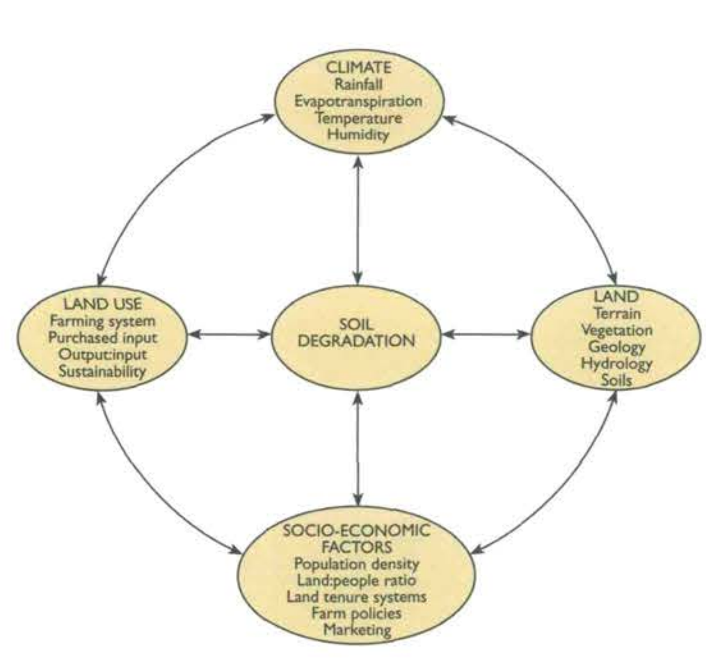


Figure 1.10 The factors causing soil degradation and their interactions (Lal and Stewart 1990)

(see page 44), and these causes all represent forms of human mismanagement. Areas where the sustainability of human land uses is threatened by natural processes, such as the blowing of salt from a salt flat on to nearby cropland, are not identified on the maps.

In the field, however, the distinction between such 'active' and 'passive' human involvement is not always clear-cut. This problem is often particularly acute in dryland areas where the environment is naturally highly dynamic. During a drought period for example, in which vegetation cover is naturally less extensive than during non-drought periods, the distinction between enhanced soil erosion driven by climate and that due to human activities will inevitably be subjective to some degree. Nonetheless, this distinction is important because it should affect the strategies adopted to combat desertification. If degradation is a function of natural processes which undermine the previously sustainable land use, the solution may be to change the land use, particularly in societies which are unable to implement expensive soil conservation or rehabilitation schemes. If, by contrast, degradation results from poor land management (Figure 1.11), then improving that form of management may be the solution. It is appropriate in either case to focus on the human side of the desertification equation, because that is the side that can be altered successfully,. Identifying whether human activities are involved actively or passively is a vital first step.

Figure 1.11 Severe gully erosion is one potential outcome of land use pressures in susceptible drylands, as in this example from NE Brazil (UNEP/Morera Hector/Topham)

The GLASOD project was executed by more than 250 soil scientists from all over the world with 20 regional co-ordinators. The first step was to divide the global land surface into physiographic mapping units. These units were delineated so that each showed a certain degree of homogeneity of topography, geology, soils, climate, vegetation and land use. The next step was to evaluate the degree, relative extent, the rate in the recent past and causative factors for each type of human-induced soil degradation shown in Table 1.2 that occurred in the physiographic unit. In the absence of scientific measurements and monitoring of soil degradation for most of the world's land surface, the data that did exist for each unit were supplemented by expert opinions from the participants who were selected for their intimate knowledge of local conditions. Using a standardised set of guidelines to ensure uniformity in reporting, soil degradation was assessed over the recent past, ideally averaged over the previous 5 or 10 years, but in some cases the time period extended over recent decades.

The involvement of a large number of scientists with personal experience of regional conditions is an important strength of GLASOD. The complex interplay of soil degradation processes and their spatial variability needs to be assessed according to local conditions and forms of land use. This point is well-illustrated in the case of off-site effects of soil erosion. Soil is often lost from steep highland slopes and deposited in lower, more level sites. If the lower site contains a reservoir, the accumulation of sediment is a problem: it causes a loss of storage capacity requiring expensive remedial efforts, as Tolouie *et al.* (1993) describe in an example from north-western Iran. In other situations, however, a similar transport of soil from upper slopes may be regarded as beneficial to lower areas. In southern Zimbabwe, Scoones (1992) reports that the transfer of sediment in this way can actually give significant advantages for production because the lower valley areas are better locations for water retention and therefore cultivation, livestock production and human occupation (Ingram 1991). The same situation has been described in the pastoral lands of central Australia (Pickup and Chewings 1988).

This spatial variability in the operation of degradation processes also illustrates an important point concerning the scale of analysis. In the Zimbabwe example, Scoones (1992) noted that despite indications of increased degradation in his study area, livestock production had not declined (although this could have been because negative effects on production lagged the initial degradation). The scale of the GLASOD maps depicted in this atlas is such that mapping polygons of large areas on the ground are coloured according to an average severity of degradation. Actual areas of degraded soil within each polygon are shown in the accompanying tables, but it should be noted that within individual polygons there may still be areas that benefit from degradation processes elsewhere, as in the examples cited above. The global maps are designed to give an overall, if exaggerated, impression of the scale of the soil degradation problem worldwide. Once key problem areas are identified on the global scale, however, more detailed appraisals of local situations are needed before appropriate solutions to degradation problems can be developed.

Areas identified as non-degraded in the GLASOD survey are designated either 'stable' or 'non-used' by human populations. Stable areas are either those regions where human intervention is minimal due to very low

Table 1.3 Proportions of stable, soil-degraded and non-used land by region for all climate zones (%)

Region	*Stable land*	*Degraded land*	*Non-used land**	*Total*
Africa	39	17	44	100
Asia	48	18	34	100
Australasia	61	12	27	100
Europe	61	23	16	100
North America	54	7	39	100
South America	72	14	14	100
World	52	15	33	100

*Non-used land is land not used as agricultural land, permanent pasture or covered by forest or woodland
Source: GLASOD

population densities, or regions where soil improvement or protection programmes have been successfully implemented. Non-used areas are those not used for agricultural purposes, permanent pasture or covered by forest or woodland. This category includes land with little value for agricultural use, such as the large tracts of hyperarid desert in the central Sahara and parts of Arabia, but land in this category may also be potentially productive, but has been put to other land uses (e.g. built-on areas and roads).

Severity is calculated according to a combination of the degree of soil degradation and the percentage of the area affected. The degree to which soil is degraded has been estimated in relation to changes in agricultural suitability, in relation to reduced productivity and in some cases in relation to its biotic functions. The degree of degradation is classified according to the following scheme:

None: there is no sign of present degradation from water or wind erosion, from chemical or physical deterioration; all original biotic functions are intact. Such land is considered stable.
Light: the terrain is suitable for use in local farming systems, but with somewhat reduced agricultural productivity. Restoration to full productivity is possible by modifications of the management system. The original biotic functions are still largely intact.
Moderate: the terrain is still suitable for use in local farming systems, but with greatly reduced agricultural productivity. Major improvements are required to restore productivity (such as draining for water-logged or salinized land, or contour banks for eroded land). The original biotic functions are partially destroyed.
Strong: The terrain is not reclaimable at the farm level. Major engineering works are required for terrain restoration. The original biotic functions are largely destroyed.
Extreme: The terrain is not reclaimable and impossible to restore. The original biotic functions are completely destroyed.

The importance of the land use in question should be noted here. While a moderately degraded soil for example may require major structural alterations to restore productivity under one particular land use, for a less

Table 1.4 Soil degradation degree by region: inside the drylands (susceptible) and outside the drylands (others) areas (million ha)

Region		*Light*	*Moderate*	*Strong*	*Extreme*	*Total degraded*	*Total non-degraded*	*Total*
Africa	Susceptible	118.0	127.2	70.7	3.5	319.4	966.6	1286.0
	Others	55.7	64.6	52.8	1.7	174.8	1504.8	1679.6
Asia	Susceptible	156.7	170.1	43.0	0.5	370.3	1301.5	1671.8
	Others	137.8	174.2	64.6	0.0	376.6	2207.6	2584.2
Australasia	Susceptible	83.6	2.4	1.1	0.4	87.5	575.8	663.3
	Others	13.0	1.6	0.8	0.0	15.4	203.5	218.9
Europe	Susceptible	13.8	80.7	1.8	3.1	99.4	200.3	299.7
	Others	46.7	63.8	8.9	0.0	119.4	531.4	650.8
North	Susceptible	13.4	58.8	7.3	0.0	79.5	652.9	732.4
America	Others	5.5	53.7	19.5	0.0	78.7	1379.8	1458.5
South	Susceptible	41.8	31.1	6.2	0.0	79.1	436.9	516.0
America	Others	63.0	82.4	18.9	0.0	164.3	1087.2	1251.5
World	Susceptible	427.3	470.3	130.1	7.5	1035.2	4134.0	5169.2
	Others	321.7	440.3	165.5	1.7	929.2	6914.3	7843.5
Total		749.0	910.6	295.6	9.2	1964.4	11 048.3	13 012.7

Source: GLASOD

demanding land use the alterations required may be less intensive.

The relative extent of degradation was expressed using five categories:

Infrequent: up to 5% of the unit is affected.
Common: 6–10% of the unit is affected.
Frequent: 11–25% of the unit is affected.
Very frequent: 26–50% of the unit is affected.
Dominant: more than 50% of the unit is affected.

With four categories for the degree of degradation, and five categories for the extent of degradation, 20 combinations are possible. These combinations have been grouped into four severity classes as illustrated below Map 1.10, and each severity class is given a different shading.

Interpreting the maps and tables

The maps on the following pages indicate the areas in which degradation occurs and the severity of that degradation according to the accompanying key. The tables, however, provide a more detailed indication of the actual areas within units affected. It is important to note that while maps indicate degradation severity, which is a combination of the degree of degradation and its extent, the tables show information according to the actual areas affected by degree of degradation.

Map 1.10 illustrates the overall global assessment of human-induced soil degradation. It does not distinguish between different types of degradation, which is dealt with in the following pages. Comparison of Map 1.10 and Table 1.3 illustrates the point that the maps are designed to give an overall indication of where degraded areas are located, but because the methodology dictates that each mapping polygon is coloured according to the degradation severity, the map appears to exaggerate the overall area affected. Hence, as Table 1.3 shows, 15% of the global land area shown in Map 1.10 suffers soil degradation (the yellow portion of Figure 1.12), while 52% is non-degraded stable land. At the continental level, Europe is shown to suffer the most widespread soil degradation problem, affecting 23% of the continent's land area. By contrast, just 7% of North America is so-affected. Table 1.3 also highlights the wide range in the relative proportions of the continents classified as non-used (i.e. not used for agriculture, permanent pasture or covered by forest or woodland). While Europe and South America both have less than 20% of their land areas in this category, more than 40% of Africa is not currently used for agricultural or other biomass uses.

Table 1.4 gives the soil degradation areas inside and outside the susceptible drylands. Worldwide, just over 1 billion ha, or 20%, of the global extent of susceptible dryland soils is currently being degraded by human activity. A similar absolute area of soils outside the susceptible drylands is being degraded, but this represents approximately 13% of the total non-susceptible dryland area. Figure 1.12 and Table 1.4 indicate that in the light, moderate and extreme categories more land area in susceptible dryland regions is being degraded than in non-dryland regions ('Others' in Table 1.4). When the total used land (disregarding non-used areas) inside and outside the susceptible drylands is considered, no less than 29% of the world's used susceptible dryland soils are degraded, in contrast to 15% of the global area used outside the susceptible drylands.

The continental breakdown of the data reveals that a greater proportion of Europe's susceptible dryland soils suffer from degradation (99.4 million ha: 32% of the total area) than in any other continent. Most of these degraded soils occur in southern Portugal, Spain, Corsica, Sicily, southern Italy, Greece, Ukraine and Russia, although the large majority of these areas are degraded to a light or moderate degree. In North America, by contrast, 11% of susceptible dryland soils are degraded, again largely to a light or moderate degree. A light and moderate degree of degradation also predominates in South America, where 15% of susceptible dryland soils are degraded. Australia's 13% affected area is very largely degraded to a light degree. Asia, with 22% of its susceptible dryland soils degraded, has far greater areas affected to a strong and extreme degree, but the dryland soil degradation situation is most critical in Africa. With 25% of its susceptible drylands affected by soil degradation, Africa has the highest proportion of its susceptible dryland soils affected to a strong and extreme degree.

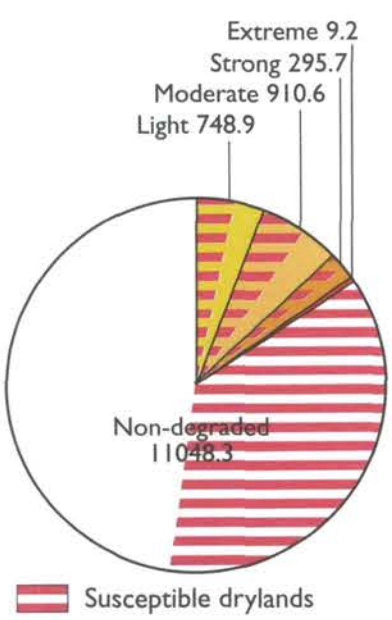


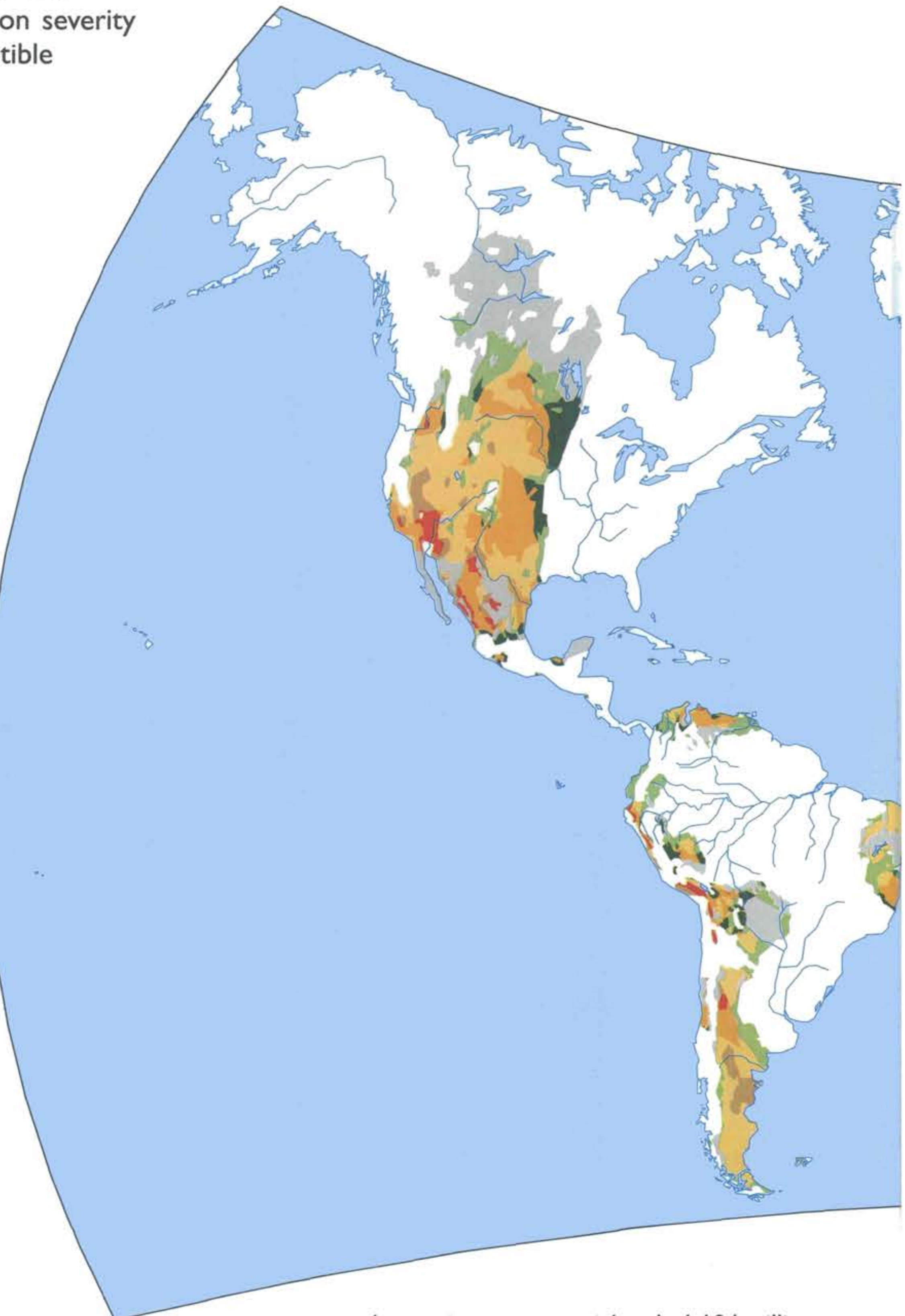
Figure 1.12 Global land area by degree of soil degradation (million ha). Source: GLASOD

Soil Degradation in Drylands

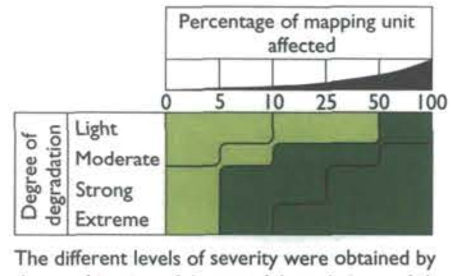
Introduction

As already explained, this atlas concentrates on arid, semiarid and dry subhumid areas (the susceptible drylands), within which almost 20% of the total land area is recorded as experiencing soil degradation. Hyperarid areas are excluded from the main consideration: they generally have very strong desert characteristics and nutrient-deficient soils, giving limited potential for degradation by many processes; and they offer only limited opportunities for degradation-inducing human land uses. A notable exception to this rule, the Nile Valley, is discussed in more detail in Section 2. Map 1.11 therefore concentrates on areas where natural dryland soil properties are susceptible to degradation and where land use activities may cause desertification.

Map 1.11 Soil degradation severity in susceptible drylands



Approximate equatorial scale 1:104 million
Source: UNEP/ISRIC, CRU/UEA



The different levels of severity were obtained by the combination of degree of degradation and the percentage of the area affected

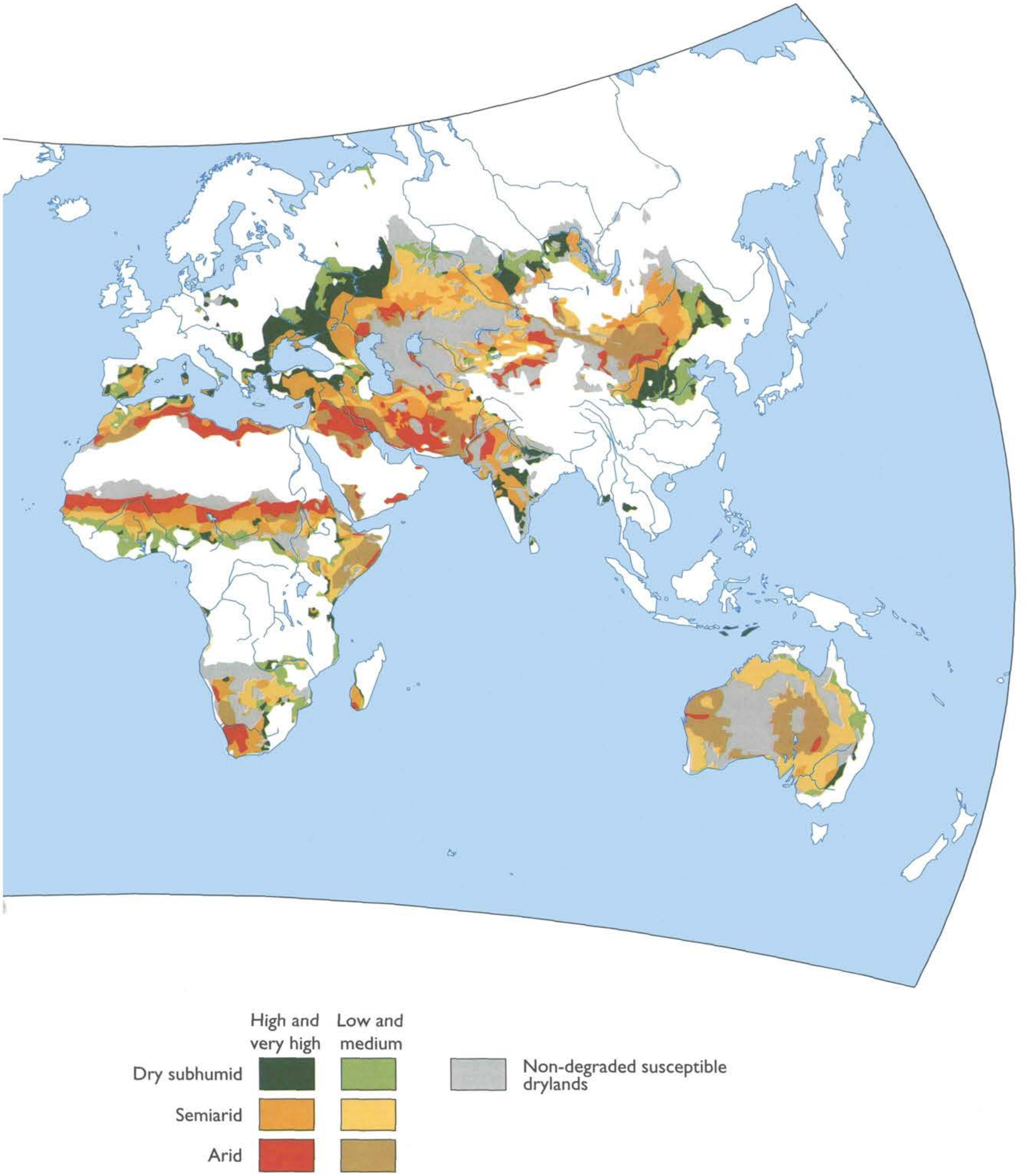

High and very high
Low and medium
Dry subhumid
Semiarid
Arid
Non-degraded susceptible drylands

Table 1.5 Predominant soils of dryland regions (after FAO 1993a, Lal 1990 and Dregne 1976)

USDA soil order	*FAO major soil groups*	*Description*	*Moisture storage capacity*	*Inherent soil fertility*	*Proportion of world land area (%)*
Entisols	Aernosols Lithisols Fluvisols	Sandy to loamy soils of recent origin formed from wind blown sands on the margins of deserts or lacustrine or marine deposits. Used for nomadic grazing, dry farming, or irrigated agriculture. Mostly on flat land, loose and easily worked and easily eroded by wind. They may receive fresh sediments and hence be regularly rejuvenated.	Low, seasonal waterlogging risk	Low to moderate	13.1
Aridisols	Xerosols Yermosols	Formed in environments with a pronounced dry season. Medium to fine textured soils that may contain high soluble salts, calcium carbonate or gypsum, forming surface or subsurface crusts, or calcite pendants. Loose structure and stoney in some places. Easily erodible by wind and water.	Low, moderate to high	Moderate to high	11.3
Mollisols	Chernozems Kastanozems Phaeonems Rendzinas	Semiarid steppe soils, mostly porous, well-aerated and stable structures with high organic matter contents. Used for pastures or dry farming. Can be easily leached of their nutrients, but less erodible.	Moderate to very high	High	3.7
Alfisols	Luvisols	Soils common in flat or gently sloping land with well defined clayey horizons. Favourable physical characteristics, suitable for a wide range of agricultural use. Usually well-drained, and are highly susceptible to water erosion.	Moderate to high	Moderate	2.1
Vertisols	Vertisols	Develop in sediments or weathered rock that are fine in texture and form smectite clay, which swells when wet and cracks when dry. These soils have low infiltration rates, high susceptibility to runoff and erosion, and are quickly affected during drought periods. They have great agricultural potentials for a variety of crops, but special management practices are required.	Moderate to high	High	1.3
Total					31.5

Soil degradation in drylands

The soils commonly found in dryland regions are distinctive in a number of ways (Dunkerley and Brown 1997). They have low organic matter contents, due to the generally low plant biomass, and are therefore dominantly mineral soils of an immature or skeletal type. Many, but not all types tend to exhibit a low clay content compared with soils from more humid areas. Low precipitation levels also mean that dryland soils are little affected by leaching, so that soluble salts tend to accumulate at a certain level in the soil profile dependent upon the local water table or the depth of moisture infiltration. A classification of dryland soil types, their characteristics and their relative preponderance is shown in Table 1.5.

An important characteristic that makes dryland soils especially vulnerable to degradation is the slowness of their recovery from a disturbance. Since water is often not available, or only in very limited amounts in a few places, new soil is formed slowly, although actual data on dryland soil formation rates are relatively hard to come by in the literature, not least because it is such a slow process. For the loess soils of the US Great Plains, Kirkby (1980) suggests a soil formation rate of about 0.2 mm y^{-1}, but this figure drops to 0.02 mm y^{-1} in the arid south-west. In semiarid Kenya, Lal (1984) reports a rate of 1 mm y^{-1} but Dunne *et al.* (1978) estimate that rates may fall below 0.01 mm y^{-1}.

The general deficiency in moisture means that salts, once accumulated, tend to remain *in situ*. Moisture deficiency also discourages recolonisation by plants that have been removed or damaged, and the build-up of organic matter is slow since it is usually consumed rapidly under warm conditions. Re-establishment rates for soil bacterial and fungal populations have been little studied, but the nitrogen fixation capability of dryland soil is thought to require at least 50 years to recover from a serious disturbance (Belnap 1995). Although dryland soils tend to be characterised by low nutrient contents (Buckley *et al.* 1987), and hence have a low level to recover after degradation, the ability of soils in dry areas to recover from negative changes in the soil/land surface is generally lower than in humid areas. In other words, dryland soils have a low resilience.

Susceptibility to degradation

In drylands, susceptibility to degradation by specific processes varies spatially and is affected by a range of environmental characteristics. Drylands are more susceptible to wind erosion than any other biome because soils tend to be dry, poorly cemented and sparsely covered by protective vegetation. Susceptibility to wind erosion once any protective vegetation cover has been disturbed, is affected by the particle size distribution of the soil. Soils with a high clay content will naturally offer greater resilience to deflation than silty or sandy soils

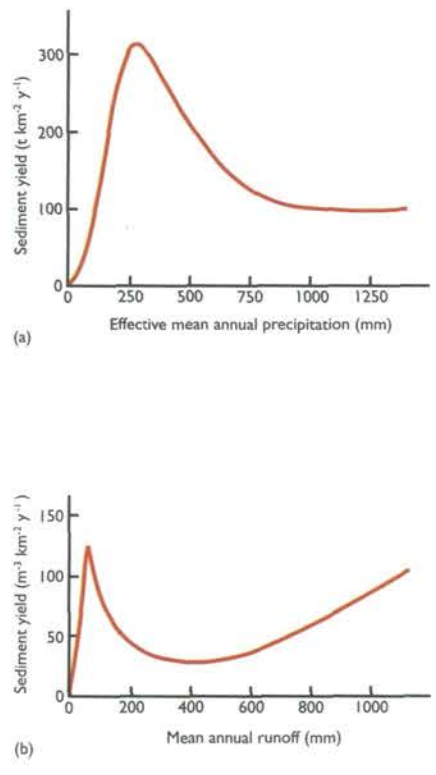


Figure 1.13 Proposed relationships between sediment yield and (a) effective annual precipitation (Langbein and Schumm 1958); (b) mean annual runoff (Douglas 1967)

because of their increased particle cohesion. With mixed grain sizes, selective winnowing of the deflatable component can dramatically reduce soil fertility and resilience (Chepil and Woodruff 1963). Extensive areas of ancient wind-lain sediments in drylands are particularly vulnerable to deflation following damage to the protective vegetation cover. Such reactivation of Quaternary aeolian sediments has been noted in many drylands, including the African Sahel (e.g. Thiemeyer 1992), the Great Plains of the USA (e.g. McCauley *et al.* 1981), north-west India (e.g. Kumar *et al.* 1993) and China (e.g. Zhu Zenda and Liu Shu 1983).

Compared to other world climate zones, dryland areas have long been recognised as particularly susceptible to water erosion (Figure 1.13) because although the precipitation levels are relatively low and do not support a year-round cover of protective vegetation, they are often highly erosive when rain does fall (Langbein and Schumm 1958). This generic relationship highlights the importance of soil degradation in drylands. In areas that receive an effective mean annual precipitation above 300 mm, increased precipitation encourages greater vegetation growth which protects the soil from water erosion, while below the 300 mm-mark, erosion declines as precipitation levels decline. Topography affects susceptibility to water erosion. High relative relief encourages runoff even when only moderate areas of the ground surface have lost the protection of a vegetation cover. Water erosion is rarely spatially continuous and often manifests itself through rilling and gullying (Moss *et al.* 1982). The soils with most potential for loss of nutrients are those that naturally contain higher nutrient concentrations in the first place. These are the very soils which offer some of the greatest potential for agricultural development.

Like wind erosion, some forms of *in situ* degradation are most commonly encountered in drylands. Salinization is an obvious example. Salt-affected soils occur mostly in dryland regions where evapotranspiration exceeds rainfall and hence leaching and transportation of salts to the oceans is not as effective as in more humid regions (Rhoades 1990). Salinization occurs locally where water is available, either from groundwater sources or from perennial rivers with headwaters in more humid areas, as in the case of parts of the Colorado River basin of the USA and the Indus valley in Pakistan. While salt-affected soils are found extensively under natural conditions, salinity problems of great concern to agriculturalists arise when previously productive soil becomes salinized as a result of irrigation (Szabolcs 1987) or the replacement of natural vegetation by certain crops (e.g. Berg *et al.* 1991), so-called secondary salinization (Thomas and Middleton 1993). Salinity problems on poorly managed irrigation schemes are also often associated with physical deterioration of dryland soils through waterlogging. This combination of degradation processes, so ironic in drylands in that they are intimately linked to excessive application of irrigation water combined with poor drainage, has been widely reported from all over the dryland realm (e.g. Abrol *et al.* 1988, Szabolcs 1987, see also page 144).

Overall, susceptibility to degradation, in total or with regard to specific processes, is by no means even throughout the drylands. The occurrence of degradation reflects a range of natural contemporary and antecedent conditions and processes and the wide variety of land uses practised by the human occupants of such regions.

Table 1.6 Soil degradation degree by region in susceptible dryland areas (million ha)

Region	*Aridity zone*	*Light and moderate*	*Strong and extreme*	*Total*
Africa	Dry subhumid	25.2	12.1	37.3
	Semiarid	69.9	39.6	109.5
	Arid	150.2	22.3	172.5
Asia	Dry subhumid	70.6	7.7	78.3
	Semiarid	124.2	17.2	141.4
	Arid	131.9	18.8	150.7
Australasia	Dry subhumid	4.2	0.6	4.8
	Semiarid	32.9	1.0	33.9
	Arid	48.9	0.0	48.9
Europe	Dry subhumid	59.0	2.3	61.3
	Semiarid	30.8	2.6	33.4
	Arid	4.8	0.0	4.8
North America	Dry subhumid	15.0	3.2	18.2
	Semiarid	50.9	2.3	53.2
	Arid	6.3	1.6	7.9
South America	Dry subhumid	21.4	2.3	23.7
	Semiarid	43.9	4.0	47.9
	Arid	7.5	0.0	7.5
Total		897.6	137.6	1035.2

Source: GLASOD

Spatial patterns

Some 1035 million ha of the world's susceptible drylands are affected by soil degradation, of which about 87% are in the light and moderate categories. The distribution by continent and by aridity zone is given in Table 1.6. High and very high severity degradation can be seen to be a phenomenon that is particularly significant in Africa, whether considered in relative or absolute terms. As noted in the previous section, soil degradation affects some 320 million ha in Africa out of a total of 1286 million, or about a quarter of the susceptible drylands.

Table 1.7 Soil degradation type by susceptible dryland climate zones (million ha)

Climate zone	*Type of soil degradation*: *Water erosion*	*Wind erosion*	*Chemical deterioration*	*Physical deterioration*	*Total*
Dry subhumid	141.0	46.8	22.5	13.2	
Semiarid	213.2	150.3	40.9	15.1	
Arid	113.3	235.3	37.3	6.5	
Total	467.4	432.4	100.7	34.7	1035.2

Note: column totals may not correspond exactly due to rounding of decimals
Source: GLASOD

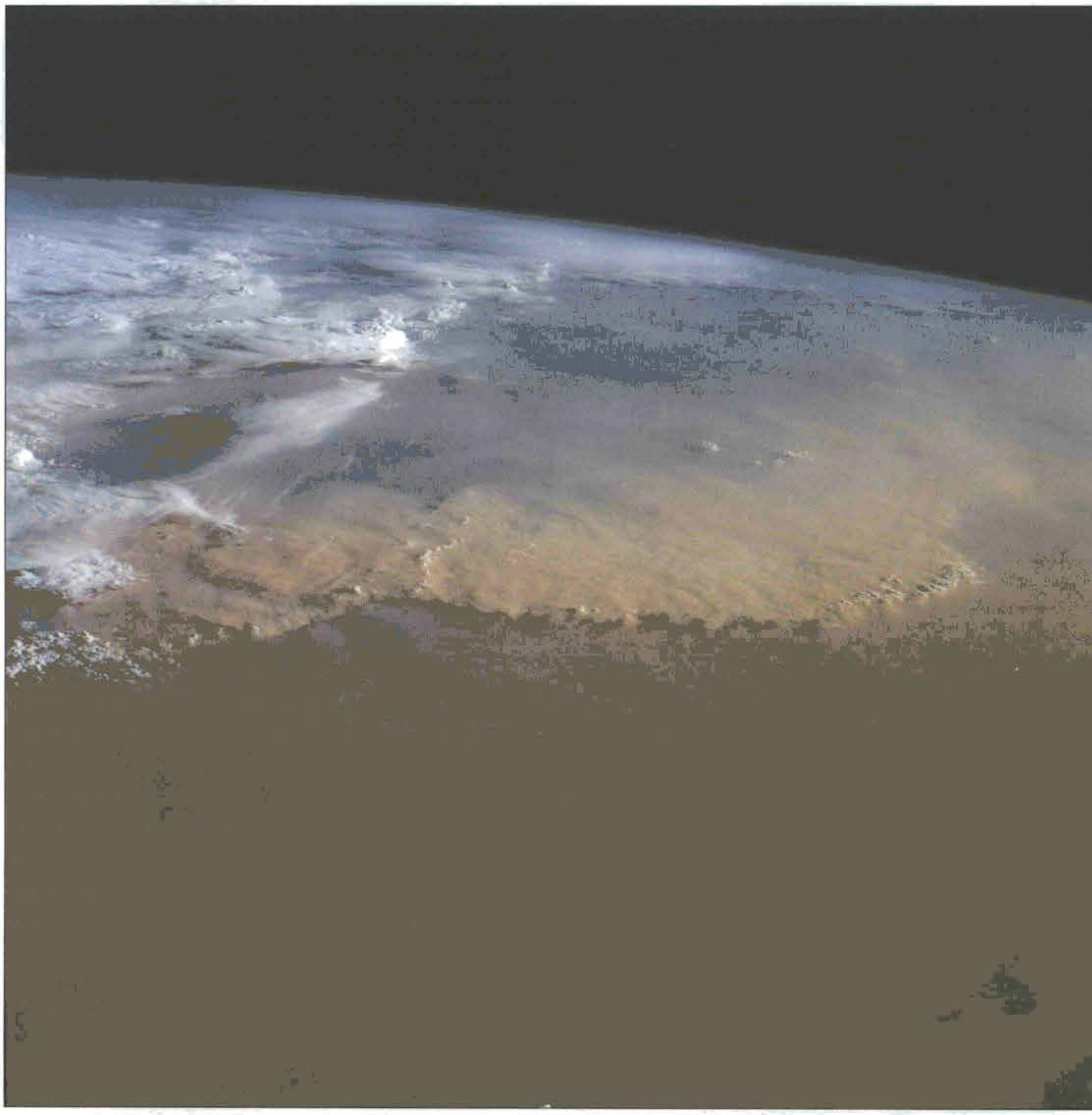


Figure 1.14 Dry, bare soils in arid environments can be susceptible to the liberation of fine particles as dust. In extreme cases, dust storms can have an impact beyond their source area. In this space shuttle photograph a major dust outbreak in the northern Sahel of Niger is moving west-south-west (NASA)

Regardless of how much of the areas are affected, the map indicates that the distribution of the severest degradation in Africa, Asia and North America occurs on the wetter margins of the drylands. Scrutiny of Table 1.6, however, suggests a rather different picture. Degradation in Africa and Asia is largely concentrated in semiarid and arid areas: actual areas affected increase from dry subhumid zones, through the semiarid zones, to peak in their extent in arid areas, although Map 1.11 indicates that degradation appears to be minimal in the northern Sahel. A similar pattern is identifiable in Australasia, albeit that the level of overall severity is consistently lower than in Africa and Asia. In the Americas, by contrast, greater areas of land are degraded in the semiarid zone than in the dry subhumid and arid zones combined. The situation is different again in Europe, where degradation in the dry subhumid zone greatly exceeds that in the semiarid and arid parts of the continent. These patterns are explained further in later sections.

The relative importance of different degradation types

At the world scale, the GLASOD database indicates that dryland degradation is dominated by soil erosion (Table 1.7). Water erosion accounts for 45% of the degraded area and wind erosion 42%. Chemical deterioration accounts for 10% and physical deterioration just 3%. This situation, however, varies according to aridity zone. Given likely variations in vegetation cover, it is not surprising that 60% of soil degradation in arid zones is by wind erosion (Figure 1.14), a figure which falls to 21% in dry subhumid areas. The reverse trend is found for water erosion, to which the wetter dryland areas are inevitably going to be more susceptible. Water erosion is the dominant form of degradation in dry subhumid and semiarid zones, accounting for 63% and 51% of the degradation in these zones respectively. In arid areas, water erosion accounts for 29% of the degradation. These and other trends are explored in greater detail in the analyses of different degradation types at the global scale.

The relative importance of water erosion for all continents except Africa is shown by the data in Table 1.8. In Asia, Europe, North America and South America water erosion is responsible for degrading slightly more land than wind erosion, while in Australasia water erosion is by far the most dominant form, affecting 80% of the susceptible drylands to wind erosion's 18%. In Africa, however, more land is degraded by wind erosion than by water erosion. Only in Asia is the proportion of drylands affected by chemical deterioration greater than the global average. Here the figure is 14%. The global average proportion of land affected by physical deterioration is exceeded only in Europe, where 9% of the susceptible drylands are affected.

Table 1.8 Soil degradation type by region in susceptible dryland areas (million ha)

Region	*Type of soil degradation* Water erosion	Wind erosion	Chemical deterioration	Physical deterioration	Total
Africa	119.1	159.9	26.5	13.9	319.4
Asia	157.5	153.2	50.2	9.6	370.5
Australasia	69.6	16.0	0.6	1.2	87.4
Europe	48.1	38.6	4.1	8.6	99.4
N America	38.4	37.8	2.2	1.0	79.4
S America	34.7	26.9	17.0	0.4	79.0
Total	467.4	432.4	100.7	34.7	1035.2

Source: GLASOD

Table 1.9 Soil degradation type by degree in susceptible dryland areas (million ha)

Degree	*Type of soil degradation* Water erosion	Wind erosion	Chemical deterioration	Physical deterioration	Total
Light	175.1	197.2	44.3	10.8	427.3
Moderate	208.5	215.4	31.4	15.0	470.3
Strong	79.0	18.0	24.2	8.9	130.1
Extreme	4.8	1.8	0.8	0.0	7.5
Total	467.4	432.4	100.7	34.7	1035.2

Note: column and row totals may not correspond exactly due to rounding of decimals
Source: GLASOD

For all types of degradation except chemical deterioration, the greatest areas of susceptible dryland affected are degraded to a moderate degree (Table 1.9). For wind erosion, 95% of all degradation is in the light and moderate categories. The proportion of land degraded by water erosion to these degrees is 82%, while for physical deterioration it is 74%. Of all types of degradation, the greatest proportion of land affected to a strong degree is by *in situ* processes: 24% of the susceptible drylands degraded by chemical deterioration, and 26% of the susceptible drylands degraded by physical deterioration. No soils affected by physical deterioration are degraded to an extreme degree.

These global patterns are investigated further in the pages on specific degradation types, followed by analysis of the human activities causing degradation and an appraisal of the relationships between soil degradation and vegetation.

Soil Erosion

Introduction

Soil erosion is a natural phenomenon occurring over much of the earth's land surface, but its extent and intensity have been greatly increased by human activities over many centuries (Brown and Wolf 1984). While wind erosion might intuitively be expected to be the most serious hazard in drylands, because of the low levels of rainfall and relatively sparse vegetation covers, these same factors do not discount the significance of erosion by water. Indeed, the occurrence of many rainfall events in association with high intensity convective storms can give rise to very high levels of surface runoff and therefore erosion (Yassoglou 1995). Soil erosion has a dual significance when land degradation is considered: not only does it affect the productivity of the land in areas experiencing the problem, but it can also have negative off-site impacts in areas that receive eroded soil, for example contributing to reservoir sedimentation (Barrow 1987) and the occurrence of dust storms that may travel hundreds of kilometres from source areas (Worster 1979). Negative off-site impacts can also threaten the productivity of agricultural systems; for example, Mohammed *et al.* (1995) report how wind blown sand is threatening the northwestern area of the Gezira irrigation schemes in the Sudan. Positive off-site impacts can sometimes accrue too; for example when erosion leads to the movement of soil from steep slopes that are difficult to cultivate to flatter, more easily accessible, valley bottoms.

Human-induced soil erosion is not a new phenomenon in drylands. It has been documented in the Mediterranean basin from as long ago as 400 BC (e.g. Rubio 1995), while sedimentary evidence points to cultivation-induced erosion occurring in Mexico before the Spanish conquest (O'Hara *et al.* 1993). However, it has been during the twentieth century, with the expansion of agriculture to lands that are marginal for crop production and the intensification of agricultural methods, that soil erosion has become an issue of considerable global concern. The 1930s 'Dust Bowl' on the Great Plains of the USA was particularly important in generating a realisation of how susceptible dryland environments can be vulnerable to soil erosion by both wind and water (e.g. Bennett 1938). Concern about the susceptibility of drylands to soil erosion, and an awareness of a need to better understand the physical processes and social pressures leading to soil loss, have been a characteristic of scientific and anti-degradation initiatives over several decades (e.g. Kellogg 1956, UNOSTD 1987, Fantechi *et al.* 1995).

Soil erosion embraces a complex set of processes and interacting factors. Whether soil is eroded or conserved depends on the balance achieved between *erosivity* and *erodibility* (Morgan 1995). Erosivity refers to the forces that can liberate particles from the main soil mass and is controlled primarily by natural criteria such as wind strength and rainfall intensity during a storm (Table 1.10). Erodibility is the susceptibility of a soil to the loss of material, which is influenced by both physical soil characteristics and land use and management techniques (Table 1.10). Some surface characteristics may enhance one erosion type but inhibit another; for example a crusted soil may be less susceptible to wind erosion but more susceptible to erosion by running water, while the timing of human actions that enhance erodibility relative to erosivity events is also important in terms of whether actual erosion is enhanced or not (Kar 1996). By reducing natural plant densi-

Table 1.10 Summary of factors affecting soil erosivity and erodibility

EROSIVITY	
OF WIND	OF WATER
frequency of strong winds	frequency of rainfall events
duration of windy events	storm duration
wind velocity	raindrop impact velocity
wind turbulence	raindrop size
ERODIBILITY	
SOIL VARIABLES	SURFACE VARIABLES
particle size and shape	slope angle (water erosion)
organic material (binding) content	vegetation cover density
clay content	plant height and shape
cohesiveness	leaf/stem fineness
infiltration capacity	presence of surface crusts
moisture content	plant orientation (wind erosion)
porosity and permeability	

BOX 1
GLASOD methodology for assessing degree of water erosion

The definitions and criteria used for the designation and identification of water erosion were as follows (after Oldeman 1988). The categories incorporate an assessment of both the loss of top soil by erosion and terrain deformation through rilling, gullying and, where appropriate, various forms of mass movement. The definitions are as follows:

Slight: For soils with a rooting depth exceeding 50 cm, part of the top soil has been removed. Shallow rills with a spacing of 20–50 m may be present. Thin soils have rills at least 50 m apart. In areas under pastoralism the perennial plant cover or the original or optimal plant cover extends over at least 70% of the surface*.

Moderate: All the top soil will have been removed from deep soils. Rills may be present, less than 20m apart. Gully development will have occurred at a spacing of 20–50 m. Thin soils will have lost part of the top soil and are likely to have rills with a 20–50 m spacing. Perennial/optimal vegetation cover in pastoral areas reduced to 30–70%*.

Strong: All the top soil and part of the subsoil will have been removed from areas of deep soils, with moderately deep gullies less than 20 m apart. All the top soil will have been removed from areas of thin soils, exposing bedrock, weathered bedrock, or a hardpan. In pastoral areas the perennial/original/optimal vegetation cover will be less than 30%*.

Extreme: The general criterion, that the land is unreclaimable and impossible to restore, applies. Map 12 shows land units in which human-induced water erosion occurs. The map representation does not necessarily mean that water erosion is the only form of degradation occurring in a particular unit, nor that water erosion is the dominant degradation process in a unit.

*Known maximum coverage of perennials under good management as practised during some time in the past.

BOX 2
GLASOD methodology for assessing wind erosion

The nature of wind erosion necessitates the recognition of three effects (Oldeman *et al.* 1990). These are the loss of *topsoil*, defined as a loss by which a uniform part of the topsoil is removed, *terrain deformation*, in which there is an irregular or uneven displacement of soil material resulting in major hollows, hummocks or dunes, and the *overblowing of sediment* affecting physical structures such as roads and buildings. Taking these three effects into account wind erosion was considered in the GLASOD survey using the following criteria:

Slight: in deep soils: topsoil partly removed and/or few (10–40% of area) shallow (0–5 cm) hollows; in shallow soils: very few (<10%) shallow hollows; in pastoral country: groundcover of perennials of the original/optimal vegetation >70%*.

Moderate: in deep soils: all topsoil removed or with common (40–70% of area) shallow (0–5 cm) hollows, or few (10–40%) moderately deep (5–15 cm) hollows; in shallow soils: topsoil partly removed or few (10–40%) shallow (0–5 cm) hollows; in pastoral areas: groundcover of perennials of the original/optimal vegetation 30–70%*.

Severe: in deep soils: all topsoil and part of subsoil removed or with many (>70% of area) shallow (0–5 cm) or common (40–70%) moderately deep (5–15 cm) or few (10–40%) deep (15 cm) hollows/blowouts; in shallow soils: all topsoil removed: bedrock or hardpan is exposed. In pastoral country: groundcover of perennials of the original/optimal vegetation is <30%*.
Map 13 shows land units in which human-induced wind erosion occurs. The map representation does not necessarily mean that wind erosion is the only form of degradation occurring in a particular unit, nor that wind erosion is the dominant degradation process in a unit.

*Known maximum coverage of perennials under good management as practised during some time in the past.

ties, replacing a perennial plant cover with a seasonal crop, ploughing steep slopes and causing surface compaction by livestock trampling or the use of mechanised farming implements, human actions can readily enhance the potential for erosion (Thomas and Middleton 1994, Belnap 1995). Ploughing during the dry season in anticipation of later rains can lead to high water erosion rates during the first rain storms that occur, but if rains fail or are late, the soft ploughed surface is left vulnerable to wind erosion (Dresch 1986, Kar 1996). Particularly in semiarid lands, there is the potential for linkages between water and wind erosion, with rain drop impacts loosening particles that can subsequently be blown away.

The GLASOD survey included an assessment of both water and wind erosion and the human factors that may contribute to enhanced erosion. Box 1 outlines the methodology for the assessment of water erosion and Box 2 that for wind erosion. The respective methodologies allowed all the key on-site components of soil erosion that lower productive potential to be assessed: top soil erosion by sheetwash and rilling (Savat and de Ploey 1982); gullying (Oostwoud Wijdenes and Bryan 1994); pipe development (Bryan and Harvey 1985); aeolian deflation (Watson 1990) and the development of deflation hollows and hummocky dunes (Zhao 1988).

Water erosion

The nature of dryland water erosion

A soil is commonly unable to absorb all the energy and mass provided by rain drops hitting the ground surface (Yariv 1976, Stocking 1977). A plant cover will act as an interceptor, reducing direct drop impact on the soil surface and reducing the energy available for erosion. Reductions in vegetation cover or changes in vegetation type, brought about by land use decisions and/or moisture-deficient periods are therefore likely to have a significant impact on erosion rates in drylands (e.g. Abrahams *et al.* 1995). Bare or partially exposed soils are vulnerable to the dislodgement of individual particles by drop impact, and any subsequent generation of overland flow which transports the particles down slope; but runoff and sediment yields fall dramatically as plant cover increases (Francis and Thornes 1990). The ability of a soil to absorb raindrop energy is therefore dependent on antecedent environmental conditions and the nature of the rainfall event.

In drylands, the sporadic nature of rainfall events makes the study of water erosion processes difficult, while the range of variables that interact to influence the actual occurrence of erosion further complicates elucidation of the problem (Thornes *et al.* 1996). To this end, soil erosion models, for example those developed by the MEDALUS research programme, are making significant contributions to enhanced understanding (e.g. Kirkby *et al.* 1990, Thornes 1995). The ability of a soil to resist erosion is dependent upon the range of particle sizes, the chemistry and organic content as well as the nature and extent of the vegetation cover (Imeson 1995). It is therefore possible to categorise the soils of drylands according to their sensitivity to erosion based on the occurrence of key criteria (Table 1.11). The depth of a soil also influences its ability to absorb and store rainfall (Yassoglou 1995), while overland flow is more likely to be generated on steeper slopes. Dryland rainfall events are often noted for their intensity, which may exceed soil infiltration rates, further encouraging overland flow, which can itself attain higher velocities than in non-dryland areas.

Processes of water erosion

Water erosion results not only in the loss of top soil and in off-site effects, but also in a reduction of water and nutrient storage capacity. The processes of water erosion that occur on slopes are as follows:

Splash erosion: the impact of raindrops may liberate particles from the soil surface. On slopes this contributes to the general downslope movement of particles, or can loosen particles which are then transported downslope by flow or wash processes.

Sheetwash or interill erosion: occurs as a continuous film of water when the ground surface is smooth or as a myriad of small interconnected rivulets on rougher surfaces. Sheetwash is effective in eroding particles loosened by both drop impact and the progressive increase in soil water content that occurs during a rainfall event (Lal 1990). Sheetwash normally affects the upper parts of hillslopes, and where it operates across an entire slope can lead to the reduction in fertility in upslope locations and a corresponding increase at the slope foot (e.g. Scoones 1992). Plant productivity can mirror this pattern. Sheetwash can be difficult to monitor and may therefore be underestimated.

Rilling: results from the concentration of overland flow (Scoging 1989). The depth of water in rills is greater and more turbulent than in sheetwash, giving the potential for larger particles to be entrained. Rills develop into networks that can, over time, extend laterally and up slope. However, they can be removed by ploughing and need not be an obstacle to agriculture, though they will reappear unless remedial action is taken to deal with their cause.

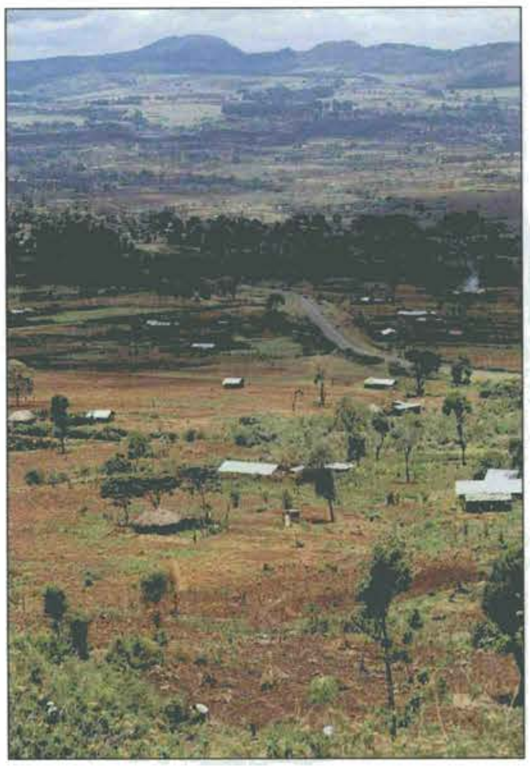


Figure 1.15 Population growth has driven the expansion of agriculture on to steep slopes in rural dryland Kenya (DSG Thomas)

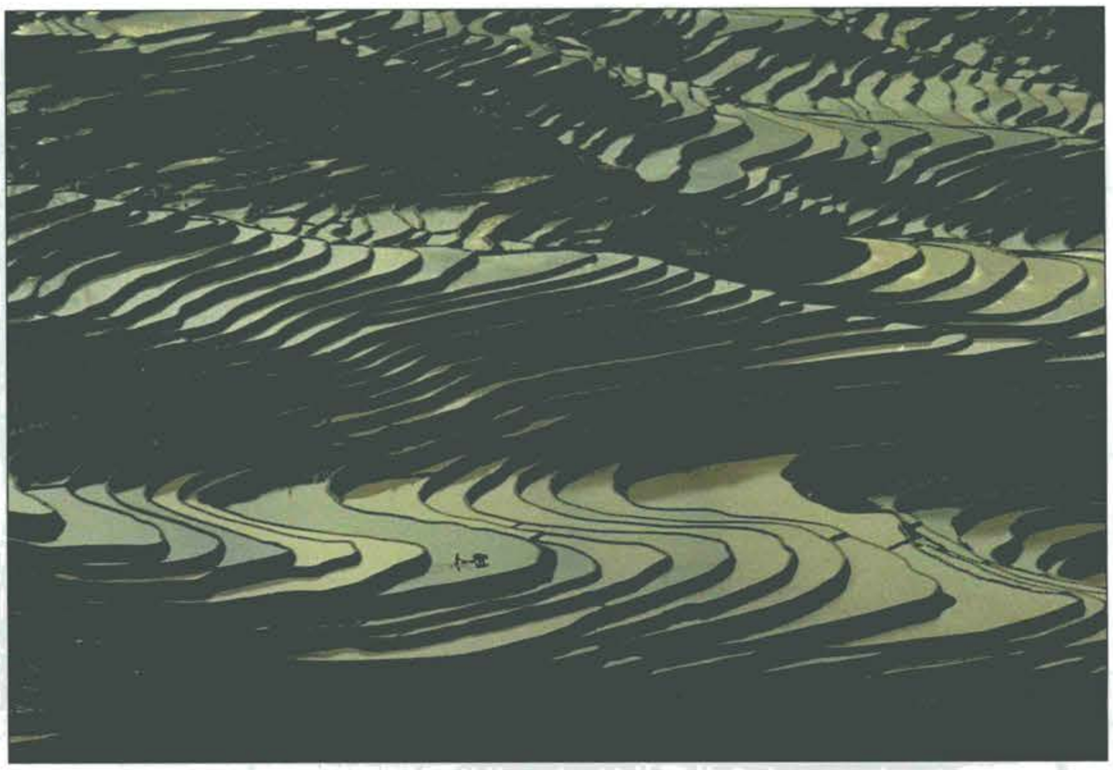


Figure 1.16 Terracing of steep slopes is one widely employed, effective measure to reduce water erosion as here in China (UNEP/Cheung Pak/Topham)

Gullying: can result from the widening and deepening of rills, or by a change in surface conditions on a slope leading to a sudden increase in runoff (Oostwoud Wijdenes and Gerits 1994). A gully can be defined as having a steep head and sides, wider than 0.3 m and deeper than 0.6 m. Development can be rapid and not only do gullies act as effective conduits for the removal of soil from fields, but they obstruct movement and inhibit the use of mechanised farming methods.

Piping: is erosion through the development of subsurface tunnels. This can occur naturally, particularly in dispersive soils (Table 1.11) or those subject to marked action by burrowing animals (Yair and Rutin 1981), but it is enhanced by a reduction in surface vegetation and a loss of internal binding by roots.

Human activities and water erosion

Water erosion is readily accelerated by many human actions in dryland ecosystems, but notably through the intensification and expansion of agriculture and a range of activities, including fuel wood collection and high intensity pastoralism, that can reduce the vegetation cover. The move towards greater farming intensities can lead to the abandonment and even removal of traditional soil conservation methods such as terracing to facilitate mechanised cultivation (Thomas and Middleton 1994). On the one hand mechanisation can lead to surface compaction (see page 40) that enhances runoff, but on the other mechanised deep ploughing can loosen soils and enhance their susceptibility to runoff erosion (Dresch 1986).

The pressures that cause the intensification or expansion of agriculture commonly accrue from the need to feed growing populations (Figure 1.15). However, more people working on the land can also reduce erosion risks by water and enhance productivity if particular attention is paid to soil conservation techniques. Such techniques include the construction or restoration of terracing on steep slopes (Figure 1.16), or the construction of bunds that trap water and sediment that moves downslope. Bunds can also be part of runoff-trapping water harvesting schemes that irrigate crops as well as reduce erosion (Rapp and Hasteen-Dahlin 1990, Atampugre 1993), and may therefore serve a dual benefit in susceptible drylands.

Dryland water erosion assessment

GLASOD data (Table 1.13) indicate that human-induced water erosion affects about 140 million ha in dry subhumid areas, 213 million ha in semiarid areas and 113 million ha in arid areas. This translates to 9% of the global susceptible drylands (Figure 1.17). It even affects 11 million ha in the hyperarid zone. Translated to percentages of the total land area by aridity zones, this indicates that 11% of the subhumid zone, 9% of the semiarid zone and 7% of the arid zone are subject to water erosion degradation, with an additional 1% of hyperarid areas affected. Water erosion affects 48% of the total degraded land area in the susceptible drylands. It is thus a substantial problem, though one that varies significantly both in terms of distribution (Table 1.12) and degree of severity.

Only European and African susceptible drylands contain areas that have experienced extreme water erosion (Map 1.12), affecting more than 2 million ha in each case (Table 1.12). In Europe, water erosion is a longstanding problem in the dry subhumid and semiarid Mediterranean lands (Grove 1996), with Yassoglou (1987) noting that about 40% of the land area of Spain and Greece has suffered serious reductions in productivity as a result. Murcia, in south-east Spain, has experienced particularly severe water erosion problems (Albaladejo 1990) with one or two severe erosion events occurring in most years (Lopez Bermudez and Albaladejo 1990). Erosion severity is very high under both traditional vine and almond stands and more intensive land use.

When overall severity is considered, in addition to parts of southern Europe, water erosion is a major degradation problem in parts of Africa's Sahel belt, for example

Table 1.11 Five categories of soils sensitive or resistant to water erosion. Modified from information in Imeson (1995)

Characteristics	*Susceptible to (+); resistant to (-)*
Soils sensitive to loss of organic matter because of low clay content	+ sheetwash erosion
Soils with moderately high clay contents that shrink and swell	+ rill and gully erosion – sheetwash erosion
Sandy soils with high infiltration rates: sensitive to crusting	if crusted + sheetwash erosion (*also* + wind erosion)
Soils with high content of water soluble salts which enhance dispersive potential	+ gully erosion + piping
Soils with high stone and rock fragment content	– all erosion types through enhanced infiltration or + erosion through funnelling of surface flow

Table 1.12 Degree of water erosion in susceptible dryland areas (million ha)

Degree	*Africa*	*Asia*	*Australasia*	*Europe*	*North America*	*South America*	*Total*
Light	28.5	49.6	67.5	6.4	10.3	12.8	175.1
Moderate	36.6	91.2	2.1	38.0	23.9	16.7	208.5
Strong	51.5	16.7	0.0	1.4	4.2	5.2	79.0
Extreme	2.5	0.0	0.0	2.3	0.0	0.0	4.8
Total	119.1	157.5	69.6	48.1	38.4	34.7	467.4

Note: column and row totals may not correspond exactly due to rounding of decimals
Source: GLASOD

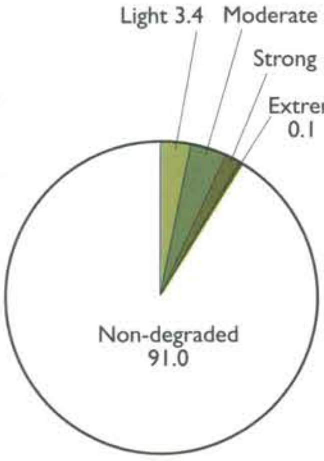


Figure 1.17 Global susceptible drylands degraded by water erosion (%). Source: GLASOD

Yatenga Province in Burkina Faso where gully erosion has been especially severe (Atampugre 1993). In northern Ethiopia up to one billion tonnes of top soil are lost each year from steep slopes (Brown and Wolf 1986). This problem also occurs in some of the more densely populated dry subhumid areas of Kenya. In the GLASOD report of Hakkeling (1989), the recent restoration of terracing is reported to be leading to reduced water erosion problems in some Kenyan areas possessing steep slopes. This is a good example of the positive actions that can be taken by local communities to lessen desertification problems. In hilly northern Somalia, conservation measures started in the 1970s have been hampered or have fallen into disrepair due to the civil war in the 1990s. However, the region is sparsely populated and it is only around settlements that erosion problems attain moderate proportions (Hakkeling 1989). In dryland Africa south of the equator, major water erosion problem areas occur notably in intensively settled former homelands in South Africa (Dardis *et al.* 1988) but also in the more sparsely settled Karoo, where sheetwash is significant (Rowntree 1988).

In some cases, erosion can be attributed to the intensification and inappropriate use of agricultural practices on steep slopes, as in the Loess Plateau area of China. Light-to-moderate degree water erosion leading to the loss of topsoil affects over 50% of the dry subhumid areas to the west and north of Beijing, according to GLASOD reports. While the clearance of natural vegetation for agriculture is the prime reason for this, the construction of terracing assists in the amelioration of the problem. In other cases, severity can be related to specific changes in human activities. In Yemen high water erosion severity is related to the recent breakdown of traditional soil management terraces and their associated cultivation systems, leading to significant erosion damage.

Wind erosion

The nature of wind erosion

When and where wind erosion occurs depends upon the mutual interaction between erosivity and erodibility factors (Bullard *et al.* 1997, Table 1.10). Before wind erosion occurs it is necessary for wind speed to exceed a threshold velocity, related to the particle size and coherence characteristics of the soil (Gillette *et al.* 1980), with atmospheric turbulence increasingly recognised as important in the process of aeolian entrainment (Wiggs 1997). Key aspects of the soil surface with regard to wind erosion include surface roughness, the presence of stones and boulders, and perhaps most importantly, the percentage cover, height, density, structure and orientation of vegetation (Ash and Wasson 1983). In some marginal drylands, for example in Rajasthan, India, ancient dune sands laid down under even drier climatic conditions in the past, are particularly susceptible to erosion when they are utilised for agriculture (Kar and Joshi 1992).

Processes of wind erosion

The wind erosion of soils has many environmental impacts, perhaps most importantly for the farmer, but also for a range of other human activities. The problems caused by wind erosion occur both on- and off-site and can be looked at conveniently according to the three fundamental phases of aeolian activity: deflation, transport and deposition.

Soil deflation, which preferentially removes sand- and silt-sized particles, occurs through three main processes. The finest, silt-sized, particles may be removed from the soil surface in *suspension*, which may transport silt grains high into the atmosphere leading to long distance transport. Fine and medium-sized sand grains are commonly moved by *saltation*,

Table 1.13 Distribution of susceptible dryland water erosion by climate zone in each continent (million ha)

Region	*Dry subhumid*	*Semiarid*	*Arid*
Africa	25.1	59.2	34.8
Asia	54.9	69.9	32.7
Australasia	4.1	26.3	39.3
Europe	34.7	12.8	0.6
N America	10.7	24.4	3.3
S America	11.5	20.6	2.5
Total	141.0	213.2	113.2

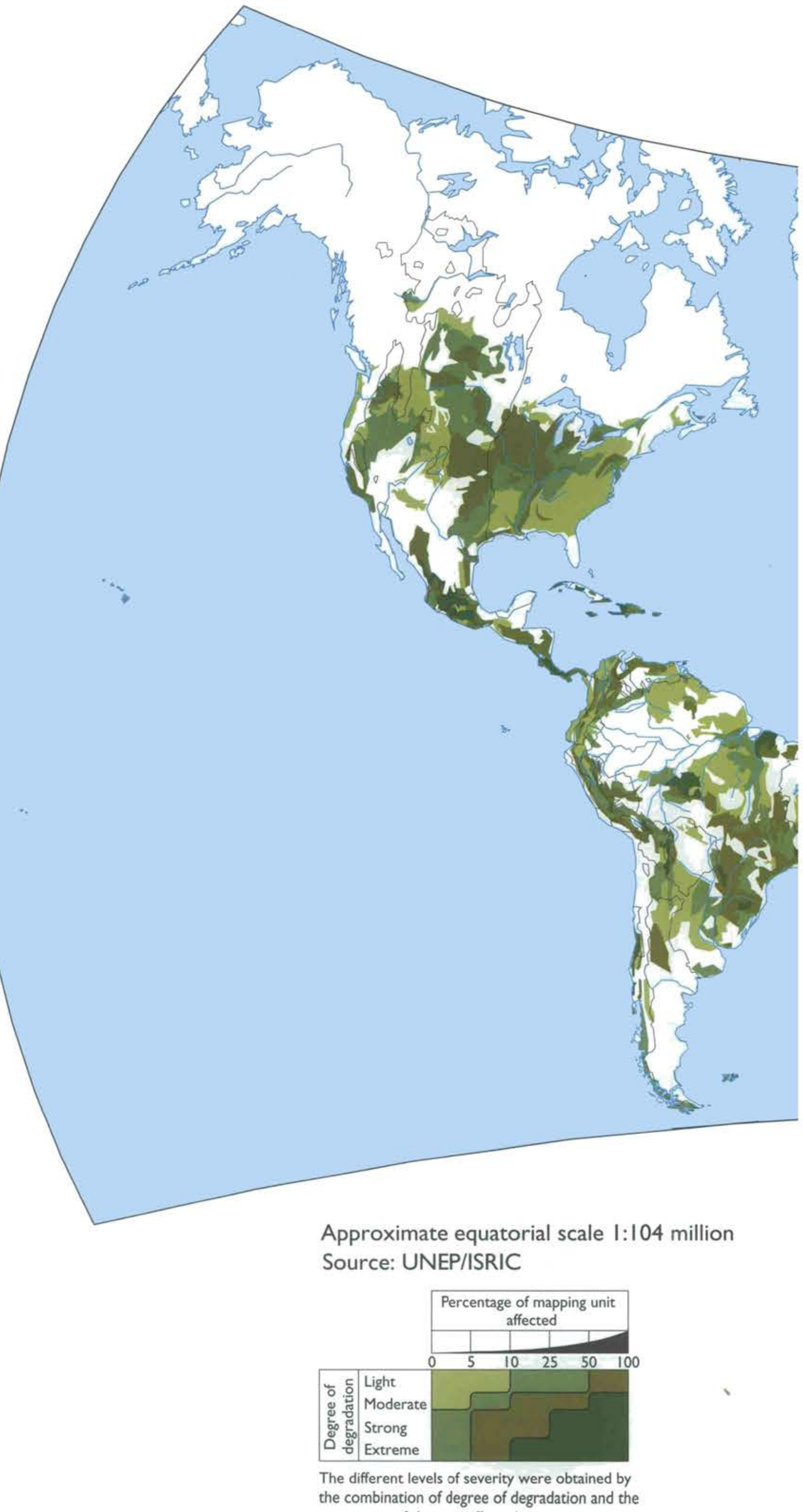
Note: column totals may not correspond exactly due to rounding of decimals
Source: GLASOD

whereby particles are raised from the ground surface and transported forward in a hopping motion. The coarsest sand grains mainly move by creep which is a forward rolling motion of grains. In practice, during a sediment moving event all three processes often operate simultaneously.

Since two of the most important influences on soil structure are the ratio of sand, silt and clay, and the presence of binding agents such as those produced by decomposing organic matter, removal of silt and organics has adverse effects on structure. These particles also exert important influences upon the soil's ability to retain moisture, hence their removal reduces a soil's moisture-retention capacity (Fryrear 1981). The fine silt and clay particles also have the maximum concentration of nutrients attached to them, so that their removal reduces fertility.

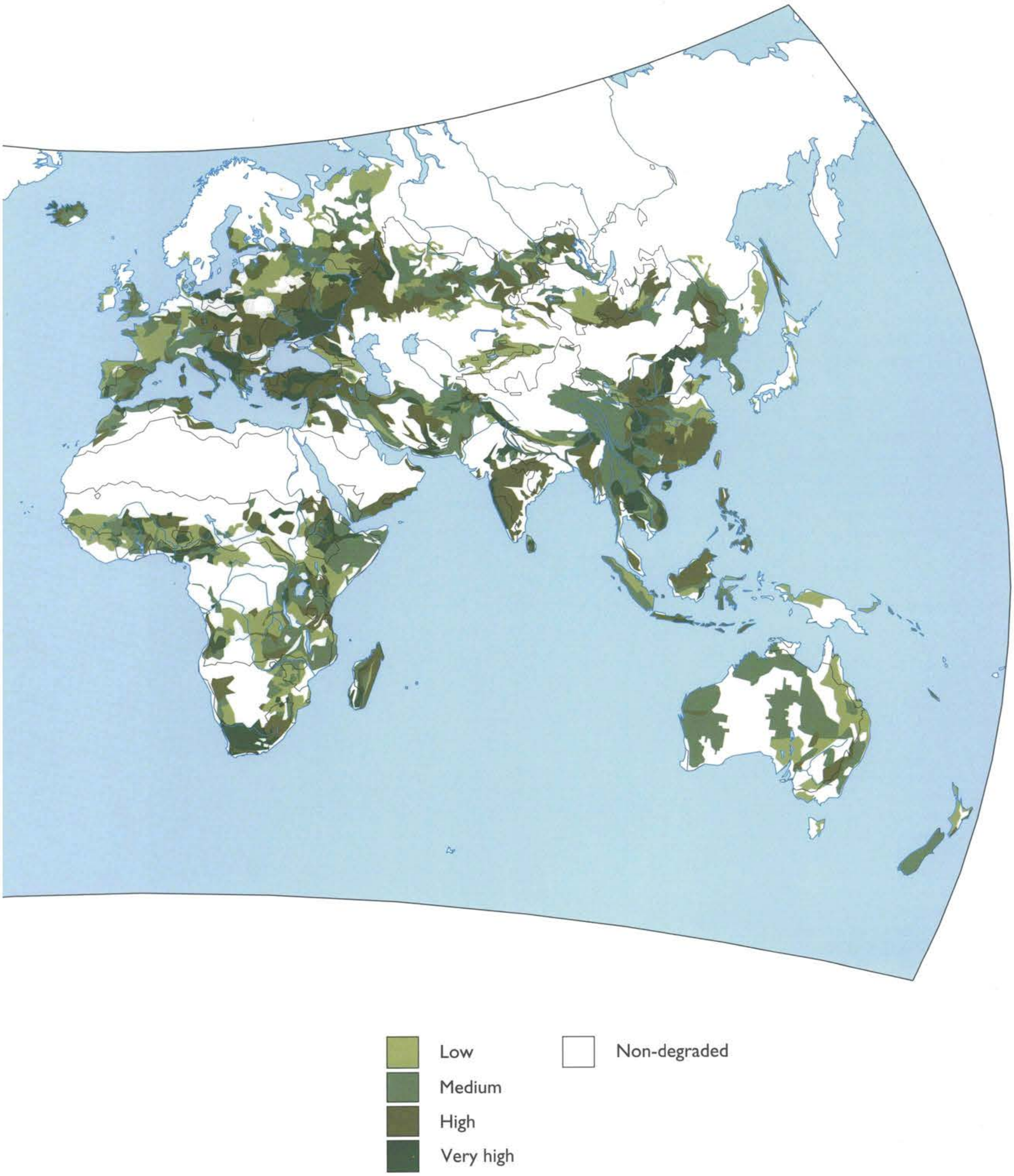
Abrasion by moving soil particles is probably the most serious problem associated with the transport phase of wind erosion. Soil clods may be blasted by bouncing particles, impoverishing soil structure and rendering it more erodible, and crops are abraded and in extreme cases cut from their roots (Fryrear *et al.* 1973). The abrasion of plants enhances evapotranspiration losses and may in fact be a more significant factor in causing falling yields than the loss of the soil itself (Thomas and Middleton 1994). Structures such as walls, telegraph poles and fences can also be affected by wind abrasion, and it may be necessary to undertake protection or stabilization measures (Figures 1.18 and 1.19). Large volumes of eroded material in dust clouds present visibility problems to road and air transport, and can adversely affect radio and satellite communications (Middleton 1997). The inhalation of fine particles can cause respiratory problems for humans and animals, and some particles may be disease-carrying pathogens (Ervin and Lee 1994).

Map 1.12 Water erosion severity



Approximate equatorial scale 1:104 million
Source: UNEP/ISRIC

The different levels of severity were obtained by the combination of degree of degradation and the percentage of the area affected



Low
Medium
High
Very high
Non-degraded

Table 1.14 Distribution of susceptible dryland wind erosion by climate zone in each continent (million ha)

Region	*Dry subhumid*	*Semiarid*	*Arid*
Africa	1.6	30.7	127.5
Asia	15.1	52.1	85.9
Australasia	0.0	6.4	9.5
Europe	17.4	17.3	4.0
N America	6.8	27.3	3.7
S America	5.9	16.4	4.6
Total	46.8	150.2	235.2

Note: column totals may not correspond exactly due to rounding of decimals
Source: GLASOD

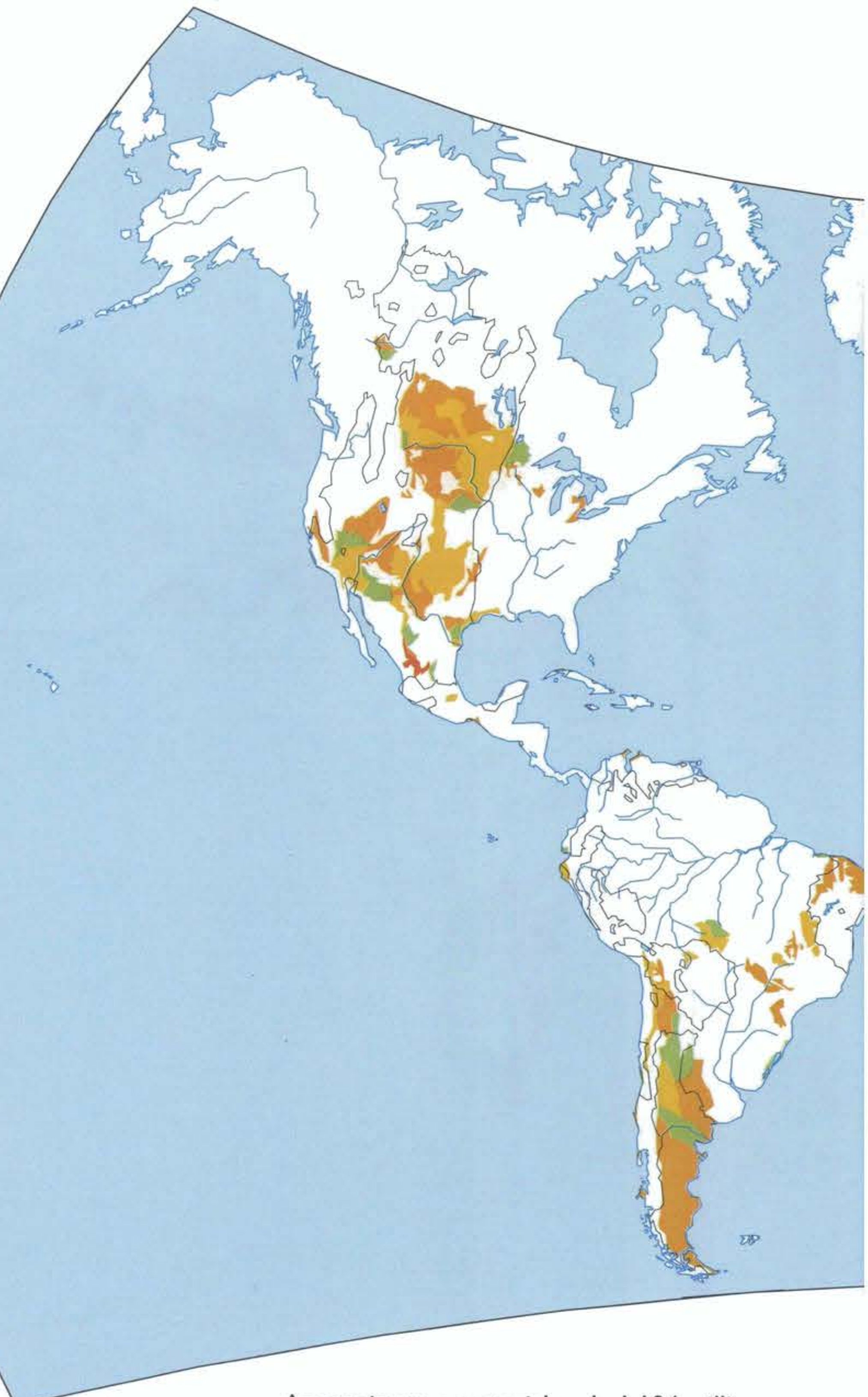
Material deposited by wind can bury and kill plants, fill ditches and block roads, railways, runways and pipelines (Watson 1990). Salts transferred by deflation events can increase the salinity of groundwater and be highly destructive of buildings. There may, however, be positive aspects to the deposition of wind-eroded soils. Their high nutrient content provides additional fertility to marine and terrestrial ecosystems, the latter both in terms of soils and as direct nutrient inputs through leaves to certain plant types such as rice, wheat and grasses.

Human activities and wind erosion

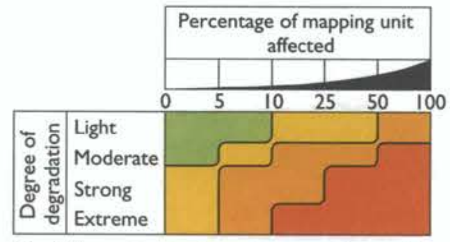
The human activities most commonly responsible for inducing wind erosion are those that change or remove vegetation cover and those that destabilise natural soil surfaces. There is a variety of causes for such environmental damage. Vegetation is cleared for agriculture and building and used for fuel and fodder. It is also modified by cropping practices. Stable soil surfaces may be disturbed by ploughing, by the trampling of animals, by off-road vehicle use, construction, mining or military manœuvres. In Kuwait, Saudi Arabia and Iraq, the breaking up of desert surfaces by tank movements during the Gulf war has led to both the activation of underlying sands and an increase in dust storms (El-Baz 1994).

Dry soils with a low organic content are most susceptible to wind erosion, and if human activities reduce surface vegetation covers in such areas then the potential for wind erosion is increased. As attempts to conduct agriculture have expanded towards the dry margins of susceptible drylands, and such soils are often found close to the limits of the hyper-arid deserts, then wind erosion may increase. The effects of wind erosion may be limited where only small fields are cultivated, but the creation of large cultivatable areas suitable for

Map 1.13 Wind erosion severity



Approximate equatorial scale 1:104 million
Source: UNEP/ISRIC



The different levels of severity were obtained by the combination of degree of degradation and the percentage of the area affected

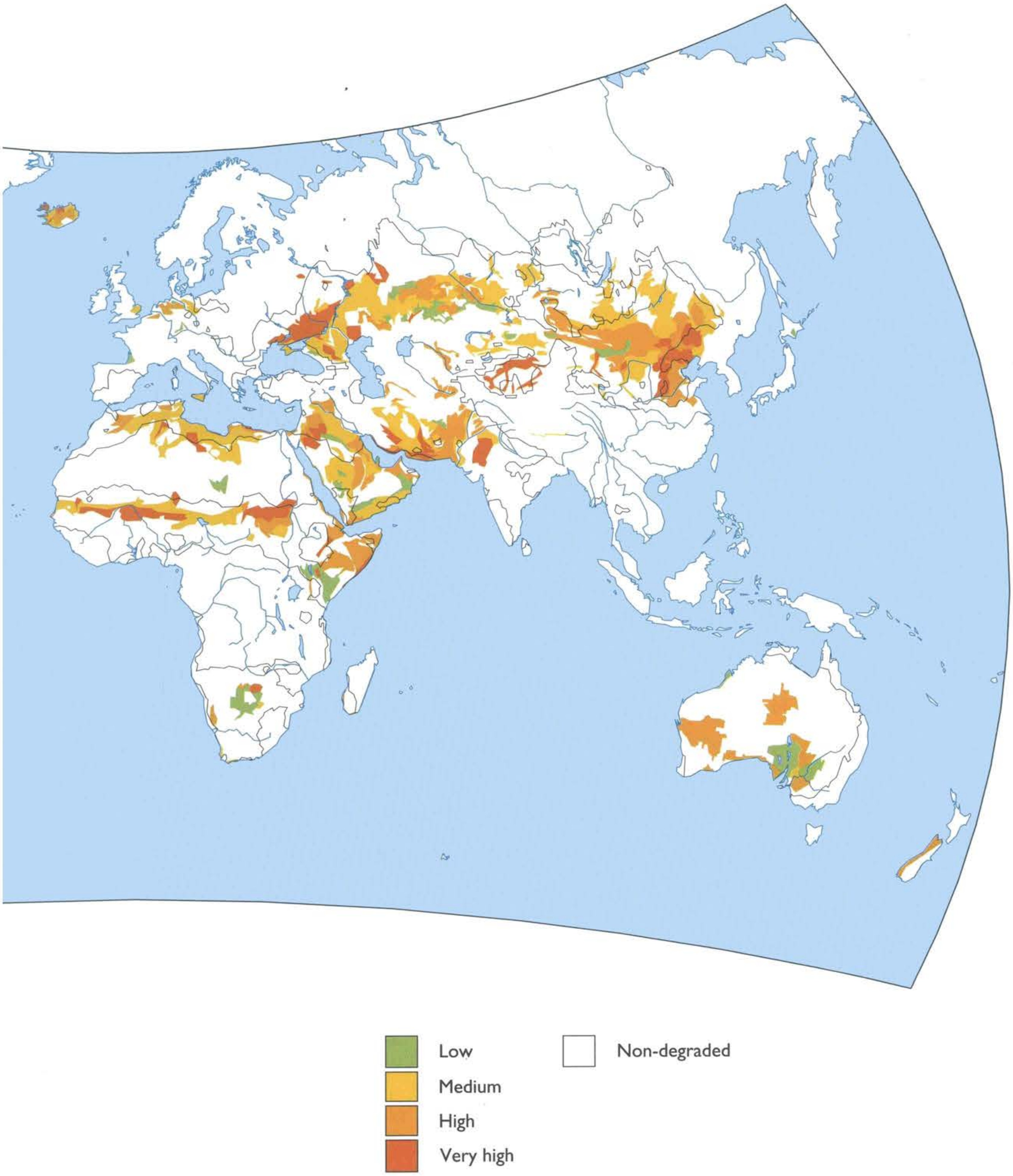

Low
Medium
High
Very high
Non-degraded

Figure 1.18 Stabilisation of mobile sand dunes, as here in Iran, can be achieved by methods including spraying with oil, tar or synthetic materials (UNEP/SA Rizehkar/Topham)

Figure 1.19 The use of a grid network of sand screens (so-called checker boards) to vegetate and stabilise mobile sand is mainly used in Chinese drylands (UNEP/Bas Yin Chaoke Tu/Topham)

mechanised techniques creates large potentially deflatable surfaces.

Livestock production is a common and appropriate activity in many dryland areas unsuitable for agriculture, which include extensive areas of infertile, sandy, soils in northern and southern Africa, Australia, and the Middle East. Excessive grazing pressure may lower vegetation covers, increasing susceptibility to deflation. Processes of bush encroachment may however occur when this happens, and while generally regarded as negative in a productivity sense (see page 45), may enhance ground cover and reduce the likelihood of wind erosion.

Dryland wind erosion assessment

Map 1.13 clearly indicates that human-induced wind erosion is very largely confined to the world's drylands. Some regions immediately become apparent as suffering from a significant wind erosion problem. These are the Sahel (e.g. Middleton 1985, Nickling and Wolfe 1994); the Maghreb; a broad belt of land stretching from the northern shores of the Black Sea to the north of the Caspian Sea, where nutrient depletion by wind is a particular problem (Petrova 1982); Mesopotamia and parts of the Levant; and the Thar Desert in India (Kaushalya 1992). The importance of treating the map as a general overview is appreciated when looking at the large zone of high wind erosion severity on the Arabian Peninsula. This large area lies in the hyperarid heartland of Saudi Arabia, where human population densities are very low and the problem is confined to highly localised situations.

Overall, wind erosion problems in the susceptible drylands increase as conditions get drier (Table 1.14). For individual continents, however, where the relative occurrence of the different climatic zones varies, this relationship does not always hold. In European drylands for example, the dominance of dry subhumid and semiarid conditions relative to arid areas means that the total extent of wind erosion-affected lands in the latter climate zone is relatively small. On the global scale, human-induced wind erosion affects 432.4 million ha, or 8% of the susceptible dryland area (Table 1.15 and Figure 1.20). In terms of the total degraded area of susceptible drylands, wind erosion is an important degradation process affecting 42% of the area.

In absolute terms, wind erosion problems in the susceptible drylands are most extensive in Africa and Asia, both showing areas in excess of 150 million ha affected. In the Sahel, wind erosion may well be the dominant geomorphic process (Nickling and Wolfe 1994), and while human activities have undoubtedly contributed to the problem (Mainguet 1985), the occurrence of prolonged drought (see page 10) has exacerbated the potential for agriculture and livestock to have erosional impacts, making it difficult to differentiate human and natural causes (Suliman 1988). In China, problems associated with drifting sand encroaching on cultivated land are well documented (e.g. Zhu Zhenda and Liu Shu 1983). The GLASOD reports show that in some areas, for example the Hetao Plain which has a mean annual rainfall of only 150–300 mm, it is the overcultivated fine soils of alluvial origin that are most susceptible to wind erosion. There are nonetheless some significant success stories in China of the stabilisation and rehabilitation of wind-eroded lands (Figure 1.19) (e.g. Mitchell and Fullen 1994 and page 86). In Inner Mongolia, for example, it has been suggested that the area of shifting sand resulting from human activities has been reduced by 90% between 1984 and 1994 (Wang Tao and Zhu Zhenda 1996).

The 16 million ha affected by human-induced wind erosion in Australia are located in three zones, in Western Australia, South Australia and Northern Territory. In South America the 27 million ha affected are largely to be found in the Argentinian regions of the Pampas and Patagonia, but problems also exist in other

Table 1.15 Degree of wind erosion by region in susceptible dryland areas (million ha)

Degree	*Africa*	*Asia*	*Australasia*	*Europe*	*North America*	*South America*	*Total*
Light	78.1	80.5	15.9	1.3	2.6	18.8	197.2
Moderate	74.2	62.9	0.0	36.6	33.6	8.1	215.4
Strong	6.6	9.7	0.1	0.0	1.6	0.0	18.0
Extreme	1.0	0.1	0.0	0.7	0.0	0.0	1.8
Total	159.9	153.2	16.0	38.6	37.8	26.9	432.4

Note: column and row totals may not correspond exactly due to rounding of decimals
Source: GLASOD

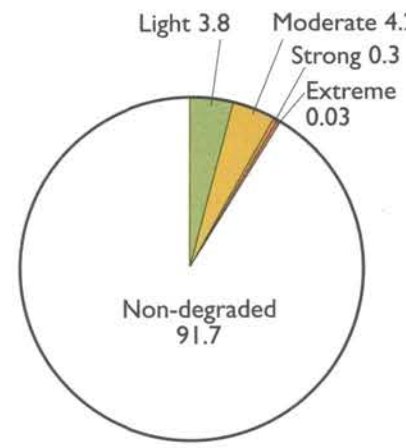


Figure 1.20 Global susceptible drylands degraded by wind erosion (%).
Source: GLASOD

areas. GLASOD reports note the deflation of top soil occurs in the cold semi-desert areas of the Bolivian altiplano. Although the windiness of this low rainfall area (*c.*200 mm p.a.) makes it susceptible to natural wind erosion, grazing pressures and the clearance of shrubs for firewood are enhancing the problem above background levels. In semiarid north-east Brazil the potential for human-induced erosion has been debated (Fearnside 1979, Le Prun 1981). The survey carried out for GLASOD notes that where clearance of trees and shrubs has taken place to facilitate the production of annual crops, particularly maize, beans and cassava, the occurrence of both wind and water erosion has increased, especially in areas of soils derived from crystalline basement rocks. In the Magdallanes region of southern Chile, intensive sheep grazing has contributed to the expansion of wind erosion within an area covering 2 million ha.

The ploughing up of grassland for grain cultivation has created massive wind erosion problems in the Great Plains of North America, notably in the 1930s, and in the wheat belts of southern Russia and Kazakhstan in the 1950s, and these continued activities are probably largely responsible for the human-induced wind erosion in these areas today (Lockeretz 1978, Ervin and Lee 1994). Similar activities go a long way to explain the wind erosion areas of the Canadian Prairies (Wheaton and Chakravarti 1990). The situation in Africa is more complex. Excessive livestock grazing pressures, excessive cultivation of dryland soils and cutting wood for fuel are commonly quoted as causes of land degradation in the Sahel for example. In Hausaland, Nigeria, and in Mali, Mainguet (1991) reports situations where the wholesale removal of topsoil has resulted from wind erosion resulting from agriculture. Despite the problems caused by wind erosion, Dregne (1992) has noted that at the regional scale the impact of soil productivity may be relatively limited, because aeolian erosion is frequently very localised, and the off-site costs and impacts, particularly of dust, may far exceed on-site impacts (Piper 1989).

Soil Deterioration

Introduction

Dryland soil degradation by processes of chemical and physical deterioration has been shown to occur on a relatively minor scale compared to the effects of soil erosion. This said, however, these forms of degradation can hit specific localities particularly hard. Such localities may also be in hyperarid regions, such as in desert oases and in the Nile Valley. Many of the notable examples in this respect are due to the fact that a number of the wide range of different processes embraced within the chemical and physical deterioration categories can be traced to a single form of human activity: irrigation. Poorly managed dryland irrigation schemes can result in soil salinization, gleysation, waterlogging and sodication. These problems reduce the crop yields from irrigated lands and ultimately can result in their abandonment. They are difficulties which have been faced since the beginning of irrigated agriculture on the floodplains of the Tigris and Euphrates in ancient Mesopotamia more than 6000 years ago (Jacobsen and Adams 1958), but the scale of the problem has increased significantly in recent decades due to large-scale efforts to bring additional areas under irrigation.

Other forms of *in situ* degradation also have a long history. Trampling by livestock, causing compaction, sealing and crusting, must have been a problem in localised areas such as water-holes for as long as people have herded animals in drylands. As with other types of *in situ* degradation, such as the gradual loss of soil nutrients due to shortening of cropland fallow periods, rising human and animal populations on desert margins have increased the scale and intensity of these human-induced dryland degradation processes in recent times (Warren *et al.* 1996).

BOX 3
GLASOD methodology for assessing degree of nutrient depletion

The criteria used to assess the degree of degradation due to nutrient depletion were the organic matter content; the parent material, and climatic conditions. Nutrient decline by leaching or due to extraction by plant roots without adequate replacement was identified by a decline in organic matter, P, and/or cation exchange capacity (Ca, Mg, K). The definitions adopted were as follows (Oldeman 1988):

Slight: Cleared and cultivated grassland or savannas on inherently poor soils in tropical regions. Formerly forested areas cleared and cultivated in tropical regions on soils with relatively rich parent materials.

Moderate: Formerly forested areas cleared and cultivated on soils with moderately rich parent materials, where subsequent annual cropping is not being sustained by adequate fertilization.

Severe: Formerly forested areas cleared and cultivated on soils with inherently poor parent materials, with a low cation exchange capacity, where all above-ground biomass is removed during clearing and subsequent crop growth is poor or non-existent and cannot be improved by the addition of N fertilizer alone.

Extreme: Formerly forested areas cleared by removal of all above-ground biomass, on soils with inherently poor parent materials, where no crop growth occurs and forest regeneration is not possible.

BOX 4
GLASOD methodology for assessing degree of salinization

The degree of salinization has been taken as the relative change in soil salinity status over the last 50 years (Oldeman 1988). Salinity can be measured in terms of electrical conductivity (EC) with exchangeable sodium percentage (ESP) and pH also delimited. Soils have been characterised as follows:

non-saline	EC <5 mS/cm,	ESP <15%, pH <8.5
slightly saline	EC 5–8 mS/cm,	ESP <15%, pH <8.5
moderately saline	EC 9–16 mS/cm,	ESP <15%, pH <8.5
severely saline	EC >16 mS/cm,	ESP <15%, pH <8.5

Human-induced salinization has been identified by changes in the soil salinity status:

Slight: salinity increase of one class;

Moderate: salinity increase of two classes;

Severe: salinity increase of three classes.

Processes of chemical deterioration

GLASOD methodology recognises several processes in the chemical deterioration category: nutrient and organic matter loss, salinization, gleysation, acidification and pollution. This section concentrates on those mechanisms particularly important in drylands: nutrient loss and salinization, and the methodologies used to determine the occurrence and degree of degradation by these processes are shown in Boxes 3 and 4 respectively.

Nutrient depletion

Soil nutrient depletion is a component of chemical degradation relevant to many dryland locations. Nutrients are essential to healthy plant growth, so that their loss from a soil often results in reduced crop yields. Nutrients become depleted when their export from a field exceeds their input, and can therefore be caused either by an increase in exports or a decrease in inputs. Export processes include extraction by crops, losses due to leaching and erosion, and to volatilization and denitrification, while common inputs are applications of fertilizer and manure, the restitution of crop residues, nitrogen fixation, atmospheric deposition in rain and dust, and enrichment by weathering of soil minerals. The depletion of nutrients is often intimately linked to a decline in soil organic matter. Soil organic matter is important not only because it is a prime source of the nutrients needed by plants, but also because of its positive effect on the water retention capacity of a soil, soil structure, biological activity and cation exchange capacity (Allison 1973).

In practice, a number of human actions tend to promote the loss of nutrients. Perhaps the most commonly quoted are overcultivation and the insufficient application of replacement nutrients. Shortening or even the total abandonment of fallowing reduces the opportunity for land to recover from producing a crop, as Khogali (1991) outlines for part of the Kordofan region of Sudan. Crops that are particularly demanding of nutrients can lead to severe nutrient depletion, often resulting in acidification of the soil. For example, in Senegal, soils of the groundnut fields immediately east of Dakar have been seriously acidified, with nearly 300 000 ha affected in 1983 according to Paye (1990).

Nutrient depletion can also occur through the clearance of natural vegetation in savanna areas of poor soils, where much of the nutrient store is held in the savanna vegetation rather than the soil (Proctor 1989). It can also result where the replenishment of soil fertility by annual flooding is prevented by dam construction and the control of river flood regimes.

Nutrient depletion can also be related to soil erosion, where increased runoff removes nutrients in solution or enhanced deflation removes them in suspension (see page 30). Conversely, nutrient depletion caused by a reduction in organic matter content may eventually result in enhanced erosion: less organic matter tends to decrease the stability of soil aggregates, rendering them more prone to destruction and entrainment.

Salinization

High evaporation rates in drylands contribute to the surface accumulation of salts that would be leached out of the system in wetter environments. Salinization therefore refers to the surface or near-surface accumulation of salts, mainly chlorides, sulphates and carbonates of sodium, calcium, and magnesium. Salt accumulation reduces soil pore space and the ability to hold soil air and nutrients. High salt concentrations are toxic to many plants especially during the seedling stage. Plants can suffer from salt burn and salt stress, causing an inability to take up the moisture necessary for growth. The salinization problem also embraces alkalization, the excess accumulation of sodium, which rises in association with the dissolved salt load of irrigation water (Rhoades 1990).

Though there are extensive areas of natural salt-affected soils, salinization is a particular problem when human activities cause soil salinity to rise significantly: so-called secondary salinization (see page 144). Drylands can be susceptible to this problem for several reasons: the predisposing climate; the need to irrigate soils to generate or increase crop yields; and the occurrence of suitable terrain for irrigation in flat, low-lying situations, the localities with a natural predilection to salinity. The area of irrigated land worldwide has increased from around 8 million ha in 1800 to about 250 million in the early 1990s (FAO 1993b), much of it in drylands, creating an enormous potential for the problem.

Human-induced salinization and alkalization are thought to affect nearly 50% of all the irrigated land in arid and semiarid regions (Abrol *et al.* 1988). They occur in one or more of the following situations according to Szabolcs (1976):

1 Accumulation of salts from poor quality irrigation water.
2 Increase in the level of groundwater:
(a) the salt content of the groundwater accumulates in deeper soil layers;
(b) the rising groundwater transports salts from the deeper soil layers to the surface or surface layers;
(c) the rising water table limits natural drainage and hinders the leaching of salts.
3 Lack or low effectiveness of drainage systems in irrigated soils.

It is a paradox of the water-deficient drylands that one of the major factors contributing to irrigation-induced salinization is waterlogging due to poor drainage. If water is applied in amounts exceeding those used by plants, the local water-table may be raised. This in turn mobilises stored soil salts, which then accumulate in the root zone or at the surface through capillary rise or 'evaporative pumping'. Even without waterlogging, evaporation will concentrate the salts carried in irrigation water and left in the soil after water use by plants. In many places this is enhanced where groundwater is used for irrigation as it is often more saline than water from surface sources.

The effects of salinity on crop yields depends upon crop type, since different crops are susceptible to different concentrations, and forms of salinity (Maas 1986). Crops such as barley, cotton and sugar beet are all fairly salt-tolerant; cowpea, rice and alfalfa much less so.

Salinization can also occur without irrigation. If natural vegetation is replaced by a crop that uses less water, root zone waterlogging and subsequent evaporative pumping can ensue, a process known as saline seep. The problem has been reported from the US Great Plains (Berg *et al.* 1991, Halvorson and Black 1974) and from southern Australia (Bettenay 1986).

Chemical deterioration in drylands

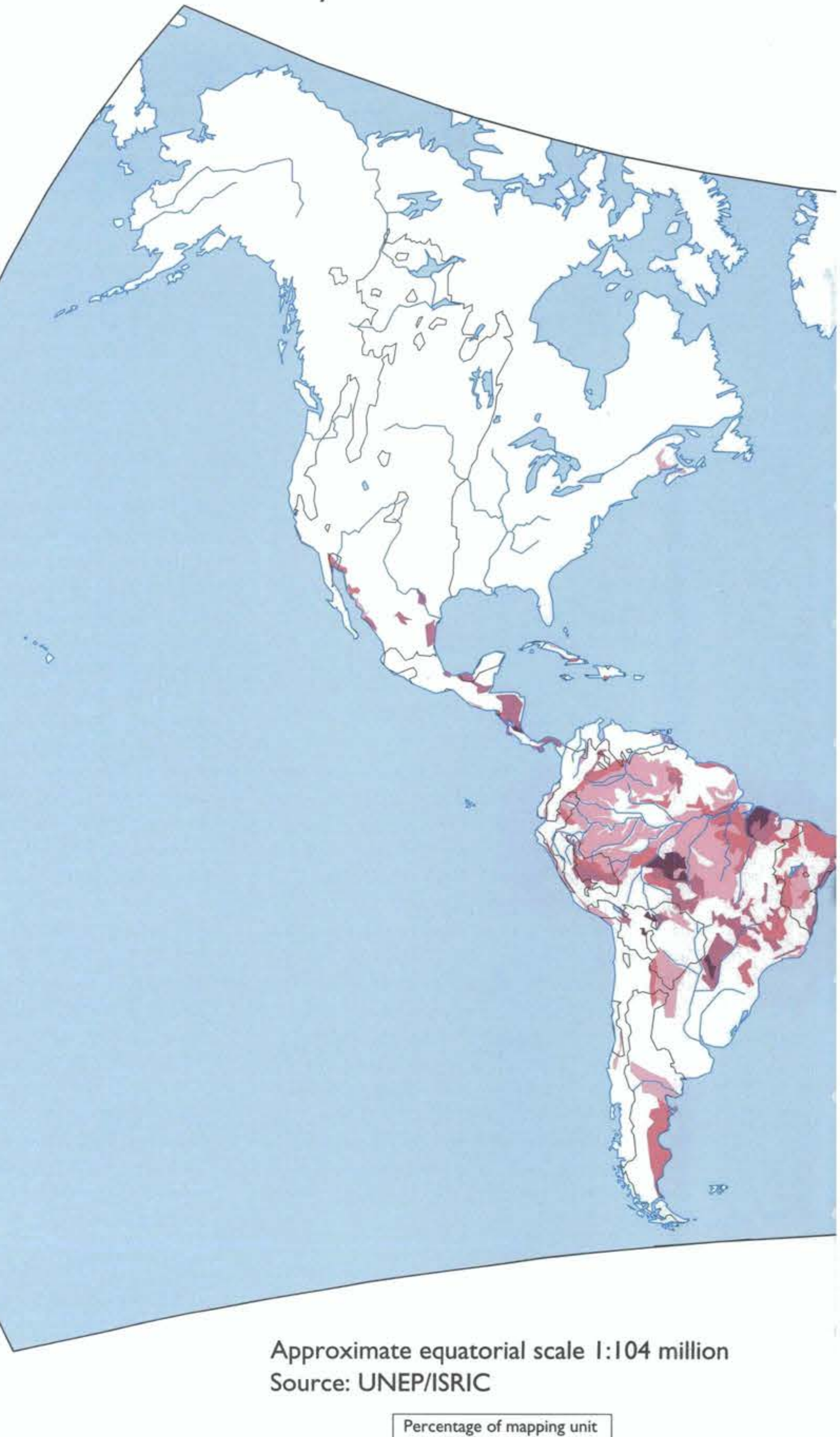
The GLASOD study indicates that in the susceptible drylands, 23 million ha in the dry subhumid aridity zone are affected by chemical deterioration, 41 million ha in semiarid areas and 37 million ha in arid areas, with an additional 11 million ha in the hyperarid aridity zone. In percentage terms, 22% of semiarid areas, 2% of dry subhumid and arid areas and 1% in the hyperarid zone are affected. The map shows all land units in which human-induced chemical deterioration occurs. It does not necessarily mean that chemical deterioration is the only form of degradation occurring in a particular unit, nor that chemical deterioration is the dominant degradation process in a unit. In total, some 10% of the soil degradation experienced in the susceptible drylands can be accounted for by chemical processes, of which undoubtedly the most dominant are nutrient depletion and salinization.

Map 1.14 indicates that very high severity chemical deterioration in the drylands occurs as pockets in Senegal and the Sudan in Africa, in Iraq and Syria in the Middle East and in the Middle Asian states. The Aral Sea Basin and the Euphrates valley are particularly affected. In Syria, where it has been estimated that about 45% of the irrigated area is affected to various degrees of soil salinization (Ilaiwi *et al.* 1992), irrigation on the Euphrates dates back more than 6000 years. However, salinity has only become a significant problem since the late 1940s when the introduction of diesel pumps allowed a significant expansion of irrigated lands. Misuse of irrigation water and a complete absence of drainage resulted in large areas being abandoned in the 1960s due to excessive salt accumulations. Downstream in Iraq, over 60% of the land irrigated under the 1953 Mussayeb Project was affected by salinization by 1970, and subsequent reclamation attempts have only produced mixed results (Iraq 1980). Salinization has been a persistent problem in Uzbekistan since irrigation commenced in 1902. The problem is particularly severe on the Golodnaya Steppe, near Tashkent, where over 80% of the irrigated area is now saline, while the irrigation schemes at the delta of the Amu Darya, where it enters the Aral Sea, are similarly affected (Smith 1992). Further details of the widespread environmental impacts of cotton monoculture in this part of central Asia are given on page 96.

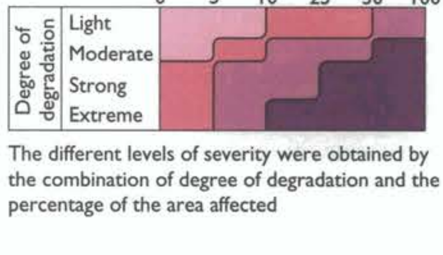
Chemical deterioration reaches high severity status in several areas. Irrigation supports about 78% of Pakistan's cropland, but the Indus Basin is now badly affected by salinization (Ghassemi *et al.* 1995). The Nile Valley in Egypt experiences persistent chemical degradation but the problem is not just caused by salinization. The construction of the Aswan High Dam, which has no provision for the passing of sediment, has deprived locations downstream of nutrient replenishment from river silt (Abu-Zeid 1989). Salinization is an increasing problem in numerous oases throughout North Africa as traditional methods of water use have been replaced by motorised pumps. Elsewhere in Africa's cultivated drylands, as fallow periods are reduced, nutrient depletion is a more serious threat to soils (Thomas and Middleton 1993).

Chemical deterioration is not restricted to developing countries. The lower Colorado River, south-western USA, supports several irrigation schemes. The Wellton–Mohawk project in Arizona, completed in 1952, has suffered particularly from waterlogging and high salinity, and though a drainage scheme has been implemented, the return of saline waste water to the Colorado generated its own set of problems for the 500 000 people in Mexico who also rely on the river's waters. Agreement on a solution to the salinity problem was reached between the USA and Mexico in 1973, but new water resources developments in the USA mean that salinity continues to be a serious issue (Holburt 1982). The severity of soil degradation through chemical deterioration also reaches a medium degree in southern areas of Western Australia where the replacement of native eucalyptus forest by shallow-rooted grasses and crops has lead to an increase in groundwater recharge rates and an increase in salinity, a process that has been reversed in some parts by a range of land management techniques including reforestation (Bari and Schofield 1992, see also page 162). In the east, the Murray River catchment has also undergone clearance of natural perennial vegetation and replacement with cereal crops and grazing land. As in Western Australia, these land uses do not use all available moisture, leading to surface waterlogging and salt accumulation, as well as to substantial changes in water flows to the lower reaches of the Murray resulting in large-scale dieback of eucalyptus trees (Grieve 1987, Taylor *et al.* 1996).

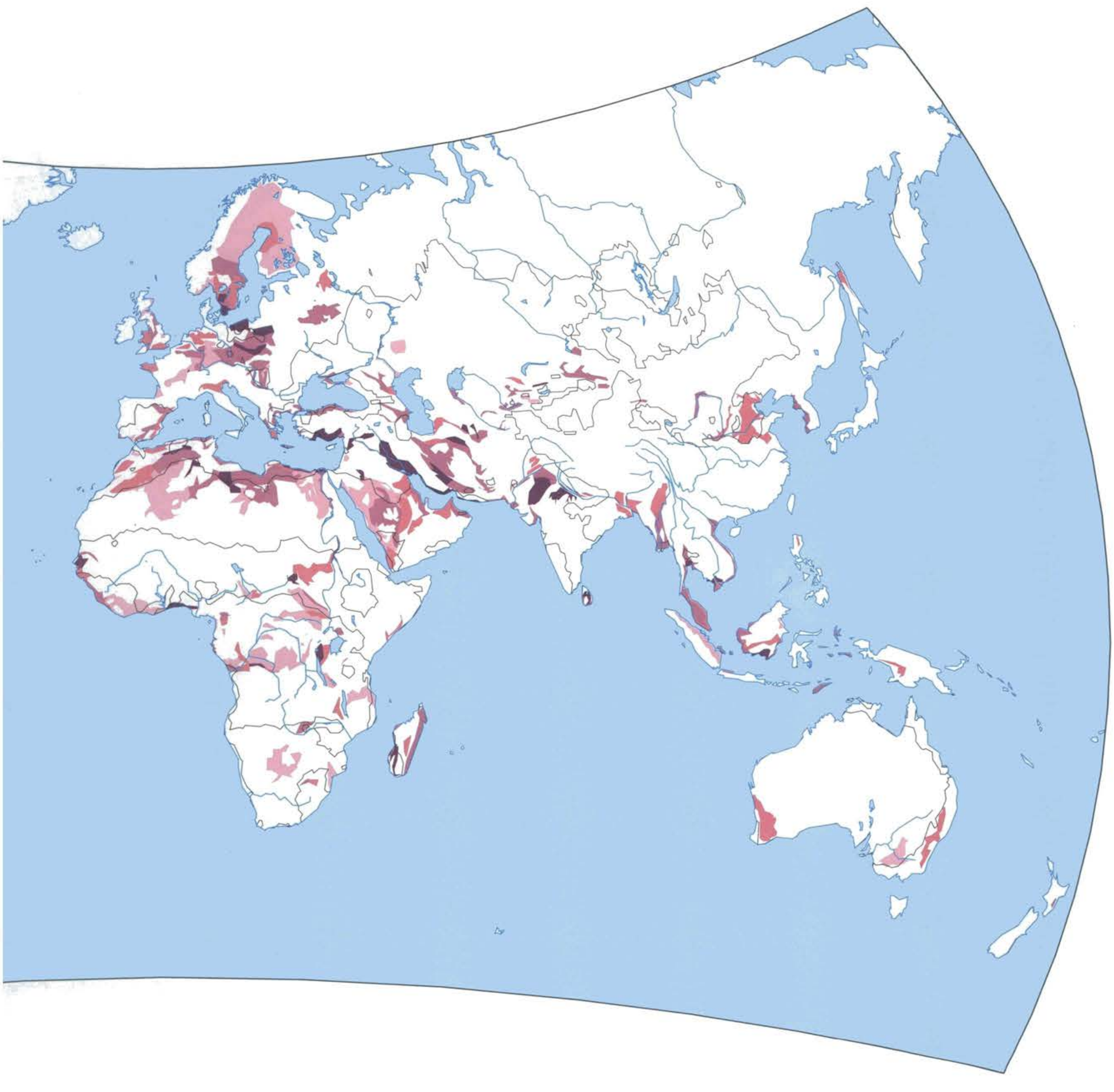
Map 1.14 Chemical deterioration severity



Approximate equatorial scale 1:104 million
Source: UNEP/ISRIC



The different levels of severity were obtained by the combination of degree of degradation and the percentage of the area affected


Low
Medium
High
Very high
Non-degraded

Processes of physical deterioration

Six forms of *in situ* soil degradation by physical processes are recognised in the GLASOD methodology. These are the sealing and crusting of topsoil, the compaction of topsoil, deterioration of soil structure due to dispersion of soil material by salts in the subsoil (sodication), waterlogging, aridification, and subsidence of organic soils (Map 1.15).

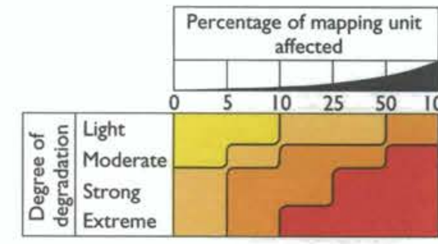
Compaction, sealing and crusting

The compaction, sealing and crusting of soil surfaces occurs under virtually all climatic and physical conditions. The most common causes of compaction are the use of heavy machinery and trampling by livestock on soils with a low structural stability. Livestock trampling can also lead to crusting, although the most common cause of crusting and sealing is due to the clogging of soil pores by fine-grained silt and clay particles dispersed by raindrop impact (Farres 1978). While the term sealing is commonly used to refer to the reorganisation of the surface soil layer during a rainstorm, crusting is the hardening of this surface seal as the soil dries out. These effects commonly occur in areas where vegetation does not adequately protect the soil surface from the impact of raindrops. The sparse vegetation cover may of course be a natural occurrence, but equally it could result from human clearance, in which case it is included in the GLASOD classification. Soils with a low humus content, poorly sorted sand fractions and appreciable silt content are particularly vulnerable. Crusting may also be a product of salinization.

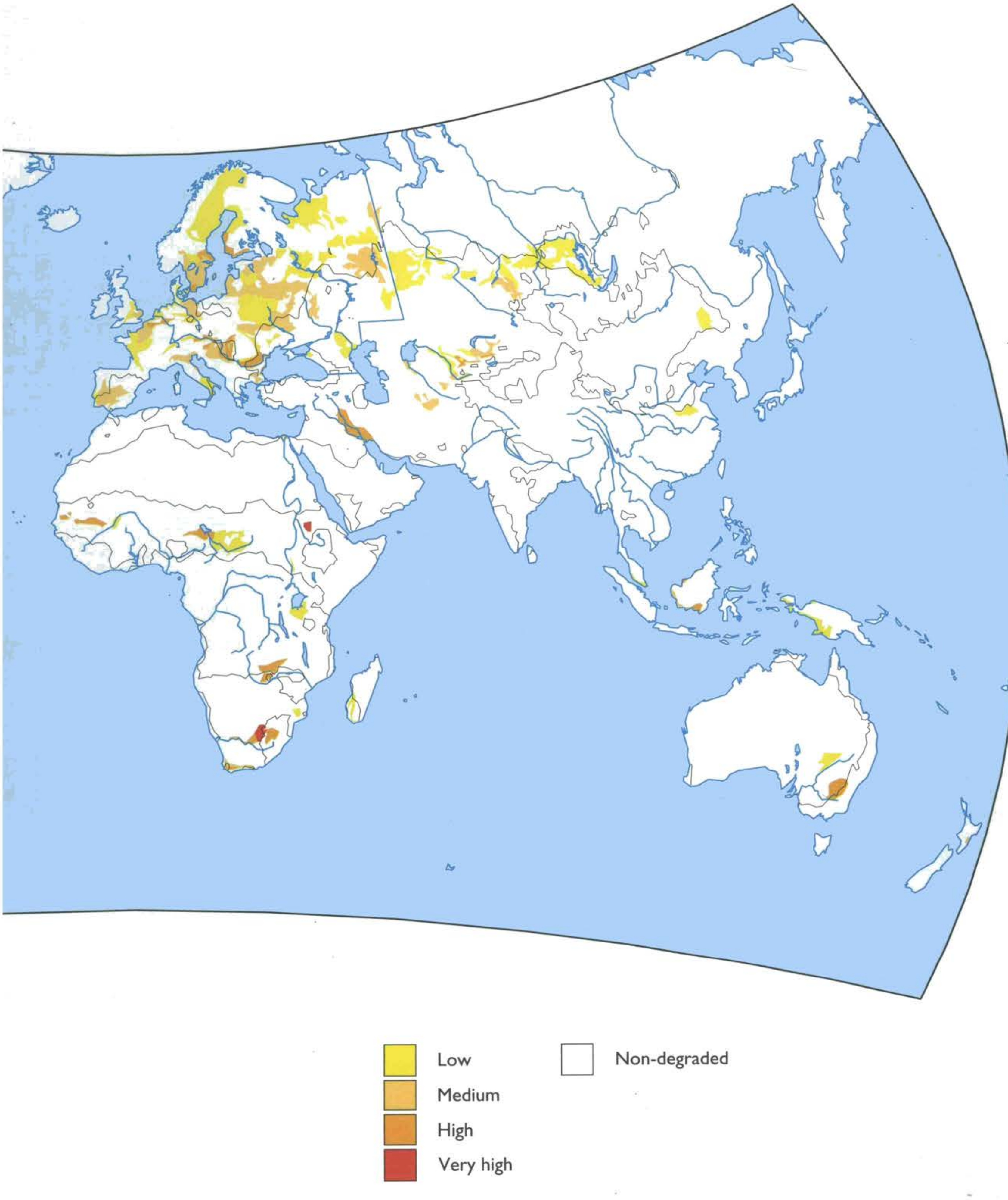
The effects of sealing, compaction and crusting are numerous. They hinder the tillage of arable soils, and impede or delay the emergence of seedlings and the penetration of roots. The diversity and abundance of soil biota may be adversely affected, and nutrient cycles can be altered by the lowered nitrogen and carbon inputs and the slowed decomposition of soil organic matter, resulting in a decrease in nutrient levels in associated vascular plants (Belnap 1995). Soil water infiltration capacity is also diminished, affecting soil moisture properties and causing increased surface runoff and often higher erosion. Field measurements in Israel, for example, show that on sandy soil crusting can reduce the infiltration capacity from 100 mm h^{-1} to 8 mm h^{-1}, and on a loess soil from 45 mm h^{-1} to 5 mm h^{-1} (Morin *et al.* 1981). Although the overall effects of rock fragments are complex and scale-dependent (Poesen and Bunte 1996), it is interesting to note that clearing of surface

Map 1.15 Physical deterioration severity

Approximate equatorial scale 1:104 million
Source: UNEP/ISRIC



The different levels of severity were obtained by the combination of degree of degradation and the percentage of the area affected



Low
Medium
High
Very high
Non-degraded

gravel deposits to expose finer soil beneath to rain drop impact, consequent sealing and crusting and enhanced runoff, has been deliberately employed as a dryland farming technique since ancient times. The increased runoff is channelled to cropland. This practice has been carried out to great effect in parts of the Middle East for millennia: Lavee *et al.* (1997) have shown that selective removal of stones from surfaces in the Negev can enhance runoff by 250% during small rainfall events. Today a greater range of compaction techniques using heavy machinery and water-repellent materials is available for the same agricultural ends, as well as for livestock, industrial and urban reservoirs. This human modification of the land surface is often referred to as 'water harvesting'.

Sodication

Sodication is a physical consequence of salinization, largely dealt with in GLASOD as a chemical degradation process. Sodication occurs when saline water in a soil, often from irrigation in drylands, is concentrated by evapotranspiration, leaving sodium ions dominant in the soil solution because calcium and magnesium components tend to precipitate as carbonates. The sodium ions tend to be adsorbed by aggregates of very fine clay particles or 'colloids', which consequently become broken down or 'deflocculated'. The result is a structureless soil which is unfavourable to root development, almost impermeable to water and highly erodible, particularly by piping (Rosewell 1970).

Waterlogging

Waterlogging includes flooding by river water and submergence by rain water when caused by human intervention in natural drainage systems. However, it usually results from poorly managed irrigation systems where water is applied in excess of the needs of the crops and the soil infiltration rate (Table 1.16). Waterlogging leads to the severe loss of soil air content. In these conditions plants are stressed due to a shortage of oxygen for metabolism by the roots, and the micro-organisms responsible for biodegradation of organic material are inhibited or killed. Organic matter accumulates as the mineralisation and humification of plant debris is retarded, freeing acids that can release toxic substances with consequent effects on plant growth (Crawford 1989). Waterlogging also causes problems of sodication salinization (see above).

Aridification

Aridification of soils is the human-induced change of the soil moisture regime towards a more water-deficient soil system. It may be caused by the lowering of the local groundwater levels, other than by deep groundwater extraction. Such depletion may occur in areas where river or lake water is used for domestic or agricultural purposes. Aridification may also occur in areas where natural vegetation is replaced by a crop that needs greater moisture for successful growth. The replacement of dryland grasses with wheat is an example here. An example of successful mitigation of aridification problems in north-western China is given in Section 4.

Subsidence of organic soils

The subsidence of organic soils, due to excessive drainage and/or oxidation, is only included in areas where the agricultural potential of the land is adversely affected. This occurs when peaty materials become susceptible to oxidation after drainage has lowered the water table, leaving the peat susceptible to oxidation and deflation, hence lowering the land in a similar manner to the way in which clay soils shrink when desiccated (Doornkamp 1993). Peat is often highly productive in the early stages of post-drainage, so that its loss affects fertility. Conversely, in many cases drainage may lead to subsidence but also an increase in the agricultural potential of the land, in which case it is not shown on the map.

Dryland physical deterioration

In terms of the area of global susceptible drylands affected, physical degradation is the least important of the four degradation types identified in the GLASOD methodology. Physical degradation affects 35 million ha, or less than 1%, of the global susceptible dryland area and is mostly confined to croplands. Most of the physical deterioration occurs in the dry subhumid (13 million ha or 1% of the area) and semiarid zones (15 million ha or

Table 1.16 Soil infiltration rates and their links with irrigation, waterlogging and crusting (including information from Gairon and Hadas 1973, and Morin *et al.* 1981)

Infiltration class	*Infiltration rate mm h^{-1}*	*Suitable irrigation type*	*Impact on waterlogging and crusting*
Very low	<5	Flood irrigation	Excessive irrigation commonly causes ponding and waterlogging that may in turn lead to salinization
Low	5–15	Low-intensity sprinklers possible	Excessive irrigation may cause ponding and waterlogging, leading to salinization
			Crusting may result on soils with naturally low infiltration rates if irrigation too intensive. Low infiltration may, however, be an outcome of crusting or compaction caused by agricultural activities.
Medium	15–25	Flood irrigation, only on small fields	Careful irrigation regimes may optimise agricultural potentials and minimise degradation
High	25–50	Sprinklers possible, flood irrigation impossible	Rapid infiltration can lead to waterlogging if impermeable sub-surface horizons present
Very high	>50	All irrigation difficult	Compaction (by livestock, mechanised agriculture) can reduce infiltration rate on sandy soild from 100 to 8 mm h^{-1} and on silty soils from 45 to 5 mm h^{-1}

Figure 1.21 Trampling by livestock is a common cause of soil crusting and compaction in the drier parts of the susceptible drylands (UNEP/Hongdao Cheng/Topham)

0.7%). Arid areas experience relatively little degradation by physical processes (7 million ha or 0.4%) but most of this degradation occurs in grazing areas (Figure 1.21).

In Africa most of the 14 million ha affected are degraded to a moderate or strong degree. Soil crusting and compaction are the most widespread types of degradation, affecting the wheat and fruit growing belts in the Western Cape and along the Orange River in South Africa and in the central parts of Sahelian latitudes around Lake Chad and in the western parts of the Sahel, largely in western Mali and on the Senegal/Mauritania border (Hoogmoed 1986, see Figure 1.21).

Asian drylands affected by physical degradation are almost exclusively degraded to a light or moderate degree. An area of high severity physical degradation due to compaction and crusting occurs in Lower Mesopotamia, while medium and low severities are found in Afghanistan, parts of Middle Asia, areas of Siberia west of Lake Baikal and on the floodplain of the lower Volga River.

The 9 million ha of susceptible drylands affected in Europe are all degraded to a light or moderate degree primarily by compaction and crusting. These areas are located in southern parts of Portugal, Spain and to the west of the Black Sea. In the Lower Alentejo region of Portugal, a long history of wheat farming has contributed to the region's extensive lithosols (soils with hard rock occurring at less than 10 cm depth). Enhanced sealing and crusting is just one of numerous, and often contradictory, effects that rock fragments can exert on soils (Poesen and Bunte 1996), and the extensive use of mechanised farming in this part of Portugal has also contributed to the degradation of structure (Roxo *et al.* 1996). Moderate degrees of compaction and crusting affect soils throughout the irrigated croplands that cover about 50% of the dry subhumid zone of southern Romania. The GLASOD survey also reported that associated problems of water erosion were widespread in this area.

Although the area of susceptible dryland affected in North America is small (1 million ha), these regions are degraded to a very high severity by waterlogging. They are located in the dryland regions of Mexico, in Sinaloa State on the Pacific coast and in Tamaulipsa State on the Gulf of Mexico.

Low severity physical degradation characterises the affected areas in Bolivia in South America. GLASOD survey reports indicated that parts of these high-altitude dry alpine grasslands, which are extensively grazed, suffer from subsidence of organic soils, as well as compaction and crusting and allied loss of topsoil by wind erosion. High severity compaction and crusting associated with agricultural activity occurs in western Venezuela.

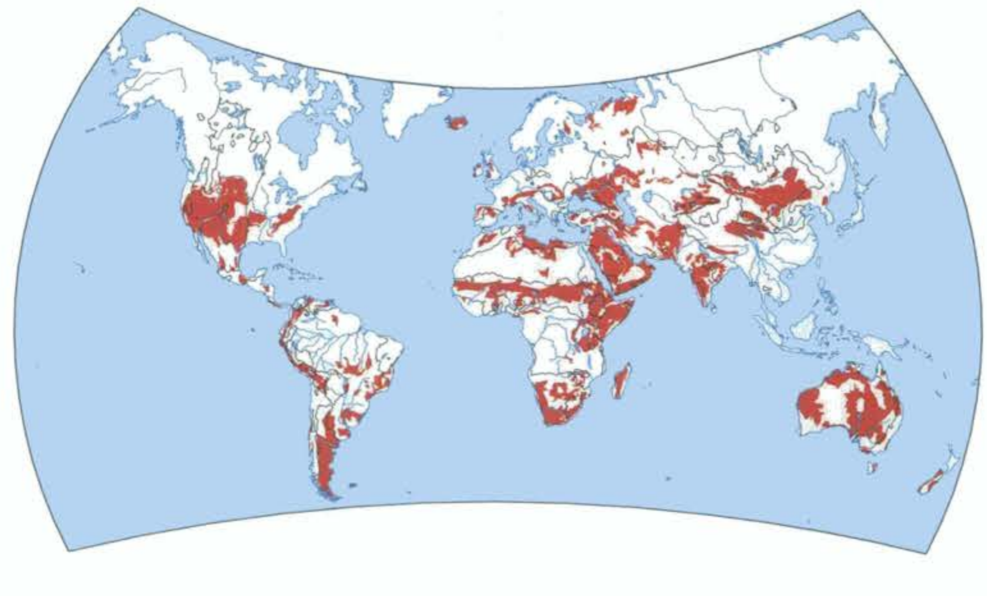
Soil compaction and crusting is widespread in the prime wheat belts north of the Murray River in New South Wales, Australia. Many years of mechanical tillage on the soils in this area has also created impervious 'plow-pans' just below the surface of some soils. These plow-pans are impenetrable to both crop roots and moisture and crops are increasingly vulnerable to drought stress as a result (Harte 1984).

Causes of Soil Degradation

Introduction

'Human-induced soil degradation' implies by definition a social problem. Many of the types of soil degradation outlined in the previous sections occur with or without human interference, but their inclusion in this atlas is dependent upon circumstances in which natural processes interact with human activities, and in most cases this means they have been initiated or accelerated by human mismanagement in a particular area. More fundamental social and economic forces can also be identified as compelling or encouraging people to cause degradation, while in some cases degradation itself may combine with such forces to cause social changes such as migration (see Section 4). Here the focus is on the actual land uses. This focus is crucial because identification of the nature of the land use that has led to soil degradation allows appropriate ameliorative management responses to be planned. Such responses must aim to make land use sustainable. This may mean either a complete change of land use or a modification of the existing one.

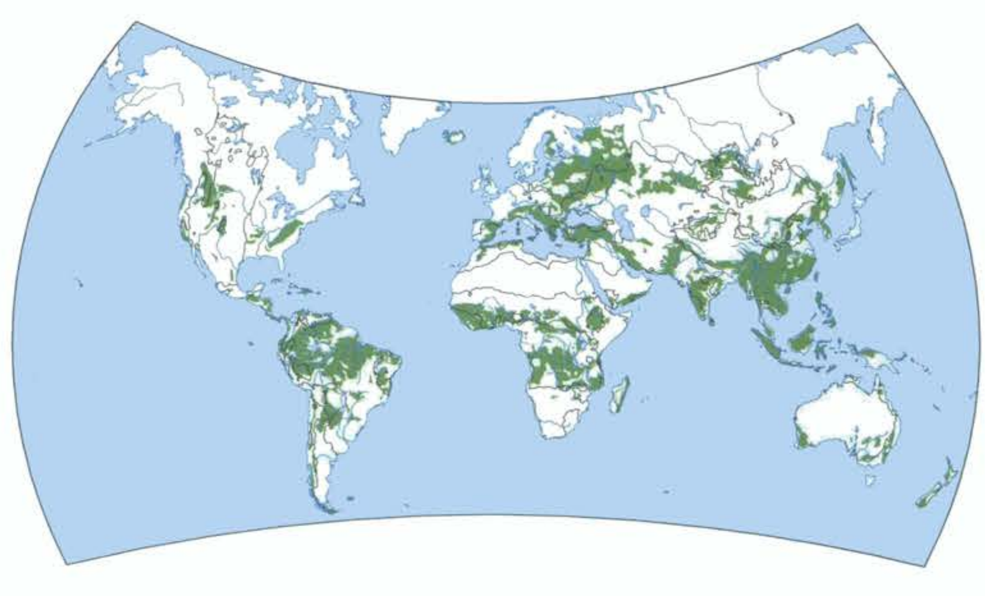
Map 1.16 Areas affected by overgrazing



Source: UNEP/ISRIC

Approximate equatorial scale 1:317 million

Map 1.17 Areas affected by deforestation



Source: UNEP/ISRIC

Approximate equatorial scale 1:317 million

The nature and effects of soil degradation causes

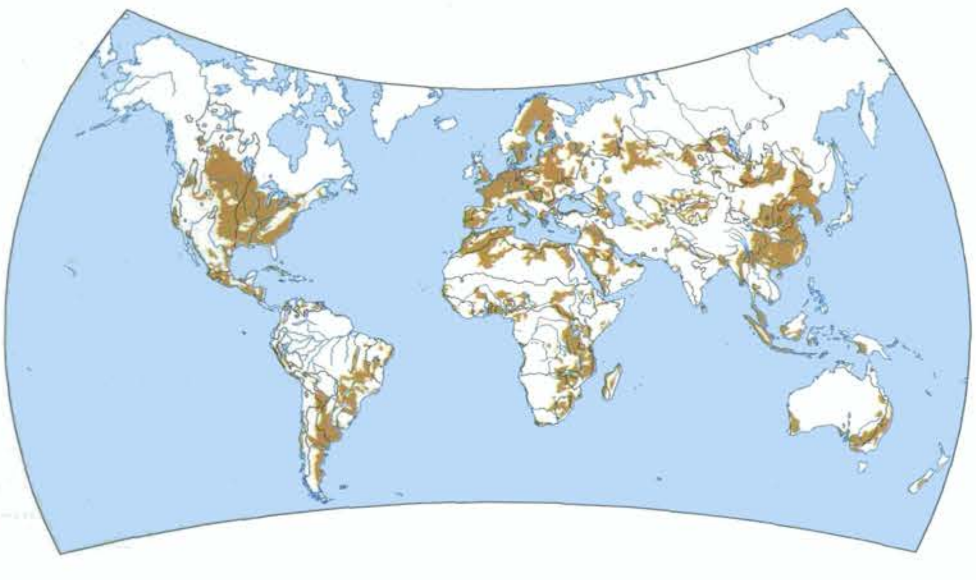
Investigators compiling the GLASOD database identified one or two of the following five soil degradation causes for each land unit: deforestation and removal of the natural vegetation; overgrazing; agricultural activities; overexploitation of vegetation for domestic use, and (bio)industrial activities. Highlighting more than one such cause is important at this scale of analysis, since single causes are unlikely to be the only ones operating in a particular mapping polygon, as other large-scale studies of vegetation change, for example, have found (e.g. Ringrose and Matheson 1992). In addition, some causes are often the precursors to others, such as the removal of natural vegetation to make way for cropland, and attributing particular types of degradation to one or the other may not be straightforward.

Deforestation and removal of the natural vegetation cover is defined as the total removal of natural vegetation from stretches of land. In most cases this natural vegetation is forest or woodland, and the degradation that often results is a function of the ability of trees to protect soils from erosion. Their root systems and the organic matter they supply help to stabilise soil, while water uptake through the roots and interception via the canopy help to reduce the frequency and intensity of raindrop impact and local runoff. Vegetation is cleared to make way for a new land use which may still depend upon a vegetative cover in the case of agricultural uses such as cropping or cattle raising, or new commercial forestry plantations. Conversely, some clearance is undertaken to remove vegetation permanently, such as for road construction, urban and industrial development.

There is a wide range of consequences stemming from such action. In areas where the vegetation removal is effectively permanent, erosion can be very high during the period between vegetation clearance and construction, but after construction the new land use effectively terminates the resource potential of the soil. None the less, the new land use may affect surrounding soils. The impermeable land surfaces of urban areas, for example, create greater runoff than from natural soils and this runoff, channelled through storm drains, can be highly erosive when it reaches uncovered soils or natural water courses (Cooke *et al.* 1982).

The methods used for land clearance affect both the amounts of soil loss and the subsequent yields of any crops planted. Mechanical clearance can significantly increase the soil

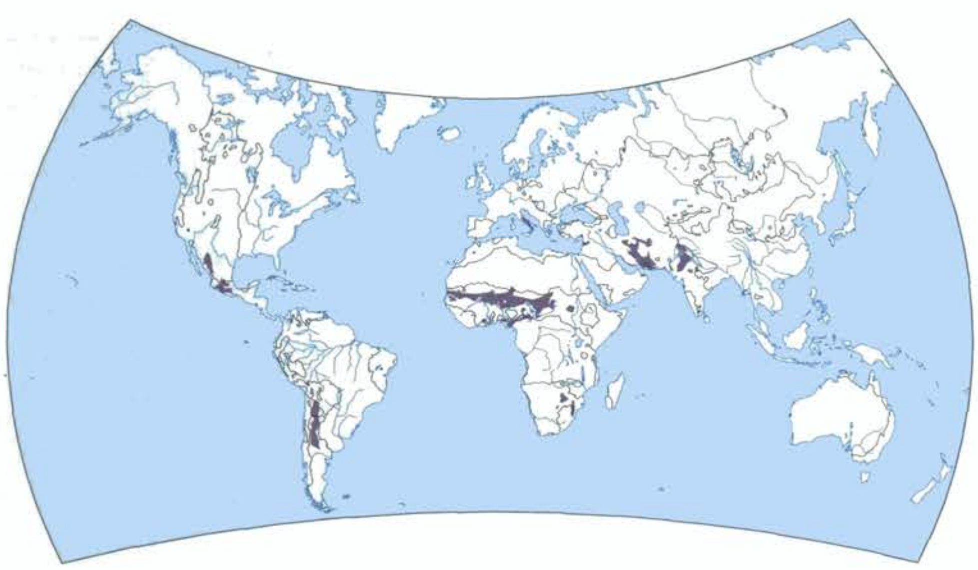
Map 1.18 Areas affected by agricultural activities



Source: UNEP/ISRIC

Approximate equatorial scale 1:317 million

Map 1.19 Areas affected by overexploitation of vegetation for domestic use



Source: UNEP/ISRIC

Approximate equatorial scale 1:317 million

bulk density and infiltration rates when compared to slash-and-burn for example, as Lal and Cummings (1979) show for an alfisol in Nigeria. The bulk density of 0.9 Mg m^{-3} on uncleared land was increased to 1.12 Mg m^{-3} after slash-and-burn clearance and 1.25 Mg m^{-3} after mechanical methods were used. The response of crop yields to different land clearance methods varies considerably, however, depending on the degree of soil disturbance and the subsequent cultivation method. Another advantage of the use of fire during clearance is that it releases phosphorus and other nutrients for use by crops, but studies on the effects of burning on semiarid gorse scrubland in south-eastern Spain indicate that such advantages are short-lived if a new vegetation cover does not become established before an erosive event (Carreira and Neill 1995). When the first significant rains fell on the study plots, the loss of nutrients by water erosion was an order of magnitude higher in the burned areas compared to the undisturbed control plot.

Once a new cover is established, however, different forms of degradation may occur as the soil establishes a new equilibrium with its vegetative overlay. Changes in vegetation quality and coverage may mean increased erosion, for example. Different plants require different types and amounts of nutrients and consequently their decomposing leaf litter similarly return different types and quantities of materials back to the soil. Any resulting degradation on cropland may then be classified under agricultural activities (see below).

Overgrazing includes both the actual removal of biomass by grazing animals and other effects of livestock such as trampling and consequent compaction. Heavy grazing and other forms of degradation due to livestock occur in areas either where too many animals are being grazed or where the wrong sort of animals are being used. A common consequence of heavy grazing pressure is a decrease in the vegetative cover, leading to increased erosion by water or wind. These effects may be concentrated in certain zones such as around water holes (e.g. Hanan *et al.* 1991), or they may extend over large areas (e.g. Takeuchi *et al.* 1995).

Another widespread effect of intensive grazing is the encroachment of unpalatable or noxious shrubs into grazing lands, but although such encroachment certainly influences grazing potential it is not identified in GLASOD as degradation unless the soil itself is affected. Typical effects of long-term grazing of semiarid grasslands in this respect are an increase in the spatial and temporal heterogeneity of water, nitrogen and other soil resources, which promotes the invasion by desert shrubs, in turn leading to a further localisation of soil resources under shrub canopies in a process of positive feedback. In the barren area between shrubs, soil fertility is decreased by erosion and gaseous emissions (Schlesinger *et al.* 1990). Increased runoff and erosion result in stripping of the soil A horizon, the formation of desert pavement in intershrub areas, and the development of rills (Abrahams *et al.* 1995).

It should also be recognised at this point, however, that some notes of caution concerning the deleterious effects of rangeland overgrazing have been sounded recently. While halos of bare, compacted soil are undoubtedly characteristic of many rangeland watering holes, the degradation represented by a lack of vegetation and trampled soils is offset to some extent by increased soil nutrients from livestock faeces and urine (Barker *et al.* 1990, Perkins and Thomas 1993a and b). Indeed, some studies have found no consistent relationship between primary production and proximity to a well (Hanan *et al.* 1991). Ideas on the effects of grazing on rangeland vegetation are also currently being substantially revised in a way that amounts to a paradigm shift (Smith 1988, Ellis and Swift 1988, see also page 50). The 'old paradigm', based on Clements' (1916) model of vegetation succession and ecological stability, and the consequent concept of a fixed carrying capacity, has been superseded in the eyes of many rangeland ecologists. Current thinking depicts semiarid ecosystems as seldom, if ever, reaching equilibrium. Rather they are in a state of more-or-less constant flux, driven by disturbances such as drought, fire and insect attack. The implications for pastoral management are now being evaluated (Scoones and Graham 1994).

Agricultural activities that lead to degradation encompass all aspects of inappropriate agricultural land management, including the introduction of techniques without adequate evaluation of their likely effects. It includes a wide variety of mismanagement types which result in various forms of degradation. Among these are the improper use of irrigation water and poor drainage leading to problems such as salinization (Rhoades 1990), the absence of anti-erosion measures (Morgan 1995), the shortening of fallow periods in shifting cultivation resulting in soil exhaustion, the insufficient or excessive use of fertilizers, and the improper use of heavy machinery.

The ways in which routine agricultural soil management practices affect soil degradation are many and varied. The net effect on wind erosion of surface ridges produced by tillage on a field, for example, depends on the height and lateral frequency of the ridges, their shape, orientation to erosive winds, and their proportion of erodible to non-erodible grains. Likewise, the crop itself influences the amount of soil lost to wind erosion by virtue of its quantity (proportion of ground surface covered) and quality (height, density and flexibility). These properties vary with vegetation type and for a given type according to the season (Middleton 1990). The extension of cropland into desert margins has been a trend noted in many parts of the world in recent decades, and many of these newly cultivated lands have suffered from widespread degradation as well as the inherent threat of drought (Glantz 1994).

The overexploitation of vegetation for domestic use encompasses the use of vegetation for such purposes as fuelwood, fencing and construction. In contrast to the above-mentioned deforestation cause, overexploitation for domestic purposes does not usually lead to the complete removal of all vegetation. The use of vegetation is however at a degree that is beyond the natural capability of vegetation to renew itself and thus results in a degraded vegetation cover. This exposes soils to increased erosion and in the longer term will rob the soil of inputs of nutrients and organic matter from decomposing leaf litter in a similar way to those described for deforestation above.

(Bio)industrial activities are those that lead to all forms of pollution outlined in the chemical deterioration section. These include the accumulation of urban and industrial wastes, the excessive use of pesticides, oil spills and acidification by airborne pollutants. Such causes are associated with intensive agricultural, industrial and urban land use, and in practice this cause shows very little impact on the world's drylands according to the GLASOD survey.

Causes of soil degradation in drylands

Overgrazing has been long regarded as a scapegoat for many dryland degradation problems (Figure 1.21), but in recent years studies by anthropologists (e.g. McCabe 1990) and ecologists (e.g. Behnke and Scoones 1993) have led to a re-evaluation of the effects of grazing pressure on dryland ecosystems. According to the GLASOD survey, overgrazing is the most important cause of degradation in the dryland areas of Australia, Africa, Europe and Asia where it affects 90%, 58%, 42% and 32% of the total degraded dryland area respectively (Table 1.17, Map 1.16). It is a problem in all dryland areas of Australia and Africa. In Australia, the loss of perennial grasses has been widespread from grasslands, savannas, and open woodland, often with replacement by unpalatable shrubs, and heavy grazing pressures continue to reduce ground cover, especially during droughts, laying landscapes bare to wind and water erosion (Ludwig and Tongway 1995). Africa is the continent perhaps most commonly associated with dryland degradation by intensive grazing, and examples of the deleterious effects of excessive grazing pressures have been cited from north of the Sahara (e.g. Sghaier and Seiwert 1993), the Sahel region (e.g. Aweto and Adejumobi 1991) and in the continent's southern drylands (e.g. Kerley *et al.* 1995). Prevailing drought in Sahelian latitudes since the late 1960s (see Figure 1.5) saw a large concentration of livestock in moister southern parts of the region as herders competed with other land users for sparse vegetative resources. In some cases, however, the effects of overgrazing are being re-examined in the light of the paradigm shift noted above, as Dean *et al.* (1995) advocate for the semiarid Karoo of South Africa.

A theme common to many examples of intensive grazing in Africa is the sedentarisation of previous nomadic peoples, whose livestock are consequently concentrated in much smaller ranges, as Sghaier and Seiwert (1993) report from the margins of the Sahara in Tunisia. Both sedentarisation and the encroachment of cropland on to traditional grazing areas, pushing herders into more marginal rangeland are also common processes throughout the Middle East (Johnson 1993). Some of the effects in the Elburz mountains in Iran are documented by Klein and Lacoste (1994). In Saudi Arabia, where sedentarisation has been encouraged by government policy since the 1950s, the nomadic proportion of the country's population has declined from 70% in the 1930s to just 3% in 1990 (Child and Grainger 1990). Sheep and goat herding remain widespread, but 60% of stock owners are now settled, semi-settled or short-range nomads, and even truly nomadic herders now tend to stay in one locality for longer. Traditionally during times of drought, when vegetation became scarce, stock numbers decreased so that environmental degradation was checked, but sedentarisation, combined with modern aids to herders such as boreholes, water trucks and supplementary forage, has undermined this traditional self-regulation. Consequent overstocking of rangelands was thought to have severely degraded 85% of the land in the 1970s (Child and Grainger 1990).

Elsewhere in Asia, degradation has also been caused by the intensification of grazing by growing numbers of livestock, as Kharin and Tsolmon (1994) report from Mongolia. Takeuchi *et al.* (1995) have documented extensive degradation in neighbouring Chinese Inner Mongolia, where Quaternary sand deposits have been disturbed on a large scale following a substantial increase in livestock in the 1950s and 1960s. The area of remobilised sand dunefields has expanded 2.3 times in the semiarid Kerqin Sandy Lands in the last 50 years. In South America, where overgrazing is the second most widespread cause of degradation, much of Argentina is affected. Widespread soil erosion in Patagonia, for example, is attributed to the heavy grazing pressures associated with sheep monoculture in the region (Iglesias 1992). In Europe the overgrazing problem is largely confined to the Ukraine and southern Russia north of the Caucasus Mountains. Ray *et al.* (1993) report that the extinction of some perennial grass species on heavily grazed parts of the Ukrainian steppes are associated with physical changes in the soils. In the Russian republic of Kalmykia, Zonn (1995) documents the widespread intensification of grazing pressures, mainly by sheep, during the period of Soviet rule.

Deforestation and removal of the natural vegetation cover (Map 1.17) is the primary

Table 1.17 Main causes of soil degradation by region in susceptible drylands and other areas (million ha)

Region	*Aridity zone*	*Over-grazing*	*Deforestation*	*Agri-cultural*	*Over-exploitation*	*Bio-industrial*	*Total degraded*	*Non-degraded*	*Total*
Africa	Susceptible	184.6	18.6	62.2	54.0	0.0	319.4	966.6	1286.0
	Others	58.5	48.2	59.2	8.7	0.2	174.8	1504.9	1679.7
Asia	Susceptible	118.8	111.5	96.7	42.3	1.0	370.3	1301.5	1671.8
	Others	78.5	186.3	107.6	3.8	0.4	376.6	2207.5	2584.1
Australasia	Susceptible	78.5	4.2	4.8	0.0	0.0	87.5	575.8	663.3
	Others	4.0	8.1	3.2	0.0	0.1	15.4	203.5	218.9
Europe	Susceptible	41.3	38.9	18.3	0.0	0.9	99.4	200.2	299.6
	Others	8.7	44.9	45.6	0.5	19.7	119.4	531.4	650.8
North	Susceptible	27.7	4.3	41.4	6.1	0.0	79.5	652.9	732.4
America	Others	10.2	13.6	49.1	5.4	0.4	78.7	1379.8	1458.5
South	Susceptible	26.2	32.2	11.6	9.1	0.0	79.1	436.9	516.0
America	Others	41.7	67.8	51.9	2.9	0.0	164.3	1087.3	1251.6
Total		678.7	578.6	551.6	132.8	22.7	1964.4	11 048.3	13 012.7

Note: column and row totals may not correspond exactly due to rounding of decimals
Source: GLASOD

cause of degradation in South America, affecting 41% of the 79 million ha of drylands damaged. These are largely concentrated in north-east Brazil, on the Caribbean coasts of Venezuela and Colombia, and in northern Argentina. GLASOD surveys of north-east Brazil found water and wind erosion problems on often shallow soils of the crystalline basement complex where deforestation of deciduous scrub, or 'caatingas', had taken place for annual crops and 'improved' pastures. The semiarid Chacoan forests of northern Argentina have been exploited for more than 100 years, initially because the wood made excellent railway sleepers, but more recent clearance has been for agricultural expansion, prompted by high grain prices and positive rainfall balances since the 1970s (Margarita and Loyarte 1996). In European and Asian drylands deforestation closely follows overgrazing as the second most important cause of degradation, affecting 39% and 30% of all degraded dryland area respectively. European areas affected include southern Spain, Sicily and southern Greece. In Asia the main deforestation problem areas are located in a broad belt from Turkey along the Zagros Mountains (Figure 1.22) and into Pakistan. Deforestation is the least extensive cause of soil degradation in African drylands and is very largely confined to dry subhumid areas as indicated in Map 1.17. In the savanna areas of northern Ghana, for example, woodland clearance to expand the grazing area and for charcoal-making was the most common cause of water erosion during the intensive rainy season according to GLASOD reports.

Figure 1.22 Forest clearance in the foothills of the Zagros Mountains, Iran (UNEP/Kapurchaly/Topham)

Agricultural activities (Map 1.18) represent the most important cause of dryland degradation in North America where they account for 52% of the degraded dryland area. These degraded zones are located in northern Mexico, the Great Plains of the USA and the Canadian Prairies. Although the effects of soil degradation in the Great Plains and the Prairies can be masked by improved crop strains and plentiful additions of fertilizers, Fryrear (1981) has noted substantial long-term declines in yields of sorghum and kafir in the Texas Panhandle over 30–40 years, a trend attributable at least in part to the effects of wind erosion. Indeed, despite the effects of the 1930s Dust Bowl, poor agricultural practices continue to play a role in exacerbating dust storms during periods of drought (Ervin and Lee 1994).

Agricultural activities are also important in Asia (26% of the degraded dryland area), Africa (19%), Europe (18%) and South

Figure 1.23 Intensive agricultural use of steep slopes in dryland Colombia (UNEP/Ruiz Jorge/Topham)

America (15%). Among the Asian areas worst affected are Mesopotamia, where degradation affects poorly managed irrigation schemes and grassland areas converted to cereal cultivation, as in Syria where extensive wind erosion has resulted. Parts of the Arabian peninsula used for irrigated crop cultivation, some areas in Siberia and Central Asia, Mongolia and northern China are also affected. In Africa, areas north of the Sahara are worst affected, where the desire to expand the cropland area has pushed the tractor and multidisc plough deeper into the desert-fringe steppe (Dresch 1986). This example of the misapplication of temperate European practices in a dryland environment is mirrored elsewhere on the continent where colonial administrators discouraged local techniques for land husbandry. The introduction of the plough to southern Zimbabwe more than 70 years ago encouraged the almost total disregard for indigenous techniques for soil and water conservation. The value of these indigenous farming practices is only now being recognised (Hagmann and Murwira 1996).

The most serious agricultural causes of soil degradation in Mediterranean Europe are linked to rural depopulation and significant changes in traditional cultivation practices since the late 1950s. Extensive grazing and wheat cultivation has been largely replaced by intensive agriculture based on tree crops, horticulture and irrigation. The abandonment of traditional terrace systems, for example, has affected runoff rates, erosion and downstream flooding. Declining demand for many traditional dry products such as almonds and figs has also resulted in abandonment of traditional tree crops in some areas. Overgrazing and fire combine to degrade the soils of these formerly cultivated areas (Margaris *et al.* 1996). In South America (Figure 1.23) the degradation problems in the highly populated, predominantly agricultural semiarid areas of north-east Brazil are outlined by Magalhães and Magee (1994), while Molina (1993) reports that about a quarter of Argentina's agricultural land suffers from some degree of erosion.

The overexploitation of vegetation for domestic use (Map 1.19) only accounts for more than a tenth of degraded drylands in Africa (17%), South America (12%) and Asia (11%). In Africa this is a problem predominantly located in the Sudano-Sahelian region where much of the resultant degradation is concentrated around urban areas that have expanded very rapidly since the late 1960s, as rural migrants fled the effects of drought. Denuded areas susceptible to enhanced erosion have been reported from numerous Sahelian cities (Michel and Louembe 1992). In the case of Niger, Spaeth (1996) suggests that at current rates of clear-cutting, for agricultural land as well as for fuelwood, the entire country's forest biome will have disappeared by the end of this decade.

Despite evidence of declining woodland resources in the hinterlands of some Sahelian cities, patterns of depletion are not always straightforward. In the Kano region of northern Nigeria, Nichol (1989) found that tree density had increased in recent times in the immediate vicinity of the city as the transport of fuelwood by donkey had been displaced by the use of long-distance trucks. A decline in tree density was recorded in the zone 70–250 km from Kano. Although there is evidence of denudation and consequent soil degradation in some parts of the Sahel, the 'fuelwood crisis' that was predicted for the region in the 1970s and 1980s has largely failed to materialise. Poor survey data, the importance of replacement fuels such as crop residues and dung, and the effect of increasing woodfuel prices as local supplies dwindle are all factors that make the situation more complex than was proposed (Leach and Mearns 1988, RPTES 1996). Distinguishing between tree felling for fuel and to clear land for agriculture is another difficulty that obscures the picture, but more recent surveys of fuelwood stocks and demand in the Sahel are much less pessimistic than those of previous decades (Millington *et al.* 1994).

In South America the overexploitation of vegetation for domestic use is largely confined to dryland areas of north-western Argentina and southern Bolivia where scrub is collected for firewood. In Asia it is mainly a cause of degradation in Iran, Pakistan and north-western India. In Pakistan, the few remaining stands of tropical thorn forests which once covered the Punjab Plains, largely cleared for irrigated agriculture, are under continuing

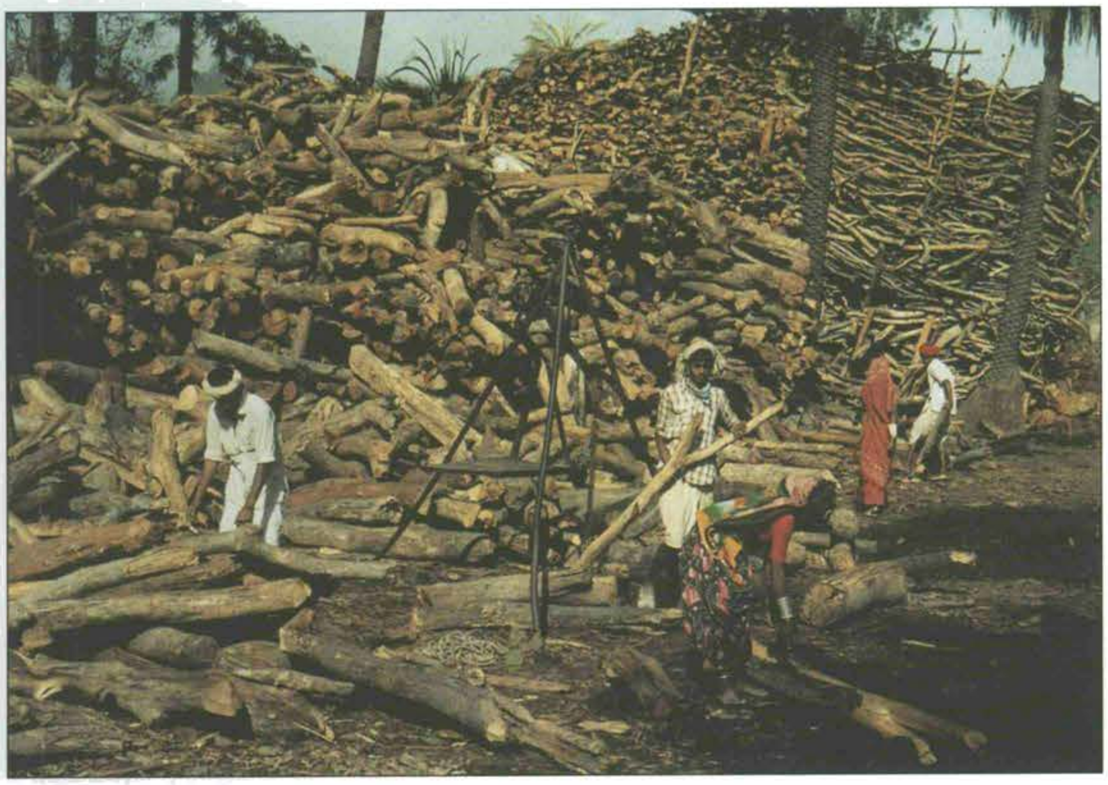


Figure 1.24 Stockpiles of fuelwood in an Indian city (UNEP/Gautan A Patel/Topham)

Table 1.18 Loss of closed forest cover around selected dryland urban centres in India (after Bowonder *et al.* 1988)

Urban centre (state)	*Closed forest cover (km²)*		*Loss (%)*
	1972–75	*1980–82*	*1972–82*
Ajmer (Rajasthan)	259	124	52
Amritsar (Punjab)	208	111	47
Bhavnagar (Gujarat)	112	9	92
Bhopal (Madhya Pradesh)	3031	1417	53
Gwalior (Madhya Pradesh)	1353	515	62
Hyderabad (Andhra Pradesh)	40	26	35
Indore (Madhya Pradesh)	3770	1070	71
Jaipur (Rajasthan)	1534	786	49

pressure for their long-standing use as a source of fuelwood (Khan 1994). Fuelwood collection around many urban centres in India has significantly reduced forested areas in their hinterlands in recent decades, as the urban poor have been forced to turn increasingly to fuelwood by rising prices of kerosene, coal and charcoal (Figure 1.24). One study of major Indian cities using satellite imagery (Bowonder et al. 1988) has shown that more than half of the closed forest cover within a 100-km radius around many dryland cities was lost in the 10 years to 1982 (Table 1.18).

In Rajasthan, the use of cattle dung to supplement fuelwood during the summer dry season and in drought periods has been decreasing due to low fodder availability and high livestock mortality (Kumar and Bhandari 1993a and b).

(Bio)industrial activities account for very small areas of dryland degradation in Asia, around Tehran in northern Iran due to industrial pollution and in the Aral Sea basin due to the excessive application of pesticides (Glazovsky 1995).

Soil Degradation and Vegetation

The significance of vegetation in soil degradation studies

The GLASOD survey focuses on degradation within the soil system. No consideration of land degradation and desertification is complete without a consideration of vegetation; however, the links between desertification, soil degradation and vegetation are complex and multifarious.

It has been proposed that plant cover is the core issue in desertification (Thornes 1995), and a range of factors point to both its environmental and social significance in dryland areas (Box 5). However, vegetation is a complex factor to incorporate in assessments of the extent of desertification for a number of reasons. First, it is now known that dryland vegetation communities are not naturally stable, but vary in response to fluctuations in controlling variables, particularly soil moisture, rainfall and natural fires. Consequently, dryland vegetation communities can be described as 'disequilibrium systems' (Smith 1988, Ellis and Swift 1988, Ellis *et al.* 1991), with the characteristics of a particular system at any one time being driven by preceding events. Second, the widespread and frequent occurrence of droughts means that the natural status of many vegetation communities in the world's drylands is likely to be highly dynamic in time. Third, this therefore hinders assessments that try to distinguish changes in vegetation systems that are a consequence of drought, and from which natural recovery is likely (Kassas 1995), from those that are caused by degrading human actions. This point is made more apparent when it is realised that the ecology of dryland vegetation communities is relatively under-researched relative to those in more temperate environments (Warren 1995).

BOX 5
The environmental and social significance of dryland vegetation

- Vegetation is a major pathway for the loss of water from drylands, through evapotranspiration.
- Plant cover is a major factor influencing the erodibility of dryland soils by both wind and water (see pages 26–32).
- Vegetation is a key source of soil nutrients and therefore changes in vegetation cover can significantly contribute to the chemical deterioration of soils (see pages 36–37).
- Natural vegetation supports pastoralism which is a major land use in dryland areas.
- Vegetation is an important source of domestic fuel in many developing world drylands.
- Vegetation communities and plant cover densities are susceptible to changes caused by natural (drought) and human factors.
- Changes in vegetation communities may be important indicator of pending changes within the soil system.

Current understanding, therefore, indicates that vegetation and soils in drylands display differing resilience to disturbance. Although vegetation communities can be readily disturbed and changed, recovery rates are relatively fast (Westoby *et al.* 1989), when compared to soil degradation, though slower in drylands than in other environments. An effectively permanent undesirable change to vegetation communities usually only occurs when either the soil resource itself or the mechanisms employed by plants to allow recovery have been severely degraded. In other situations, where rangeland degradation seems to have occurred for example, it often appears to be the land use system that maintains the vegetation in a degraded or changed state, rather than a change of soil properties that would make the vegetation degradation irreversible (e.g. Dougill *et al.* 1997). In many locations, rigorous evidence that would allow an assessment of whether effectively permanent vegetation change has occurred is sorely lacking (Dean *et al.* 1995). There is therefore an obvious need for long-term monitoring programmes (Dean *et al.* 1996) and the development of methodologies which permit the significance of vegetation changes to be assessed (Pickup *et al.* 1994).

An additional problem arises as changes in vegetation that are 'effectively permanent' can be interpreted in a number of ways, for example, in terms relevant to a particular production strategy, to the average periodicity of natural vegetation changes, or in terms of longer time scales. Where significant vegetation changes are occurring, their relationship to degradation can also be complex. For example, bush encroachment, which is the replacement of grasses by perennial herbaceous plants, may in some livestock systems lower production (e.g. Ringrose *et al.* 1990) and therefore be regarded as significant degradation, but in others it may be regarded as offering opportunities, as the browse resources that are created can be a useful grazing substitute at times of moisture stress, particularly in mixed livestock systems (e.g. Behnke and Scoones 1993, Cox and Dougill 1995). When bush encroachment reaches a very dense state, as often occurs in distinct annular zones in African grazing systems (Perkins and Thomas 1993b), it also increases ground cover and can therefore inhibit soil erosion. However, if it results in a reduction in biodiversity, it can lower the overall biological resource base. It is issues such as these that contribute to the debates and controversies that surround current understanding and interpretations of the significance of dryland vegetation changes (e.g. Adams 1996, Cox and Dougill 1996). What is clear, however, is that both soil and vegetation degradation are of great importance; however, they are not necessarily coincident as indicators of land degradation.

Strategies displayed by arid land plants for survival at times of moisture deficiency include reducing production and lying dormant during dry periods (Tolsma *et al.* 1987), and generating large seed banks during productive periods (Skarpe 1991). In fact many dryland vegetation communities respond to rainfall when it occurs but otherwise display very limited or no productivity. It may thus be difficult to distinguish whether a particular vegetation state at a particular time is a consequence of natural short-term climatic variability, livestock or human impacts, or a longer-term trend induced by soil degradation. These factors contribute to the absence of an adequate data base of vegetation degradation, but assessments of the extent of rangeland vegetation change have been made at the global scale. For example, Kassas *et al.* (1991) estimated that, in addition to the 1035 million ha of susceptible drylands that the GLASOD survey identified as having degraded soils, a further 2559 million ha, or 50% of the total susceptible dryland area, was subject to degradation of vegetation. It should be stressed, in the light of the previous discussion, that further detailed studies are needed to evaluate the nature of, and to address, this issue. There is however, according to Warren *et al.* (1996), a formidable body of evidence pointing to the occurrence of excessive grazing pressures that threaten sustainability in some semiarid areas. Evidence that supports this contention comes from recent studies in parts of Middle Asia, for example in the Kyrgyz Republic where there is marked overutilisation of lowland ecosystems by sheep herders (Schillhorn van Veen 1995); China including Inner Mongolia where in some areas up to 25% of vegetation is heavily degraded with a further 55% experiencing light and moderate degradation (Humphrey and Sneath 1996); and areas of the Sahel belt of Africa (Le Houérou 1990).

Two useful relationships between soil degradation and vegetation can be determined. First, vegetation cover may help to indicate vulnerability to soil degradation. A limited plant cover or low biomass, whether natural or the result of human disturbance, can often indicate a greater susceptibility to degradation by soil displacement (Thornes 1995). Second, vegetation cover or community type may indicate that soil degradation has occurred or is taking place. The latter is difficult to determine meaningfully except through detailed ground survey (Dean *et al.* 1996) at a greater resolution than that used for studies of natural climatic variability, but useful information relating to the former relationship can be collected at global (Justice *et al.* 1985) and regional (e.g. Ringrose *et al.* 1990) scales.

Characterising vegetation

Vegetation can be characterised in many ways, by plant community composition for example. Production is another useful way of characterising vegetation in a form that allows large scale interregional comparisons to be made and can also be incorporated in studies that attempt to identify the causes of such changes. Studies that have evaluated the causes of changes in vegetation production in parts of the Sahel have, for example, found that those caused by rainfall variability are greater than those related to livestock impacts in the Ferlo area of Senegal (Hanan *et al.* 1991) and the Gourma area of Mali (Hiernaux 1996).

Primary vegetation production can be defined in two ways:

Gross primary production equals the energy fixed by plants during photosynthesis.

Net primary production equals the energy fixed by plants in photosynthesis minus the energy lost by transpiration. Net primary production can be measured on the ground by **biomass**, the volume of plant matter per unit area. Although this is a static measure, and is perhaps less environmentally significant in degradation studies than the maximum potential production for a given environment, it can be approximately evaluated from remotely sensed data allowing global patterns to be determined. Thomas and Middleton (1994) evaluate the contributions of different remote sensing sources to desertification studies, which include the use of Landsat MSS (multispectral scanner) data (e.g. Tsoar *et al.* 1991, Matheson and Ringrose 1994), Landsat TM (thematic mapper) data (Olsson 1984) and high resolution SPOT data (Guyot 1990) to evaluate regional vegetation change. National Oceanic and Atmospheric Administration (NOAA) satellite data has perhaps had the greatest utility because of its wide spatial coverage and high temporal resolution.

A global vegetation assessment: NDVI and GVI

Within ecosystems, it is possible to identify changes in the patterns of vegetation, and the spatial patterns of change through time, by using satellite data sources. The Normalised Difference Vegetation Index (NDVI) is a qualitative index of vegetation phenology. The Global Vegetation Index (GVI), supplied by NOAA, is a weekly NDVI value, available with global coverage, derived from surface reflectance data generated from NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite waveband information. GVI values have a 16 km x 16 km spatial resolution and are supplied in the form of the highest value occurring each week (Dregne and Tucker 1988). A simple mean of daily values cannot be used because of the problems that values for days with cloud cover, for example, would introduce. GVI values are non-specified but they generally relate to the capacity of plants to photosynthesise and the relationship of plant canopy to evapotranspiration rates. The index can therefore be used as an indicator of vegetation biomass (Tucker 1980, Justice *et al.* 1985), though several studies suggest that the correspondence of the index with actual values is weak under some environmental conditions (Tucker *et al.* 1985a, b, c).

In the context of this study a global GVI surface has been produced taking the mean of individual monthly maxima for the timeband 1983 to 1990. The continuous spectrum of GVI values is represented on the map as a five-grade scale from low to high indicating biomass differences. It should be noted that, as with the map of aridity zones, GVI values are not static, as they will respond not just to human disturbance but to natural meteorological variability, particularly seasonal variability in drylands.

Interpreting the soil degradation and vegetation map

Map 1.20 gives an integrated assessment of overall soil degradation from the GLASOD survey and vegetation production from the NDVI. The four degrees of degradation severity have been combined with the five grades of the vegetation index to produce a 20-colour grid showing general relationships between the degree of degradation in susceptible areas and vegetation production.

The meaning of the relationship between the two variables requires careful interpretation. No causal links can be inferred from this map between vegetation production and soil degradation, nor one between the severity of degradation and types of vegetation community. An indication of low vegetation production does not mean that it has been directly or indirectly influenced by human actions. The map gives no indication of natural or managed vegetation communities or vegetation quality. It might generally be assumed that a high vegetation index value indicates a more luxuriant and beneficial vegetation, but in semiarid rangeland areas for example, it could represent the replacement of palatable grassland with scrub vegetation through the process of bush encroachment which may in fact offer protection to the ground surface against further soil erosion. High values can therefore also include disturbed vegetation communities.

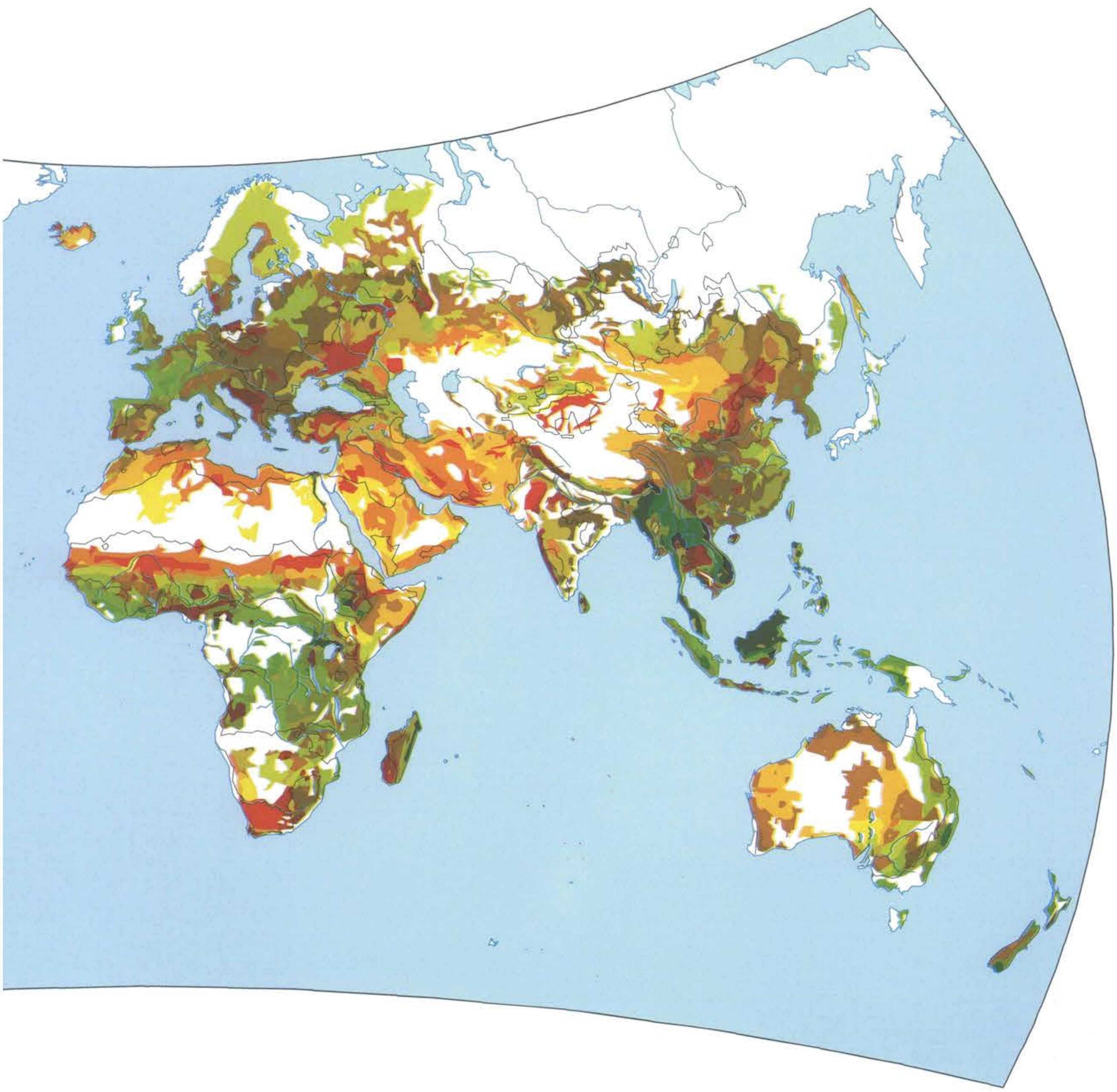
Best use can be made by taking the map to highlight areas within which susceptibility to soil or vegetation degradation may exist or have been realised. For example, mapping units possessing a colour from the top left part of the grid key may well contain areas susceptible to wind and water erosion. This is because degradation severity during the GLASOD survey period was low, but with a low vegetation index also indicated, ground cover is probably restricted in at least part of the mapping unit, creating soils vulnerable to wind or water erosion. The most productive and least degraded environments are represented by colours from the top right of the key. With high GVI values, such areas also possessed the least susceptibility to soil erosion during the study period.

Conversely, parts of the map represented by colours from the bottom left of the key are most likely to contain ecosystems displaying the greatest overall response to damage by human actions. Soil degradation is high, creating situations unfavourable to biotic processes, with plant communities appearing to have realised this negative potential by having low biomass. Caution needs to be exercised when interpreting the spatial extent of such conditions though, because of the range of scenarios that any degradation severity category can represent and the size of individual mapping polygons.

Spatial patterns within drylands

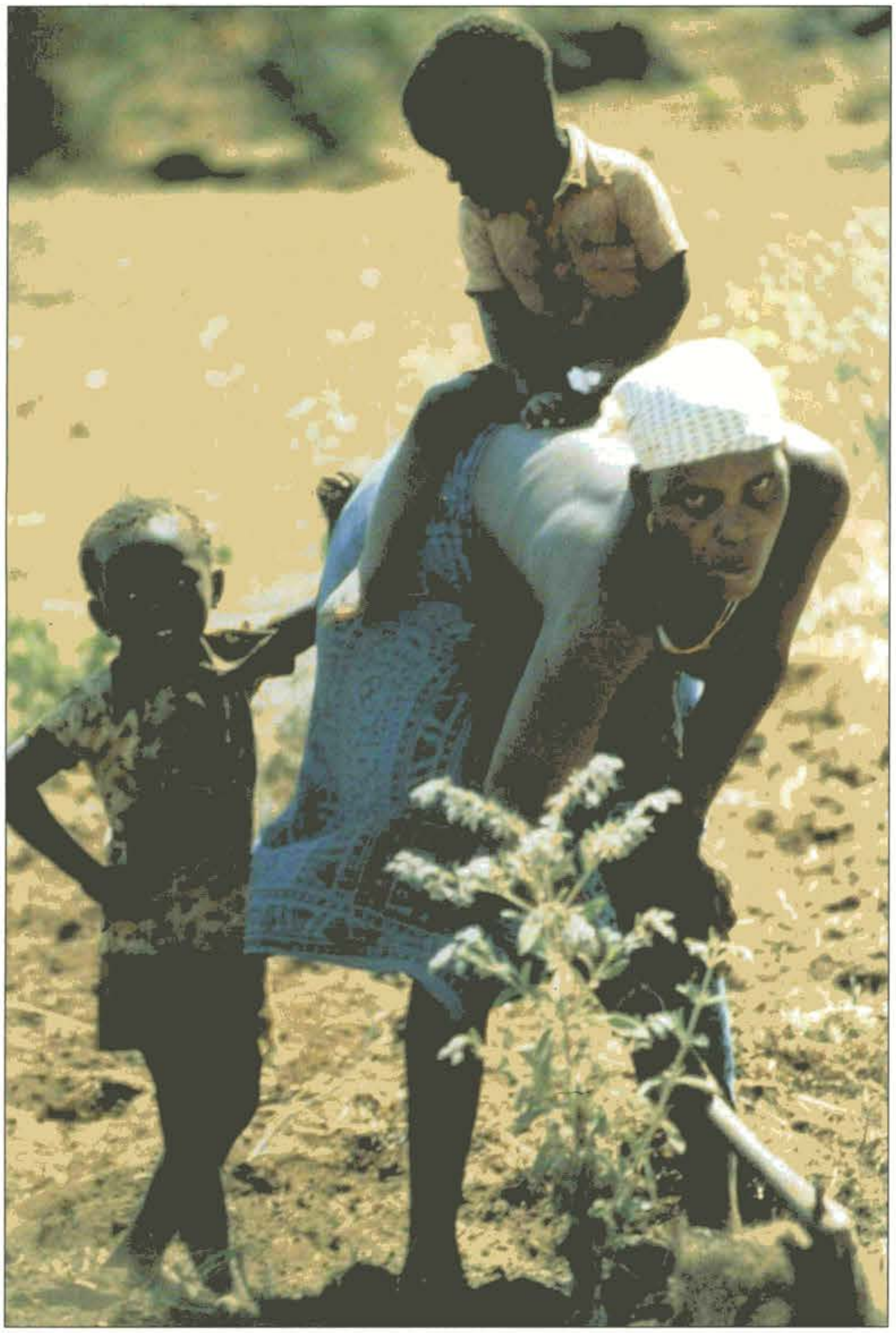
Map 1.20 allows several general interpretations to be made cautiously. High severity-low biomass areas are found throughout the susceptible drylands of north Africa, parts of southern Africa, Arabia, Iran, Pakistan, the southern steppes of Middle Asia and in Spain. These are the drylands containing areas where the greatest overall environmental degradation has occurred. Although many mapping polygons in Australia and North America, with the exception of the lower Colorado River basin and the Alberta badlands contain areas that have experienced limited soil degradation, low to medium biomass values suggest that these are locations where potential for degradation by erosion exists, especially if land uses were to intensify (Pickup and Chewings 1988). In the semiarid Patagonian grasslands of Argentina, local factors such as aspect may also be important in determining the critical relationship between moisture availability, biomass and degradation (Coronato and Bertiller 1996). Finally, the drylands in the rain-shadow area of south-eastern Peru possess the unusual situation of soils that have been highly degraded but which also appear to have high GVI values. The ability of the map to highlight such features and situations which are difficult to explain points to their usefulness in indicating areas where the status and origins of degradation, and relationships between soil degradation and vegetation status, warrant more detailed investigation.

Map 1.20 Soil degradation severity and vegetation



Approximate equatorial scale 1:104 million
Source: UNEP/ISRIC, NOAA

Non-degraded areas



UNEP/TITEL FELDARBEIT/TOPHAM

Africa

2

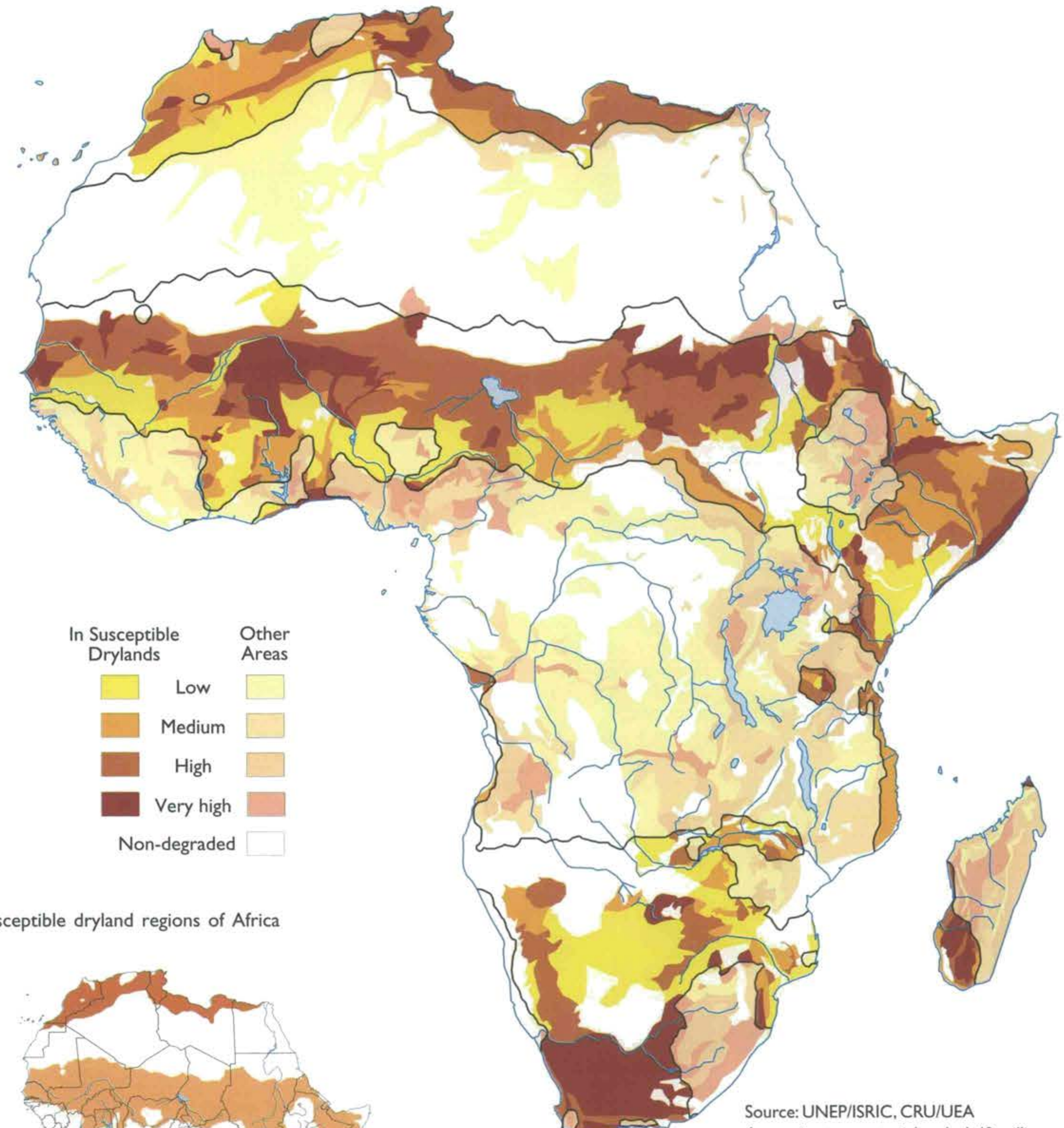
Section 2 focuses on Africa, concentrating on human-induced soil degradation in African drylands as delimited in the global study in Section 1. While the boundaries of the susceptible dryland remain the same, however, the appraisal of human-induced soil degradation in the following pages is based on a more detailed continental-scale GLASOD investigation of Africa.

At the global level, the African land surface was divided into 383 map units, plus lakes. The delimitation of map units was based on natural physiographic regions, defined by homogeneity of factors such as soil type, climate and topography. In the Africa database, the number of map units covering the continent has been increased to 898 plus lakes. The same basis of internal unit homogeneity has been applied for the new database, but to achieve a greater and more refined map unit density the individual designating criteria have been further analysed to achieve a greater degree of internal consistency. In many cases this has resulted in a simple subdivision of the global scale map units, but in others it has involved a more complex reassessment. For example, two adjacent map units at the global scale might be dryland drainage basins. With a further refinement of the data for the continental scale study these could become three map units: two low relief areas of fertile fluvially derived soils with an intervening, high relief physiographic zone dominated by bare rock surfaces and alluvial fans representing the watershed region.

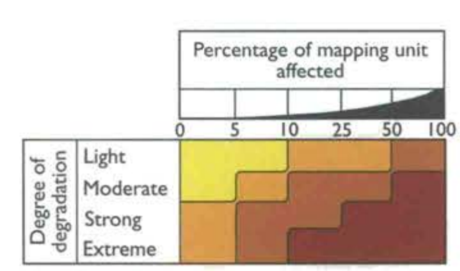
The African maps that follow, therefore, have a greater resolution than the coverage of Africa in the global section. They should, however, be used primarily to provide continental and regional overviews of the degradation problem. The text accompanying each map provides examples of the issues under consideration and the complexities of the interrelationships between the causes and effects of degradation.

Soil Degradation

Map 2.1 Soil degradation severity

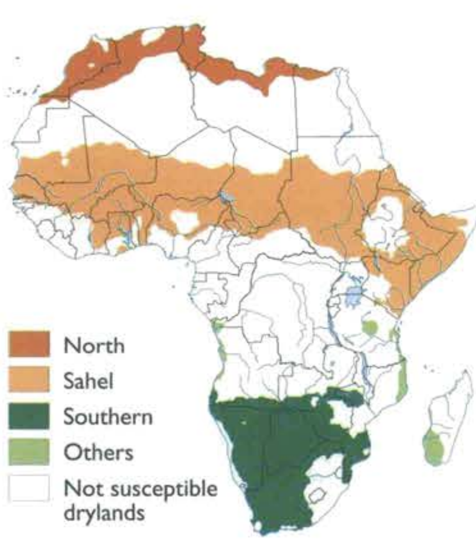


Source: UNEP/ISRIC, CRU/UEA
Approximate equatorial scale 1:40 million



The different levels of severity were obtained by the combination of degree of degradation and the percentage of the area affected

Map 2.2 Susceptible dryland regions of Africa



Source: UNEP/GRID
Approximate equatorial scale 1:122 million

Interpreting the African database

An important consequence of the change in the level of analysis from Section 1 is that it not only results in a greater spatial resolution, but also in a refined scientific database for the analysis of dryland soil degradation. A major result of the reduction in average map unit size is that less generalisation of the spatial extent of degradation occurs (see Map 2.1). More map units in the western Sahel, for example, means that the area shaded as having very high severity degradation is smaller on the continental scale map than on its equivalent global map. This is because a global map unit with very high severity degradation may have been subdivided into two units, one with very high severity degradation and the other with a lesser severity. Consequently a higher degree of spatial resolution and precision is given to the visual interpretation of the Africa maps. In the hyperarid Sahara, areas with degraded land have been highlighted where oases based on groundwater availability allow human settlement and cultivation. Some of these areas were completely absent at the global scale – a consequence of new map units being added and further degradation being identified in map unit sub-areas because of the greater resolution of the Africa database.

It is important to note that for these very reasons direct detailed comparison between Africa as represented in the global maps and the continental scale maps should be avoided, though the delimitation of the aridity zones has not changed. As with the global database, however, the representation of a particular severity of degradation for a whole map unit does not necessarily mean that all the land within the map unit is degraded to a particular degree. Reference to the key will show the percentage range of map unit areas that a particular level of severity can embrace.

Geographical regions

To facilitate description and explanation of soil degradation in susceptible drylands from the continental database, African drylands have been divided into three geographical regions which cover most of the areas under consideration. A fourth category, 'Other' covers the remaining areas (see Table 2.1, Map 2.2).

Africa north of the Sahara This region contains the susceptible drylands of the countries of the Greater Maghreb: Morocco, Algeria, Tunisia, Libya and Egypt (though not Mauritania, which is included in the Sahel), plus Western Sahara. It is important to note that the Nile Valley in Egypt falls within the hyperarid zone of the Sahara. Yet the special life-sustaining characteristics of the river, which has its sources in the humid zone, make it atypical and uncharacteristic of hyperarid areas. Consequently it is able to support high population densities and agriculture and experiences major degradation problems. For these reasons, it is appropriate to treat the Nile Valley as a susceptible area and include it in discussion of Africa north of the Sahara. It has not, however, been included in any of the tables.

Table 2.1 Land area in Africa by aridity zones (million ha)

	Region				
Aridity zone	*North*	*Sahel*	*Southern*	*Others*	*Total*
Hyperarid	385.4	276.4	8.2	0.0	670.0
Arid	98.1	348.6	54.1	2.7	503.5
Semiarid	37.4	303.7	159.4	13.3	513.8
Dry subhumid	15.1	150.1	81.5	22.0	268.7
Humid	9.3	260.0	127.7	612.6	1009.6
Total	545.3	1338.8	430.9	650.6	2965.6

Source: CRU/UEA

Table 2.2 Soil degradation degree in Africa by region in susceptible dryland areas (million ha)

	Region				
Aridity zone	*North*	*Sahel*	*Southern*	*Others*	*Total*
Light	25.6	109.8	6.4	2.4	144.2
Moderate	13.4	80.3	15.9	2.6	112.2
Strong	1.7	30.8	36.4	3.9	72.8
Extreme	0.0	3.1	0.0	0.0	3.1
Total degraded	40.7	224.0	58.7	8.9	332.3
Total non-degraded	109.9	578.4	236.3	29.1	953.7

Note: column and row totals may not correspond due to rounding of decimals
Source: GLASOD

The Sahel The susceptible drylands of the Sahel, extending for approximately 7000 km across a continuous west–east belt that is over 1000 km wide for much of its length, are probably those most commonly associated with desertification issues. The Sahel region includes the susceptible drylands of the Economic Community of West African States (ECOWAS) countries, of which Senegal, Mauritania, Mali, Burkina Faso and Niger in particular experience severe degradation problems, plus Chad and the members of the Intergovernmental Authority on Development (IGAD). On climatic grounds it also includes north-eastern Uganda and most of Kenya, but excludes the central and southern portion of the Ethiopian Highlands, which though suffering from severe degradation problems fall into the humid category. Cape Verde and the Gambia are also included in this region. During the period in which the information used for the compilation of the GLASOD database was collected, much of the Sahel experienced intermittent drought, exacerbating the problems of human-induced land degradation.

Southern Africa The susceptible drylands in this region includes large parts of South Africa, all of Botswana and Namibia, except the hyperarid Namib Desert; a southern strip of Angola; southern Zambia and much of Zimbabwe including the low-lying, Middle Zambezi Valley; and central Mozambique and part of the Swaziland Lowveld.

Other susceptible dryland areas This category includes south-western Madagascar, coastal Tanzania, including Zanzibar and extending into northern Mozambique; an area in central Tanzania south-east of Lake Victoria, and much of the Angolan coast, including the enclave of Cabinda and the small area of the Congo Democratic Republic west of the Congo River. On physiographic and climatic grounds, it is not possible to include these areas in either the Sahel or southern African regions.

Vulnerability to degradation

Map 2.1 and Table 2.2 show the severity of overall human-induced soil degradation. The distribution and density of the human population is obviously important in influencing where, to what degree and at what extent human-induced soil degradation occurs, a factor explored in Section 4 (see page 104).

Soil vulnerability to degradation is affected by two general environmental considerations. First, agricultural activities, which in themselves are affected by factors such as soil type, climate parameters and water resources. Irrigated arable farming can only take place where there is a source of water, either within a fluvial system or from groundwater. In some environments, such as the Kalahari of Botswana, arable activities are almost totally excluded as a possible degradation cause because of extremely low soil nutrient status and sandy soils, which in all but a few very localised areas even preclude irrigation because of their considerable permeability (Thomas and Shaw 1991).

Second, natural environmental factors affect which degradation processes occur at specific locations, even where the cause is the same. As an example, intensive grazing in Tunisia has led to water erosion (Roose 1991) but in many locations south of the Sahara wind erosion has taken place (Akhtar and Mensching 1993, Thiemeyer 1992). In the former, the problem has arisen on steep slopes which favour runoff during rainfall events. In the latter cases, and in many locations within the Sahel and in central southern Africa, overgrazing is occurring where the soil consists of ancient wind deposited sands: such sediments are readily remobilised by the wind when the protective vegetation cover has been disturbed.

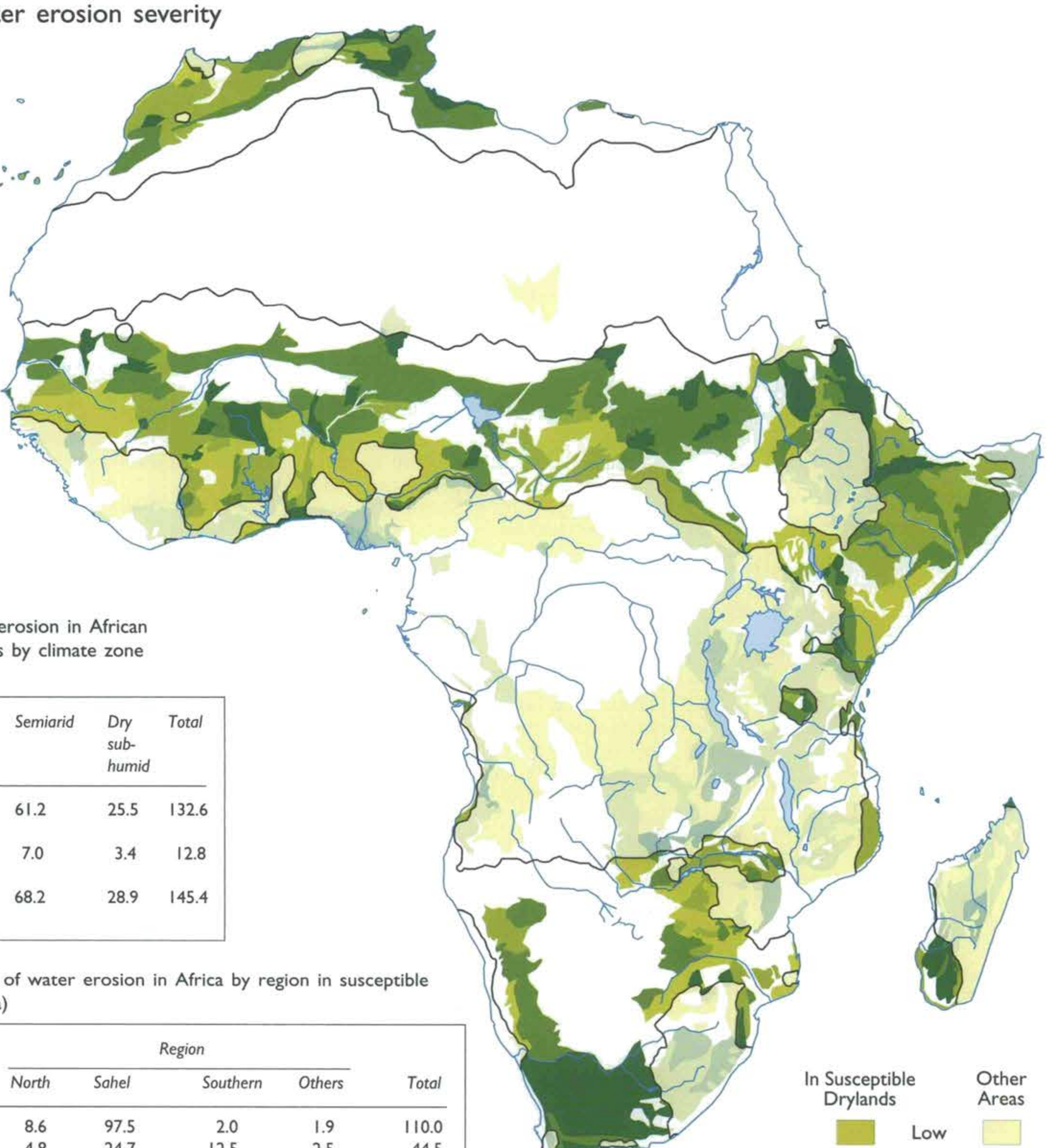
Soil Erosion

Water erosion

Africa's susceptible drylands are widely affected by water erosion. GLASOD focuses on the component of water erosion that is a consequence of human actions. Table 2.4 shows the regional breakdown of water erosion in Africa's susceptible drylands, while Table 2.3 shows the occurrence of water eroded lands within the different climatic zones, distinguishing topsoil erosion and terrain deformation (gullying and rilling). Loss of topsoil is the greatest problem, accounting for over 10 times as much water erosion as terrain deformation.

The problem is clearly not confined to the more humid drylands; indeed, Map 2.3 shows that many of the localities where severity is greatest are within the arid climatic zone. In total, in Africa's susceptible drylands almost 50 million ha in the arid zone have been affected by water erosion, in comparison to 30 million ha in dry subhumid areas. Examples

Map 2.3 Water erosion severity



Source: UNEP/ISRIC, CRU/UEA
Approximate equatorial scale 1:40 million

Table 2.3 Water erosion in African susceptible drylands by climate zone (million ha)

Water erosion type	*Arid*	*Semiarid*	*Dry sub-humid*	*Total*
Loss of topsoil	45.9	61.2	25.5	132.6
Terrain deformation	2.4	7.0	3.4	12.8
Total	48.3	68.2	28.9	145.4

Source: GLASOD

Table 2.4 Degree of water erosion in Africa by region in susceptible drylands (million ha)

	Region				
Degree	*North*	*Sahel*	*Southern*	*Others*	*Total*
Light	8.6	97.5	2.0	1.9	110.0
Moderate	4.8	24.7	12.5	2.5	44.5
Strong	1.7	18.2	30.9	3.0	53.8
Extreme	0.0	2.2	0.0	0.0	2.2
Non-degraded	134.5	659.7	250.6	30.6	1075.4
Total	149.6	802.3	296.0	38.0	1285.9

Note: column and row totals may not correspond due to rounding of decimals
Source: GLASOD

of affected arid areas are in eastern Namibia and the Northern Cape Province, South Africa, in northern Niger, northern Chad and in the Sudan to the west of Khartoum. Several underlying environmental factors affect the vulnerability of a given area to water erosion including soil type and relative relief. These may present situations where runoff and erosion are particularly favoured after human actions have disturbed the vegetation cover, particularly as dryland rainfall events tend to be intensive with a high erosive potential.

More positively, the careful application of soil conservation techniques in these same highly susceptible areas can both reduce erosion by water and increase food production. The use of terracing, check dams and other technologically simple devices can simultaneously improve water infiltration and reduce soil loss, both trends that promote successful agriculture (Rapp and Håsteen-Dahlin 1990). There are a number of examples where such measures have successfully been carried out in Africa's drylands (e.g. Atampugre 1993; Critchley *et al.* 1994). Soil conservation projects in Africa increasingly involve actions by local communities, who directly benefit from the outcomes: they are therefore excellent examples of the approaches encouraged in the Convention to Combat Desertification (see pages 120–125).

Africa north of the Sahara

Water erosion is a widespread degradation process in the Maghreb region, with severity highest at the western and eastern ends of the Atlas Mountains and in the Rif Mountains. Natural vegetation has been damaged by grazing pressure, focused on point water sources such as wells and boreholes, in part a consequence of the settlement of pastoral nomads, the expansion and intensification of arable farming and deforestation, which in places has led to 'badland' development on steeper slopes. Water erosion has been exacerbated by population growth, for example in the high plateau of Algeria. In the Algerian Atlas and Moroccan Rif, tree planting programmes have been in operation for more than a decade in an attempt to reduce runoff and degradation. The Algerian 'Green Dam' is intended to cover 3 million ha of the Atlas mountains (Grainger 1990). In the Jebel Al-Akhdar, east of Benghazi in Libya, loss of topsoil by water erosion is attributed in GLASOD reports to deforestation. The creation of national parks, for example at Al-Kouf, is contributing to the protection of areas sensitive to this problem.

In lower lying parts of both Algeria and Tunisia, however, soil erosion has been increasing because of the breakdown of centuries-old traditional soil conservation techniques (Mainguet 1991). Rainfed runoff farming in the Matmata region of eastern Tunisia is dependent on intricate networks of terraces and check dams, known as 'jessour'. But the loessic soils of the area are highly erodible, and the conservation methods require constant maintenance. An estimated 10 million olive trees have been grown through the use of runoff farming in central Tunisia (Le Houérou 1958). In recent years rural depopulation has led to a reduction in the maintenance of soil conservation systems and the development of deep gully systems (Thomas and Middleton 1994) that have had to be infilled using mechanised methods.

While there are many cases of problems caused by water erosion in the Maghreb, there are also reported developments in land use that appear not to be leading to degradation. For example, a detailed study by Homewood (1993), in the El-Kala area in northern Algeria, shows that where mixed livestock and agricultural activities occur, there is little evidence of ecological or soil degradation, even though pastoral activities have been modernised and in some cases intensified.

The Sahel

Many of the upland areas of the Sahel, such as the Ennedi Highlands of Chad and adjoining Jebel Marah in the Sudan, and the Ader Doutchi in Niger have been affected by very high severity water erosion. The problem, however, is also of high severity in many low relative relief areas, such as the Moshi plateau and Yatenga Province in Burkina Faso (Atampugre 1993). Matheson and Ringrose (1994) have used Landsat MSS imagery to map the distribution of erosion features in several areas of the central and western Sahel. Their study shows that sheetwash, rilling and gullying features occur particularly on pasture and cultivated lands in Niger and Benin, and indicates that even where all environmental criteria favouring vulnerability to water erosion are not fully met, the combination of land use pressure and drought, especially when exacerbated by the effects of post-drought rains falling on bare ground, can lead to erosional problems. In Ghana, GLASOD reports indicate that sheetwash erosion is a serious problem affecting leptosols and luvisols in the heavily populated north-eastern Savanna Highlands. Tree clearance, livestock and agriculture combine to create significant environmental pressures in this region.

In Eritrea and northern Tigray in Ethiopia, extending into adjacent humid areas, soil erosion by water has reached critical levels, a consequence of deforestation of steep slopes as farmers seek new lands to cultivate away from the overcrowded areas. Overgrazing is also a cause of water erosion in the region, with a third of Ethiopia's livestock found in the highlands. Brown and Wolfe (1986) and IGADD (1990) estimated that soil loss was occurring at a rate between 1 and 2 billion m^3 per annum, with perhaps up to 4 million ha of the highlands irreversibly degraded. However, care needs to be exercised when projecting long-term rates from such data since soil erosion, especially in drylands, is highly variable in both space and time.

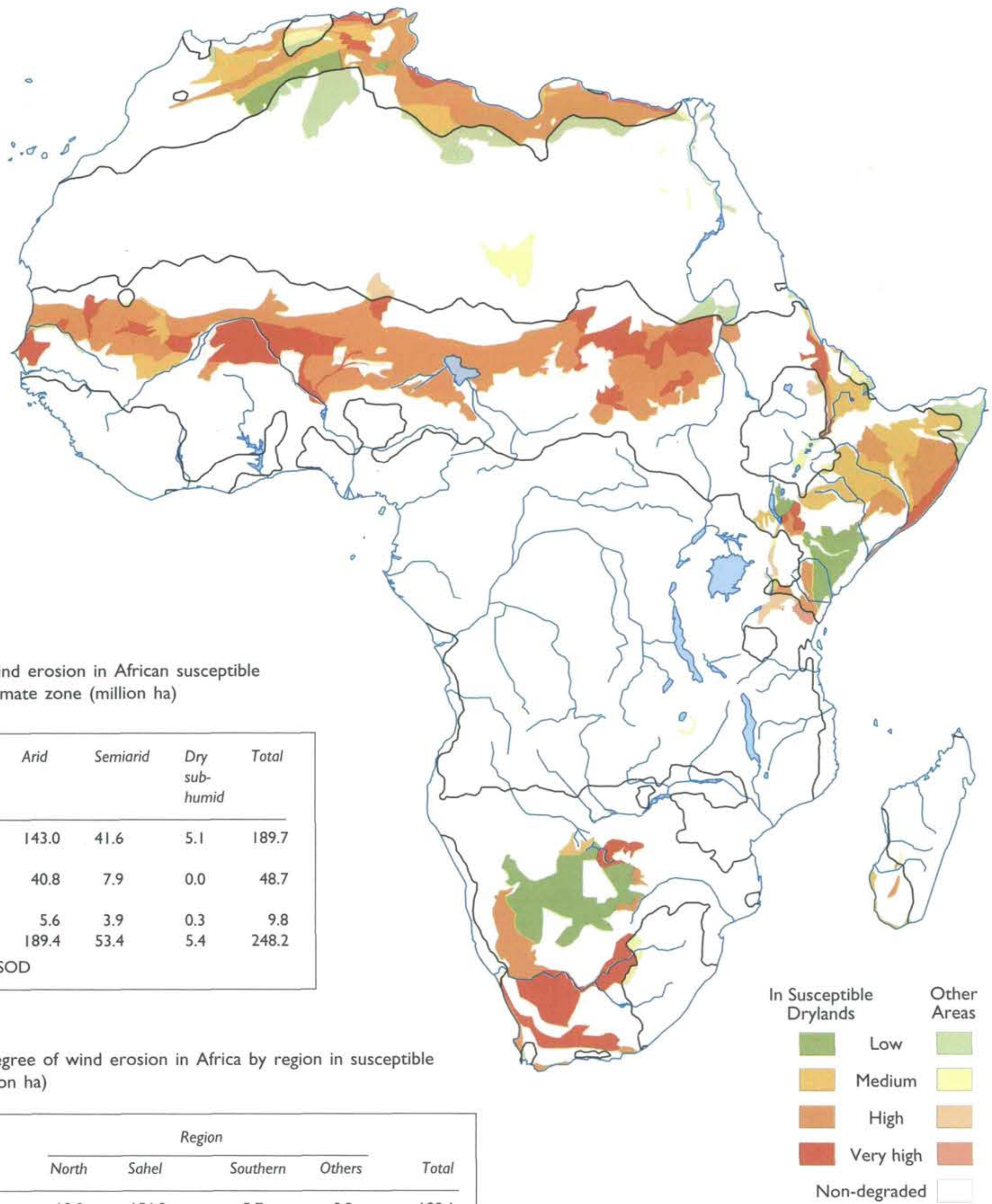
More positive signals come from the slopes of the Machakos and Makueni districts of Kenya (Tiffen *et al.* 1994). Here, changes in land tenure and a resurgence of local land ownership and decision-making in the post-colonial era have seen crop yields increase and erosion decrease in some areas as local farmers have contributed to the construction of terracing, the filling in of gullies and recovery of hill slopes that were once regarded as highly degraded. As Stocking (1995) notes, soil conservation in Kenya is increasingly now part of overall strategies for sustainable farming rather than being treated as a independent activity.

Southern Africa

Southern African susceptible drylands experience water erosion caused by both pastoral and arable activities. Water erosion is perhaps most significant on communal pastoral lands, for example in Namibia, eastern Botswana and Zimbabwe. In southern Zimbabwe where soil erosion is serious in some communal areas, Scoones (1992) has detected no parallel decline in livestock production. This is because erosion predominates on steep upper slopes, while both pastoralism and arable cultivation are concentrated on lower slopes and in valleys. The erosion may therefore actually enhance the quality of the most utilised lands by improving nutrient supply and water retention capabilities (Ingram 1991). Such interpretations need to take into account the eventual loss of soil from lower slopes however, particularly if the stripping of soil from upper slopes eventually leads to higher runoff rates and greater erosive power.

In eastern Botswana, Abel and Blaikie (1989) and Biot (1992) have suggested that rates of human-induced soil loss are very low. Consequently it is suggested that, at current soil erosion rates, the sustainability of present land use practices will only be brought into question in 300–500 years time. Such projections are brought into question by the notorious temporal variability of erosion rates, which means that any projections based on current rates are tenuous. Climate variability can alter rates through times, while even if rates remain steady, topsoil, which is most productive, is eroded first. In Zimbabwe, a survey of soil erosion by Whitlow (1988), that included the country's dryland areas, has shown that correlations between predicted erosion risk and actual erosion occurrence are poor because human factors are very variable and subject to change due to political and economic changes. These and other studies from southern Africa illustrate how difficult it can be to interpret the consequences of water erosion for production, even in situations where the physical processes are reasonably well monitored. The GLASOD report for Zimbabwe notes that the distribution of erosion problems is heavily influenced by the pre-independence legacy of land tenure, with heavily populated communal lands having the most severe water erosion problems. Similar issues apply in South Africa, especially in the now defunct 'bantustans' set up under the former apartheid regime.

Map 2.4 Wind erosion severity



Source: UNEP/ISRIC, CRU/UEA
Approximate equatorial scale 1: 40 million

Table 2.6 Wind erosion in African susceptible drylands by climate zone (million ha)

Wind erosion type	*Arid*	*Semiarid*	*Dry sub-humid*	*Total*
Loss of topsoil	143.0	41.6	5.1	189.7
Terrain deformation	40.8	7.9	0.0	48.7
Overblowing	5.6	3.9	0.3	9.8
Total	189.4	53.4	5.4	248.2

Source: GLASOD

Table 2.5 Degree of wind erosion in Africa by region in susceptible drylands (million ha)

	Region				
Degree	*North*	*Sahel*	*Southern*	*Others*	*Total*
Light	18.0	156.2	5.7	0.2	180.1
Moderate	8.8	99.5	16.1	0.0	124.4
Strong	0.0	4.9	4.1	0.0	9.0
Extreme	0.0	0.8	0.0	0.0	0.8
Non-degraded	122.8	540.9	270.1	37.8	971.6
Total	149.6	802.3	296.0	38.0	1285.9

Note: column and row totals may not correspond due to rounding of decimals
Source: GLASOD

Wind erosion

Table 2.5 shows the regional occurrence of soil erosion by wind that is enhanced by human actions, with Map 2.4 locating the mapping units affected. Table 2.6 shows the distribution of wind erosion by climate zone, also distinguishing between the three different subtypes of wind erosion assessed in the GLASOD continental survey. Whether it is loss of topsoil, terrain deformation or overblowing by wind erosion, it is arid areas that are most affected with a total degraded area of 190 million ha. However, nearly 130 million ha of this area is only affected by light degree wind erosion. The wind erosion problem is relatively limited in occurrence in dry subhumid areas, affecting 5 million ha in total.

Although the human activities that lead to enhanced wind erosion are well-documented, it is important to consider that many parts of African drylands, notably the Sahel belt, have experienced prolonged drought during the period of the GLASOD study and that the natural response of ecosystems to drought – drier soils and less substantial vegetation cover, will also enhance deflation. It may therefore be very difficult to distinguish between human-induced wind erosion and that triggered by climatic variability.

Africa north of the Sahara

Grazing pressure leading to reduced plant cover is the major cause of wind erosion in Africa north of the Sahara, affecting large areas in the northern parts of Algeria and Tunisia where mean annual rainfall is up to 500 mm. The GLASOD report for Libya and Egypt indicates that grazing-induced deflation of topsoil is a pervasive problem in coastal areas. In many areas of Libya, Tunisia and Algeria, the sedentarisation of previously nomadic herders (Sghaier and Seiwart 1993), or restrictions to their range resulting from expanding cultivation, have contributed to the focusing of pastoralism either around oases or in drier regions (Dresch 1986; Middleton 1990). Overstocking of sheep and goats is the main problem in the northern steppe zone of Algeria, Morocco and in the grasslands of Libya (Clark and Munn 1986). Libyan pastures are also suffering from enhanced wind erosion as they are converted to grain cultivation.

Programmes to control aeolian erosion and to reduce the impact of mobile sand on settlements are numerous in the Maghreb countries. A range of techniques are in use (Floret 1987), many involving planting grasses to stabilise susceptible surfaces or establishing fences and palm barriers to protect threatened settlements and structures (Livingstone and Warren 1996).

The Sahel

Wind erosion involving both the movement of sand and the generation of airborne dust is widely documented for the Sahel. Pastoralism (Nickling and Wolfe 1994), intensifying cultivation including deep-ploughing (Thomas and Middleton 1994) and drought that makes the soil more susceptible to disturbance by human actions (Matheson and Ringrose 1994) all contribute to a complex web of factors that have favoured enhanced wind erosion over the last two decades.

Across the northern Sahel are systems of ancient Quaternary-age dunes that are testimony to more arid climates in the past. Human pressures, particularly livestock grazing during times of drought, have contributed to the destabilisation of aeolian deposits, for example in the Sudanese Provinces of Darfur and Kordofan, Hausaland in Niger (Mainguet 1985) and Burkina Faso (Besler and Pfeiffer 1992). Some studies in Kordofan indicate that overgrazing has also led to declining plant species diversity (Warren and Khogali 1992) as well as reduced vegetation coverage (Hellden 1984), especially in areas close to permanent population centres (Thiemeyer 1992).

Wind erosion can also have important off-site impacts. Nickling and Wolfe (1994) have shown how in the Mopti region of Mali areas of formerly cultivated fertile soils have seen the development of *nebkhas,* small dunes that result from sand accumulation around plants. Larger-scale sand encroachment is affecting the Gezira irrigation scheme in the Sudan, with negative impacts that include the infilling of irrigation canals. The correct design and planting of shelter belts can do much to reduce these effects (Mohammed *et al.* 1995). Enhanced dust storm activity, resulting from the erosion of fine particles from agricultural land, has also occurred in the 1970s and 1980s (Middleton 1985).

The largely arid coastal plain and interior rangelands of Somalia are subject to very high and high severity wind erosion respectively. Grazing pressure from sheep, goats, camels and cattle, particularly in areas near to waterholes and settlements, is the most serious problem in these regions, and the GLASOD report for the country notes that livestock are exacerbating naturally occurring deflation in interior areas. Somali herds greatly increased in the 30 years before the beginning of the civil war in 1990 as exports of livestock to the Arabian peninsula rose (Janzen 1994). Numbers of small stock (sheep and goats) have increased particularly quickly. Reactivation of sand dunes and sand sheets in the coastal regions is one of the problems caused by pressure on the stabilising herbs and grasses. A number of sand stabilisation projects have been established with varying levels of success (Grainger 1990), but it is noted in GLASOD reports that their success has been hindered by the civil war.

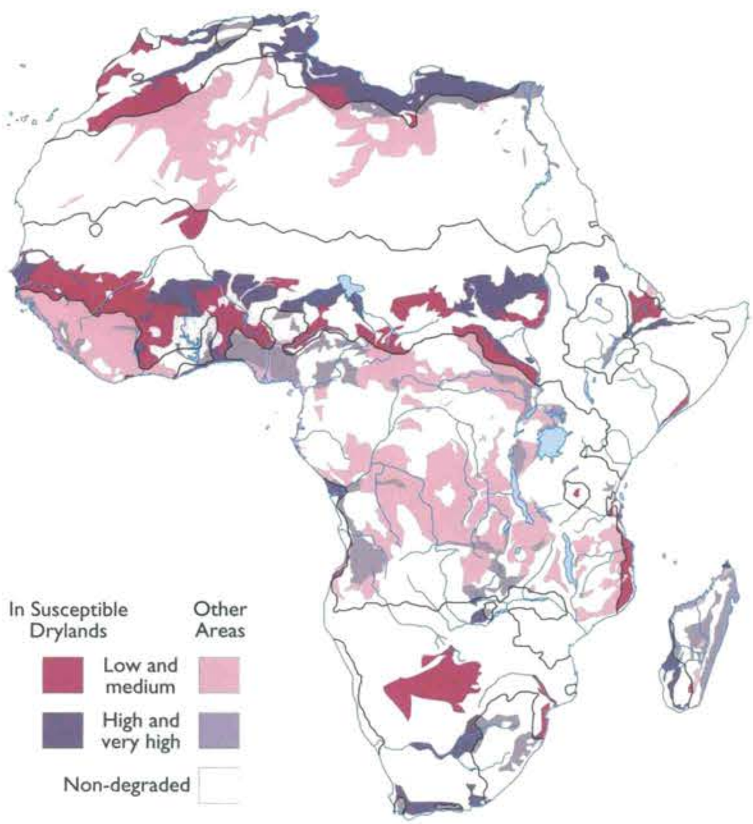
Southern Africa

Wind erosion is a problem in dryland areas of southern Africa from the coastal areas of the Western Cape, South Africa, through to northern Botswana. In the Kalahari of Botswana, as in many parts of the Sahel, it is ancient aeolian sands that are susceptible to deflation (Thomas and Shaw 1991). However, the impact of wind erosion, even where it does occur, is lower than might be expected for two reasons. First, the Kalahari sands have very low concentrations of nutrients (Skarpe and Bergstrom 1986), so that the loss of sediment does not necessarily result in reduced fertility. Second, in many areas where wind erosion occurs, it is very localised in occurrence, concentrated around boreholes, such that long distance transport of material does not occur (Perkins and Thomas 1993a). So long as new boreholes are not sunk, and the distance between boreholes therefore reduced, there is little likelihood that the problem will take on greater spatial dimensions. GLASOD reports also indicate that the presence of major game reserves in the sandveld effectively eliminates the possibility of livestock-induced wind erosion over large areas.

In the coastal areas of the Western Cape, South Africa, it is intensive mechanised agriculture that has contributed to high severity wind erosion. The adoption of soil conservation practices, notably strip cultivation whereby areas of natural vegetation alternate with cultivated areas, however, is being widely adopted as a means of reducing the likelihood of aeolian entrainment taking place.

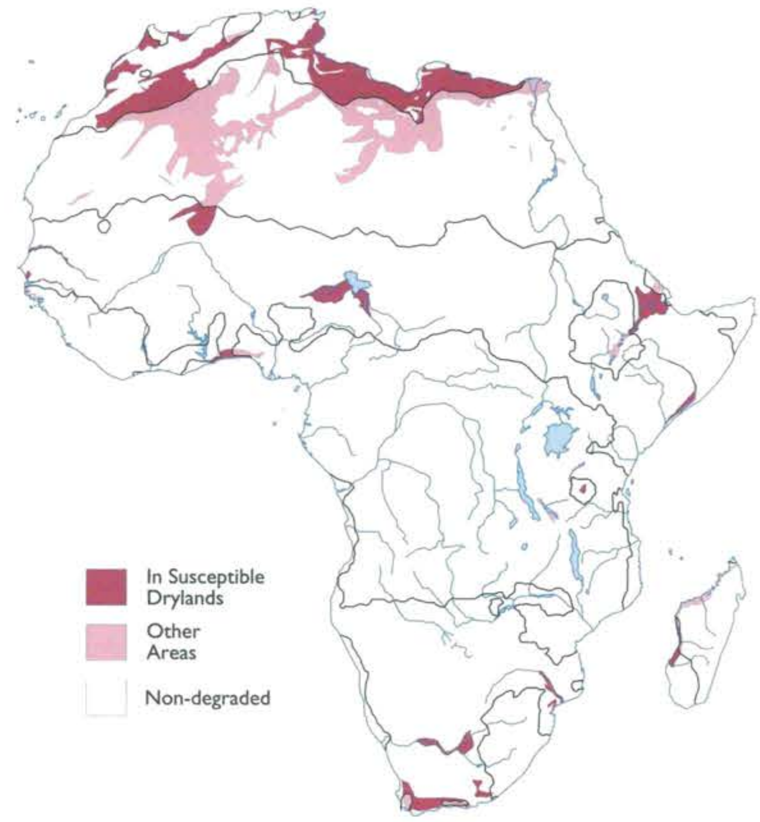
Soil Deterioration

Map 2.5 Chemical deterioration severity



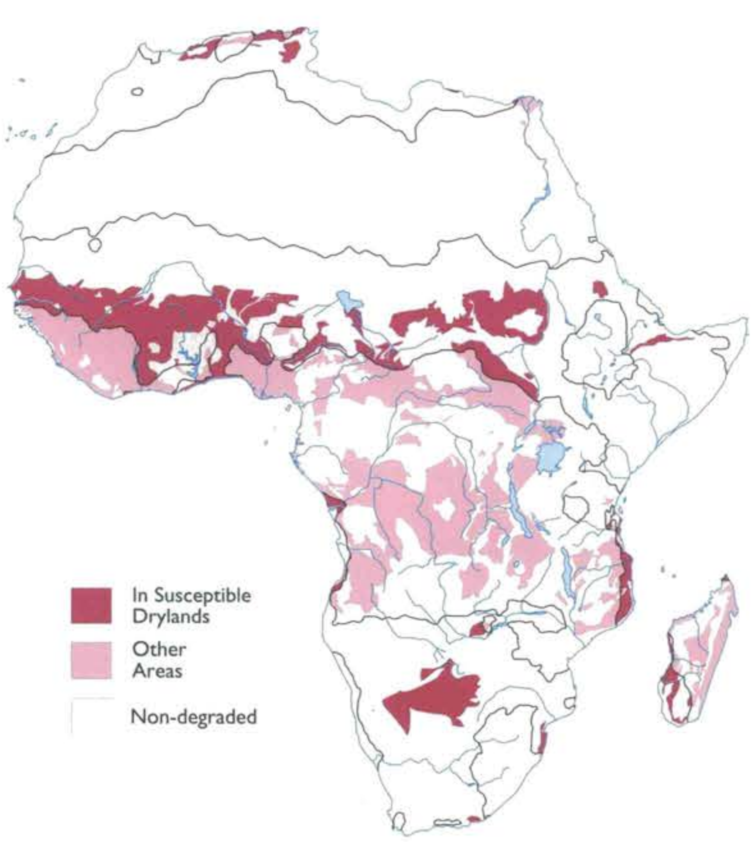
Source: UNEP/ISRIC, CRU/UEA
Approximate equatorial scale 1:81 million

Map 2.6 Salinization



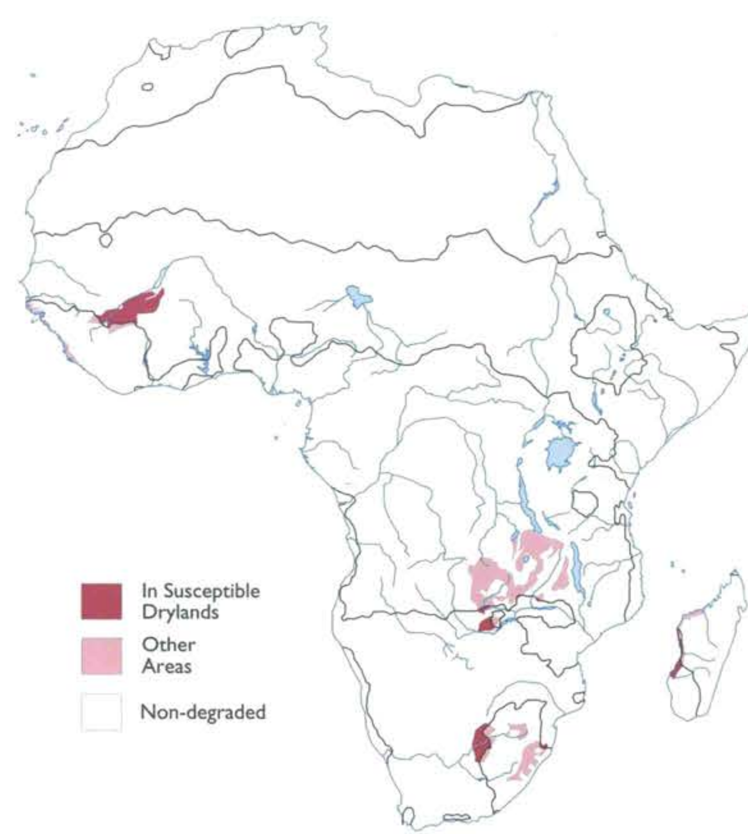
Source: UNEP/ISRIC, CRU/UEA
Approximate equatorial scale 1:81 million

Map 2.7 Loss of nutrients



Source: UNEP/ISRIC, CRU/UEA
Approximate equatorial scale 1:81 million

Map 2.8 Acidification



Source: UNEP/ISRIC, CRU/UEA
Approximate equatorial scale 1:81 million

Eight main classes of vegetation have been mapped. In some cases, the resolution of the satellite data and the difficulties of determining, say, tree densities in open plant communities, have resulted in some large generalised classes being created. Vegetation communities in the susceptible drylands of Africa are remarkably species-rich, especially given the low average availability of moisture (Meadows 1996). The map simplifies these communities into five categories:

Predominantly woodland, savanna woodland and tree savanna. This class excludes dense humid tropical woodland but covers a range of woodland types which cannot be readily distinguished from satellite imagery. It has thus not been possible to distinguish for example between the relatively dense woodlands of subhumid areas in Côte d'Ivoire and Zimbabwe and the dry steppe woodland of Mali and Burkina Faso. These include areas where domestic overexploitation (Prior and Tuohy 1987) and deforestation (Middleton 1995) are the major causes of soil degradation. This class presently covers 24% of the African intertropical land surface.

Grass savanna and other mainly grass-dominated communities. This class, well-discriminated in satellite imagery, covers the almost treeless savannas. It includes the grasslands of the sandy Kalahari soils (Thomas and Shaw 1991) and the volcanic soils of east Africa where grazing pressure is an important contributor to degradation.

Swampy areas with edaphic grass species. This class includes seasonally flooded areas of the Nile basin and several dryland lake basins including Lake Chad and the Makgadikgadi basin in Botswana. More localised valley bottom wetlands, which are important for pastoralism in, for example, Zaria, Nigeria, Yatenga in Burkina Faso and Chiota, Zimbabwe (Scoones 1992), are too small to appear on the map.

Steppic vegetation and subdesert communities. It is difficult to subdivide the range of communities covered by this class, which can be numerous in any one area (e.g. Weare and Yalala 1971) because in imagery the spectral response of the somewhat sparse vegetation is masked by that of the underlying soils. Consequently it is not possible to distinguish from the imagery the southern hemisphere communities containing an important succulent component, such as in Namibia, Botswana and the Karoo (Milton *et al.* 1995) of South Africa, and the Acacia steppe communities of the Sahelian zone (Lewis and Berry 1988). Twenty-two per cent of intertropical Africa falls within this class.

Deserts, including Saharo-mountain vegetation. This broad class includes hyperarid areas, therefore extending beyond the susceptible drylands, and desert mountain areas.

Vegetation and soil degradation

It can be seen that while some of the major zonal trends appear to be similar in the GVI and vegetation community maps, the different scientific and methodological bases of the maps preclude their direct comparison. Each has its own merits. The community map, for example, provides a possible basis for more detailed studies of the actual changes in plant community structure and composition resulting from overall land degradation. Useful local studies of this nature have been conducted, for example, in the Machakos District of Kenya (Farah 1991) and in Zvishavane District, Zimbabwe (Scoones 1989). It may also offer a basis, not pursued in this atlas, for an examination of the relationships between degradation causes and vegetation, as the initial vegetation communities in some instances limit the uses to which a land area can be put, for example in terms of grazing or arable farming.

From the perspective of soil degradation, however, the GVI map permits a useful comparison between biomass and degradation severity, as shown in the global section of the atlas, and even between degradation type and GVI. The latter point is examined in Figure 2.3, where the four degradation types used in this study have been compared with the GVI index by combining the degradation and vegetation databases. The horizontal axis shows the range of GVI values found in the African susceptible drylands; examination of the main map indicates that this covers about half of the total GVI scale. The vertical axis indicates the percentage of the area affected by each of the degradation causes occurring at different points along the GVI scale. This relationship is shown for all four degradation causes, and highlights a number of important points.

Wind erosion peaks markedly on the right-hand side of the diagram. This clearly indicates that wind erosion is effective where the ground has a sparse vegetation cover (the low GVI values indicating low biomass). The curve rapidly diminishes to the left of the diagram as increasing biomass acts as an buffer against sediment transport by wind. Water erosion also peaks under low GVI conditions, though the peak is less marked. Again, low ground cover allows running water to erode the soil. The peak is less marked than for wind erosion because water erosion, particularly by sheetwash, is able to operate even when the vegetation cover is moderately high. This is particularly so under the influence of high intensity dryland rainfall events.

Explanations for the relationship between the distribution of chemical and physical deterioration and GVI are less straightforward. Both peak towards the centre and left-hand side of the diagram and diminish markedly under low GVI conditions. Examination of the range of degradation processes that these causal categories embrace provides the answer. The chemical processes of nutrient depletion and salinization and the physical processes of waterlogging, compaction and crusting are all largely associated with attempts to intensify agricultural output (see pages 36–42, Thomas and Middleton 1993). Land under crops gives relatively high GVI values, especially in the dryland context, accounting for the position on the graph of the peaks for these two degradation categories. Overall, while the graph cannot be used to cite specific values for the GVI-degradation relationship, because of the qualitative nature of GVI and the summary characteristics of the data in the graph, it none the less provides a useful indication of the general relationships that exist between vegetation and degradation causes in the susceptible drylands of Africa.

Degradation and temporal variations in vegetation communities

It is known that there are natural variations in the vegetation of susceptible drylands, linked to the fluctuations which occur in moisture availability (e.g. Ellis and Swift 1988). It is important that, in order to improve the ability to tackle root causes of desertification, investigations of vegetation change in drylands attempt to evaluate the relative contributions made by natural forcing mechanisms and the degrading effects of human activities (Thomas and Middleton 1994, Thornes 1995).

Map 2.14 shows averaged GVI for the 1983–90 period. Comparison of GVI data for individual years has been used by Dregne and Tucker (1988) and Tucker *et al.* (1991) to examine season-to-season and year-to-year fluctuations in biomass in the Sahel belt and Sahara Desert. These studies are of especial interest in the investigation of desertification as they can be used to elucidate the causes of temporal biomass changes. Figure 2.4 shows a plot of the year-to-year changes in the extent of biomass zones taken by Tucker *et al.* (1991) to represent the hyperarid Sahara Desert, and a plot of percentage annual rainfall departures from mean values from data for weather stations in the same area. Expansions and contractions in the low-biomass Sahara system

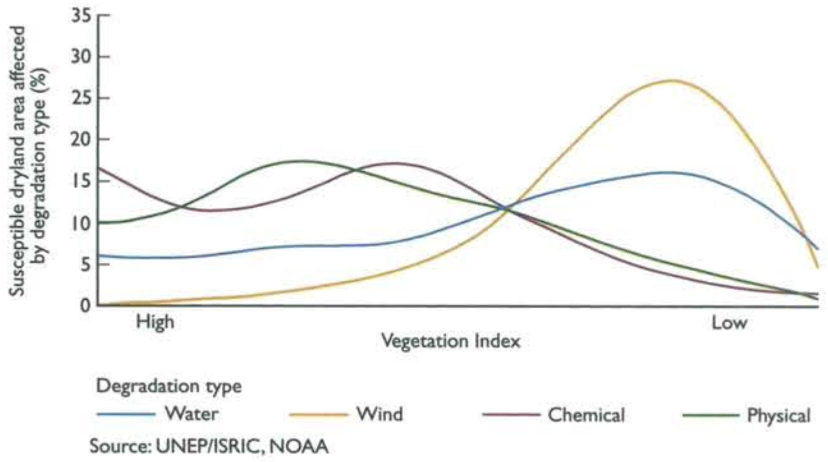


Figure 2.3 Degradation type by GVI in susceptible drylands. Source: UNEP/ISRIC, NOAA

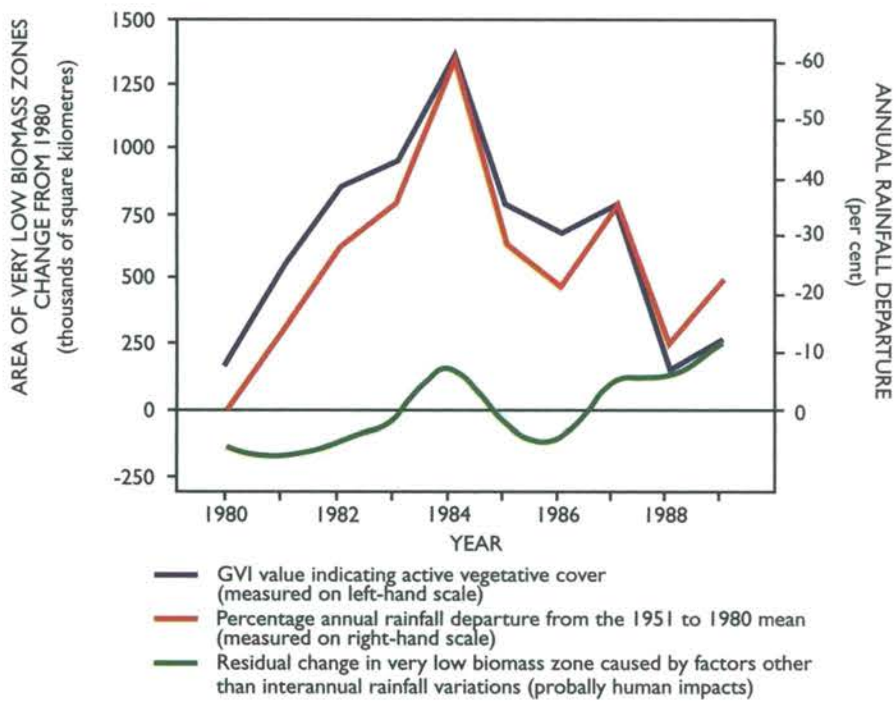


Figure 2.4 Fluctuations in very low desert biomass zones of the southern Sahara and links with rainfall (after Hulme and Kelly 1993)

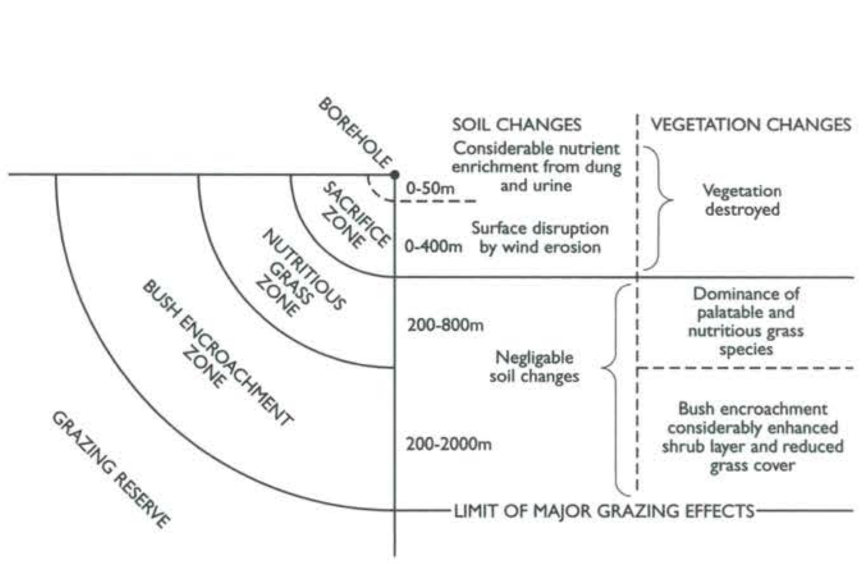


Figure 2.5 Zone of vegetation and soil changes around boreholes in the semiarid eastern Kalahari, Botswana (after Perkins and Thomas, 1993b)

is concomitant with reductions and expansions in more biologically productive Sahelian systems. Statistically, 87% of the fluctuations are explained by interannual rainfall variations, the remainder being due to other impacts, principally human activities that destroy biological resources (Hulme and Kelly 1993). More detailed case studies by Lindqvist and Tengberg (1993) in Burkina Faso show that human pressures during drought have inhibited the re-establishment of plant communities on sandy soils and led to the persistence of bare areas during times of improved rainfall. Extensive surveys using satellite data and detailed site-specific field studies are therefore both valuable in assessing natural versus human impacts on dryland vegetation.

Spatial variations in vegetation and degradation

As well as temporal fluctuations in vegetation communities occurring in susceptible drylands, there is now considerable evidence to show that most human-induced vegetation changes do not advance along a progressive desertification front as was once supposed (e.g. Lamprey 1975), but that spatial patterns of change can be very complex. Spatial patterns in part depend on the type of land use system in operation, for example intensive irrigation systems such as that practised in the Gezira area of the Sudan (Mohammed *et al.* 1995) will affect natural vegetation more significantly than localised subsistence patch agriculture. Most attention on vegetation change in Africa, however, focuses on pastoral systems which for the most part depend on natural vegetation for their success. The impacts of transhumance systems, for example in the El Kala area of Algeria (Homewood 1993) and Gourma region of Mali (de Leeuw *et al.* 1993), which embrace a number of different ecological zones within the seasonal livestock movements; the unfenced 'cattlepost' system traditionally practised in both sandveld (Perkins and Thomas 1993a) and hardveld areas (Biot 1988) of Botswana; and fenced cattle ranches, are all likely to differ in terms of their impacts on vegetation communities.

In many parts of the Sahel and in central southern Africa, livestock systems are often based on point water sources that may be boreholes and pumps. Livestock use of the vegetation resources around these water sources can lead to a zonation of the impacts that animals have on vegetation communities, radiating out from the central point (Glantz 1977). The zones that result are called piospheres. If livestock numbers are allowed to proliferate, and are supported by the import of artificial feeds during times of drought and environmental stress, then the

Chemical deterioration

Chemical deterioration of soils presents a serious problem in the susceptible drylands of Africa (Map 2.5), affecting 51 million ha in total (Table 2.7). Continental appraisals (Thomas and Middleton 1993, Stoorvogel *et al.* 1993) have confirmed the impression given in Map 2.7 that nutrient depletion is the most widespread form of chemical deterioration. Nutrient depletion is a problem affecting more than 40 million ha of Africa's susceptible drylands, compared to less than 6 million ha affected by salinity problems (Tables 2.8 and 2.9). Thomas and Middleton (1993) show that secondary salinization accounts for about 10% of Africa's saline soils, though it does affect half the area of irrigated land, much of which is devoted to the production of cash crops. Nutrient depletion, by contrast, is a problem largely faced by individual subsistence farmers, and much of the dryland nutrient loss is from the semiarid and dry subhumid zones, a simple reflection of the more humid conditions necessary for dryland farming. Stoorvogel *et al.*'s (1993) study of arable soils in 38 sub-Saharan countries, inside and outside the susceptible drylands, indicates the alarming scale on which African farmers are effectively mining soil nutrients. The annual average nutrient loss for sub-Saharan Africa in 1982–84 was 22 kg ha^{-1} nitrogen, 2.5 kg ha^{-1} phosphorous, and 15 kg ha^{-1} potassium, and was projected to reach levels of 26 kg ha^{-1} nitrogen, 3 kg ha^{-1} phosphorous, and 19 kg ha^{-1} potassium by the year 2000 should current practices continue.

It should be noted that the seemingly large parts of the Sahara affected by chemical deterioration by salinization in Maps 2.5 and 2.6 represent deterioration in oases. Many of these small areas are treated together in the GLASOD database, giving an exaggerated picture of the extent of the problem on the maps, since whole polygons have been shaded. This is a limitation of the mapping technique.

Africa north of the Sahara

Low severity chemical degradation is widespread in Tunisia, Libya and Egypt: that is, it affects no more than 10% of individual map units. Chemical degradation is more severe to the west, in the area between the Atlas Mountains and the Mediterranean coast, where the primary process is nutrient depletion.

The Nile Valley in Egypt contains 2.8 million ha of irrigated land and experiences substantial chemical degradation problems, involving both salinization and nutrient depletion (Kishk 1986). While allowing total control of the river's flood regime and the creation of over 500 000 ha of new irrigated land, the Aswan High Dam has deprived agricultural land downstream of nutrient enriching flood-borne silts. The need to increase food production to supply Egypt's rapidly growing population, which stood at 63 million in 1995, has also meant that two or three crops are grown annually on the old irrigated lands in the valley. This requires a concomitant increase in the application of irrigation water and has lead to very severe salinization, a problem now also affecting the new irrigation lands and causing an estimated 30% of all Egypt's croplands to be salinized. The salt problem is at its greatest in the Nile Delta where it has been compounded by the reduction in the river's flow regime, allowing the incursion of sea water (Stanley and Warne 1993).

Table 2.7 Degree of chemical deterioration in Africa by region in susceptible drylands (million ha)

	Region				
Aridity zone	*North*	*Sahel*	*Southern*	*Others*	*Total**
Light	3.8	25.6	2.2	1.7	33.3
Moderate	1.7	8.8	0.3	0.8	11.6
Strong	0.0	5.0	0.1	1.0	6.1
Extreme	0.0	0.0	0.0	0.0	0.0
Non-degraded	144.1	762.9	293.4	34.5	1234.9
Total*	149.6	802.3	296.0	38.0	1285.9

Source: GLASOD

Table 2.8 Degree of degradation by loss of nutrients by climate zone (million ha)

	Climate zone			
Degree	*Arid*	*Semiarid*	*Dry subhumid*	*Total**
Light	0.7	16.6	9.8	27.1
Moderate	2.3	4.3	2.1	8.7
Strong	0.6	4.2	1.2	6.0
Extreme	0.0	0.0	0.0	0.0
Total*	3.6	25.1	13.1	41.8

Source: GLASOD

Table 2.9 Degree of degradation by salinization by climate zone (million ha)

	Climate zone			
Degree	*Arid*	*Semiarid*	*Dry subhumid*	*Total**
Light	2.2	1.2	0.2	3.6
Moderate	1.2	0.8	0.1	2.1
Strong	0.0	0.0	0.0	0.0
Extreme	0.0	0.0	0.0	0.0
Total*	3.4	2.0	0.3	5.7

Source: GLASOD

Table 2.10 Degree of degradation by acidification by climate zone (million ha)

	Climate zone			
Degree	*Arid*	*Semiarid*	*Dry subhumid*	*Total**
Light	0.0	1.2	1.4	2.6
Moderate	0.0	0.0	0.0	0.0
Strong	0.0	0.0	0.0	0.0
Extreme	0.0	0.0	0.0	0.0
Total*	0.0	1.2	1.4	2.6

Source: GLASOD

*Note: column and row totals may not correspond due to rounding of decimals

The Sahel

Nutrient depletion is the most widespread type of chemical deterioration affecting Sahelian soils. High and very high severity degradation is recorded in Senegal's groundnut fields (Paye 1990), in central Burkina Faso, and in Sudan's Kordofan and Darfur Provinces (Khogali 1991). In central Sudan the introduction of mechanised agriculture, primarily for growing sorghum, has led to tree clearance. Monocultivation has caused degradation of the sandy soils by nutrient depletion through overcultivation, with substantial soil depletion and land abandonment occurring as little as 3 years after the start of cultivation. Loss of nutrients from Sahelian soils is not solely confined to cultivated areas, however. The nutrient-depleting effects of grazing and burning savannas in Nigeria have been shown by Aweto and Adejumobi (1991). Increased soil exposure and decline in soil organic matter leads to enhanced nutrient loss through both erosion and leaching. The risk of nutrient depletion from such savanna sites has also been highlighted by Kadeba (1994).

Soil acidification associated with a loss of nutrients is a serious issue on the croplands east of Bamako in southern Mali. Nutrient deficits are caused by traditional cereal crops, but also by cotton and especially by groundnuts. The latter two crops are fertilized, but insufficiently. An assessment of the degree of 'soil mining' by agricultural production in the area has been made by Van-Der-Pol and Traore (1993) whose most optimistic estimates suggest large deficits for nitrogen, potassium and magnesium. For the region as a whole, the calculated deficits were -25 kg ha^{-1} N, -20 kg ha^{-1} K and -5 kg ha^{-1} Mg. These authors expect further acidification to occur, particularly in areas where cotton is grown.

Salinization in the Sahel affects many irrigation schemes, such as the South Chad Irrigation Project which is located in north-eastern Nigeria. This scheme began in 1974 and was to have irrigated 106 000 ha, but the fluctuations of Lake Chad have severely restricted the success of this project; the lack of available water and high evapotranspiration rates exacerbating salinization (Kolawole 1987). Numerous riverine irrigation schemes are also affected. They include those on the Senegal River, the Hadejia River in Nigeria, the Logone River (part of the Chari system) in northern Cameroon, the Awash River in Ethiopia, and the lower Shabelle River in southern Somalia. Notable by their absence, however, are such irrigated areas as the inland delta of the Niger and the Sudan's large schemes along the Nile and its tributaries. It should also be noted that not all of the Sahel's salinization problems are human-induced. Increased salinity of West African estuarine lands, the 'tannes' of the rivers Casamance, Saloum, and Gambia has been caused by marine intrusion as river flows depleted by the prolonged drought of the last three decades have allowed sea water to penetrate further upstream (Thomas and Middleton 1993, see Figure 2.1). This is a good example of desertification that is substantially attributable to variations in climate.

Southern Africa

Relatively small areas are affected by chemical deterioration in southern Africa as compared to the Sahel. Salinization affects the lower Limpopo River in southern Mozambique, South Africa's Western Cape and the Orange River, an area of which is also affected by acidification. Salinity in the Breed River catchment east of Cape Town increases downstream due to saline return flows from irrigated vines, orchards and alfalfa although the problems are offset to some extent by freshwater releases from the Brandvlei Dam (Flügel 1989). Extensive areas of Botswana are indicated to be suffering from nutrient depletion. Although Kalahari soils typically have naturally low nutrient contents (Skarpe and Berstrom 1986), heavy grazing has been cited as a cause of substantial reduction in nutrients in the herb and grass layer of some Botswana savanna types (Ernst and Tolsma 1989), with consequent effects on the soil.

Madagascar

The GLASOD survey indicates that the dryland area of south-western Madagascar experiences high severity degradation by nutrient depletion. In Toliara Province, for example, this has resulted from the expansion and intensification of cultivation, primarily of maize and manioc, through traditional and mechanised farming. Loss of nutrients has been a function of the shortening of fallow periods as well as the thorough destruction of the natural xerophytic thorn forest. The extension of cattle raising into the area exacerbates the problem.

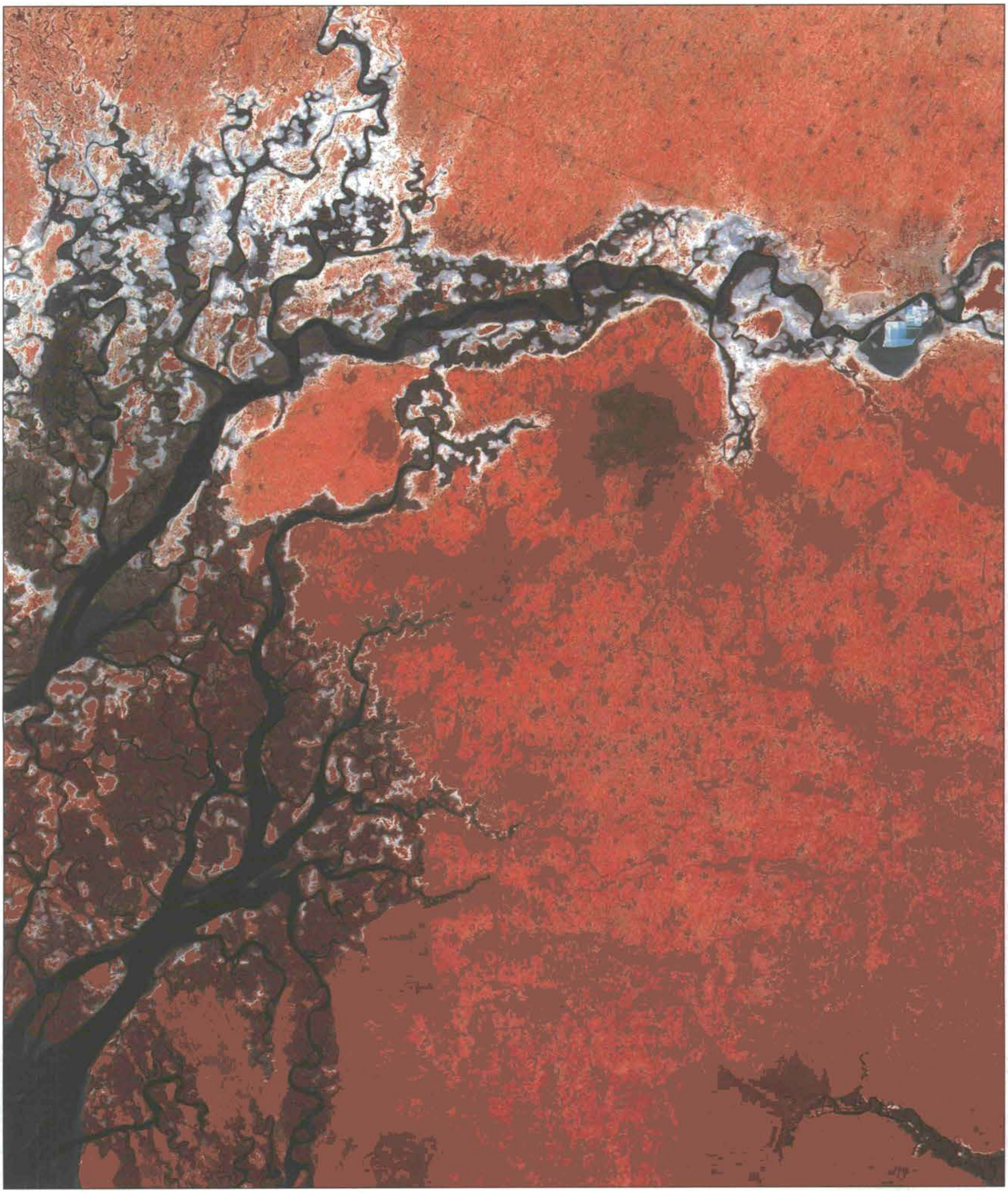


Figure 2.1 Tidal flats and estuaries on the Saloum River in Senegal. This Landsat MSS image, taken in October 1992 shows highly saline areas in white. These areas have become increasingly saline due to drought that has persisted in the area since 1968

Physical deterioration

Most areas of Africa worst affected by physical deterioration are found in the continent's susceptible drylands (see Map 2.9 and Table 2.11). Although the physical deterioration category is the least extensive of the four degradation categories recognised by GLASOD, it nevertheless presents serious problems in specific areas. As Tables 2.12 and 2.13 indicate, compaction and crusting are by far the most widespread forms of physical deterioration.

Africa north of the Sahara

Much of a broad swath of land stretching from Tripoli in Libya, through the 'telle' zone and into the Tunisian Atlas Mountains are affected by medium or high severity physical degradation. In the Nile Delta, medium severity due to waterlogging has become a problem

Map 2.9 Physical deterioration severity

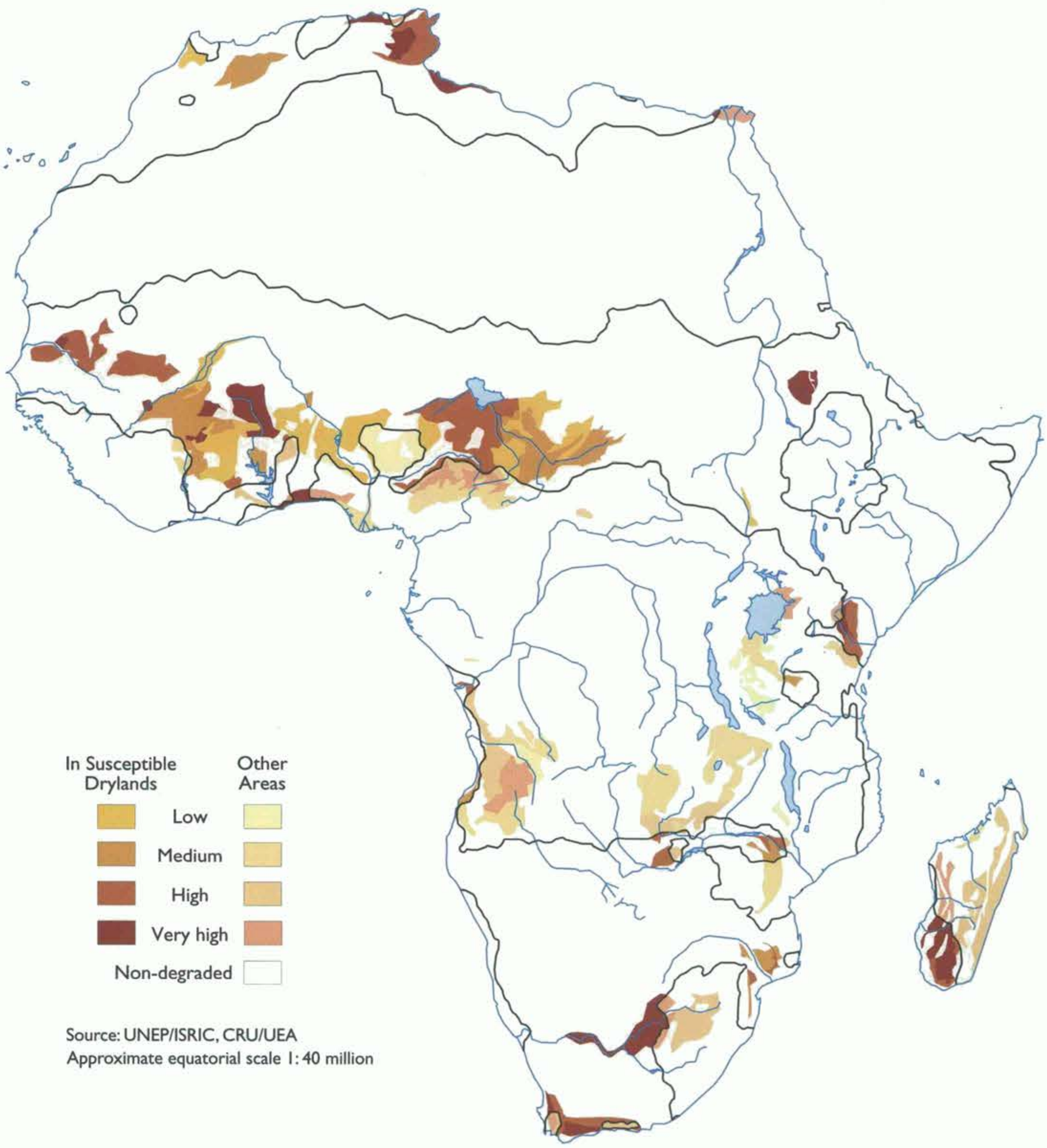


Table 2.11 Degree of physical deterioration in Africa by region in susceptible dryland areas (million ha)

Aridity zone	Region: North	Sahel	Southern	Others	Total*
Light	4.7	18.7	1.2	0.2	24.8
Moderate	1.0	8.7	1.1	2.8	13.6
Strong	0.0	3.1	4.1	0.0	7.2
Extreme	0.0	0.0	0.0	0.0	0.0
Non-degraded	143.9	771.8	289.6	35.0	1240.3
Total*	149.6	802.3	296.0	38.0	1285.9

Source: GLASOD

Table 2.12 Degree of degradation by compaction/crusting by climate zone (million ha)

Degree	Climate zone: Arid	Semiarid	Dry subhumid	Total*
Light	1.9	12.0	5.3	19.2
Moderate	2.6	8.6	1.4	12.6
Strong	1.0	4.1	2.1	7.2
Extreme	0.0	0.0	0.0	0.0
Total*	5.5	24.7	8.8	39.0

Source: GLASOD

Table 2.13 Degree of degradation by waterlogging by climate zone (million ha)

Degree	Climate zone: Arid	Semiarid	Dry subhumid	Total*
Light	0.0	0.1	0.2	0.3
Moderate	0.0	0.1	0.0	0.1
Strong	0.0	0.0	0.0	0.0
Extreme	0.0	0.0	0.0	0.0
Total*	0.0	0.2	0.2	0.4

Source: GLASOD

*Note: column and row totals may not correspond due to rounding of decimals

since the completion of the Aswan High Dam in the 1960s (Stanley and Warne 1993).

The Sahel

Soil compaction and crusting are the most serious forms of physical degradation affecting several irrigated areas of the Sahel. They have become a major problem of very high severity in the Khashm el Girba project in Kassala Province, north-eastern Sudan, where irrigation water from the dammed Atbara River is fed by gravity flow to 150 000 ha of cotton, wheat and groundnuts. Although much of the Atbara's heavy load of fine silts from the basaltic Ethiopian Highlands had cut the reservoir capacity by half in the 20 years of the dam's life to 1983, irrigation water from the reservoir contains sufficient silt to clog soil pores and to create crusting problems. The Khashm el Girba soils are vertisols, requiring careful water management to avoid such effects. Further west in the Sahel zone, an extended area around the southern banks of Lake Chad suffers significantly from compaction and crusting. The South Chad Irrigation Project is partly to blame, combined with more widespread excessive trampling of sandy soils by cattle, although a distinction between these human-induced causes and the natural effects of drought is difficult to make according to the GLASOD reports. These compacted soils are known as 'nagas' in Chad and 'hardés' in northern Cameroun.

High severity degradation affects much of central and northern Burkina Faso. Heavy grazing and associated trampling during prolonged drought has been responsible for large losses in savanna vegetation cover and consequent soil compaction on the Mossi plateau of central Burkina Faso (Poppel and Lekkerkerker 1991) and in more northerly areas of the country (Lindqvist and Tengberg 1993). In the former study, analysis of satellite imagery indicated that the extent of degraded savanna had increased from one-third to two-thirds of the Mossi plateau between 1975 and 1987. Using archive aerial photography and satellite imagery, Lindqvist and Tengberg (1993) also identified the expansion of areas bare of vegetation between 1955 and 1990, a trend to be expected since the 1950s was a period of good rainfall in the area followed by prolonged deficits in the 1970s and early 1980s. But although rainfall had recovered in the late 1980s, vegetation coverage had not been restored. In one area, however, a more complex situation was found. At the Boukouma site, runoff from degraded interfluves had improved vegetation coverage in depressions.

Overgrazing and fuelwood collection are the causative factors in the high severity Ferlo area of northern Senegal and the very high severity Brakna region of southern Mauritania. Both these areas have suffered a more-or-less continuous drought since the late 1960s which has exacerbated human overuse of the area. Increasing demand for fuelwood and charcoal in Nouakchott, a city swelled by drought refugees, has been partly satisfied from Brakna's forest resources (Mauritania 1986). The drought has also led to concentration of cattle around boreholes in the Ferlo, leading to soil compaction by trampling (Hanan *et al.* 1991). This is not the only aspect of land degradation which can be partly attributed to cattle in this area. The replacement of perennial grasses with annuals and the loss of trees to more xerophytic woody species are partly a response to drought, but have also been affected by heavy grazing pressure.

Southern Africa

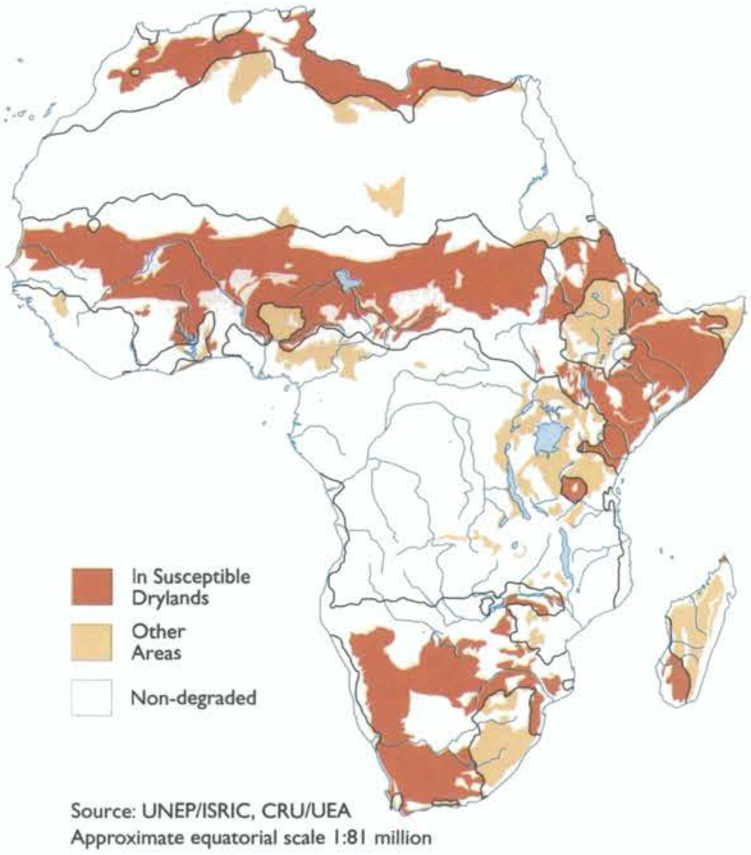
Two areas in South Africa are badly affected by compaction and crusting. In the Western Cape region the problems are caused by agricultural activities, where wheat, vineyards and irrigated fruit orchards are the main land use types. The other problem area, affected by a high severity of physical degradation due to agriculture and overgrazing, lies along the Orange River and its tributary the Vaal, from the northern Karoo to the Namibian border. Irrigated fruit production is the main land use in this part of South Africa. High severity deterioration is also recorded along the Changane River, a tributary of the Limpopo in southern Mozambique.

Madagascar

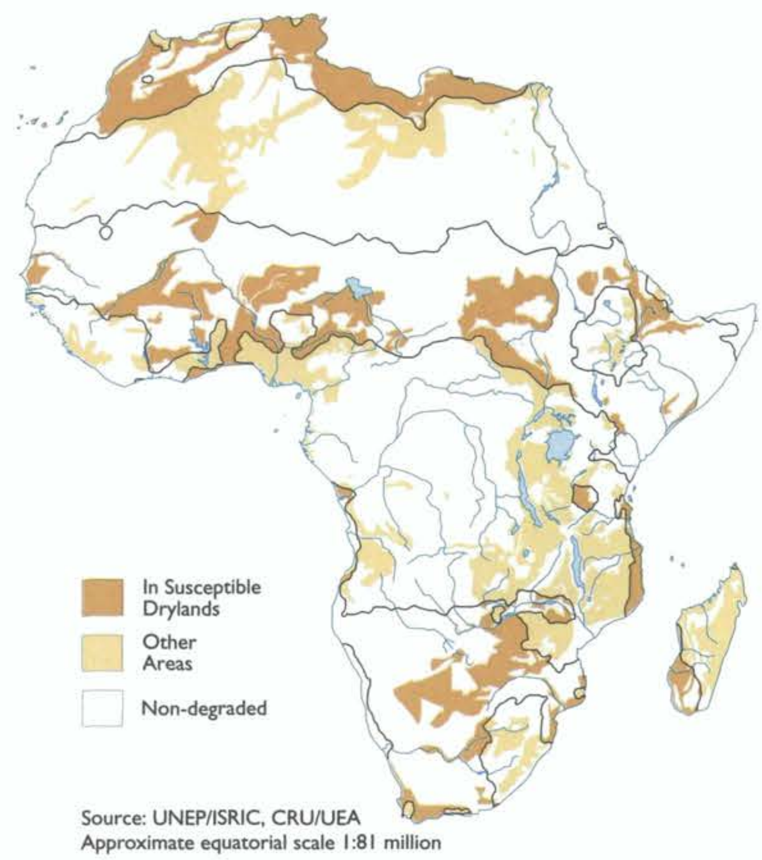
The GLASOD survey found very high severity degradation by compaction and crusting due to heavy grazing pressures in south-western Madagascar.

Causes of Soil Degradation

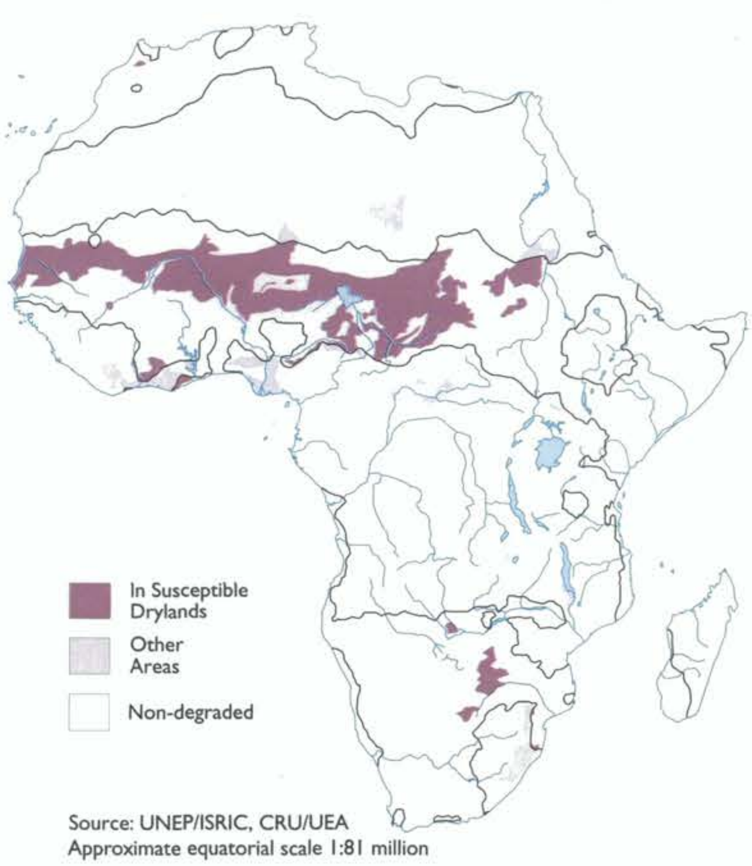
Map 2.10 Areas affected by overgrazing



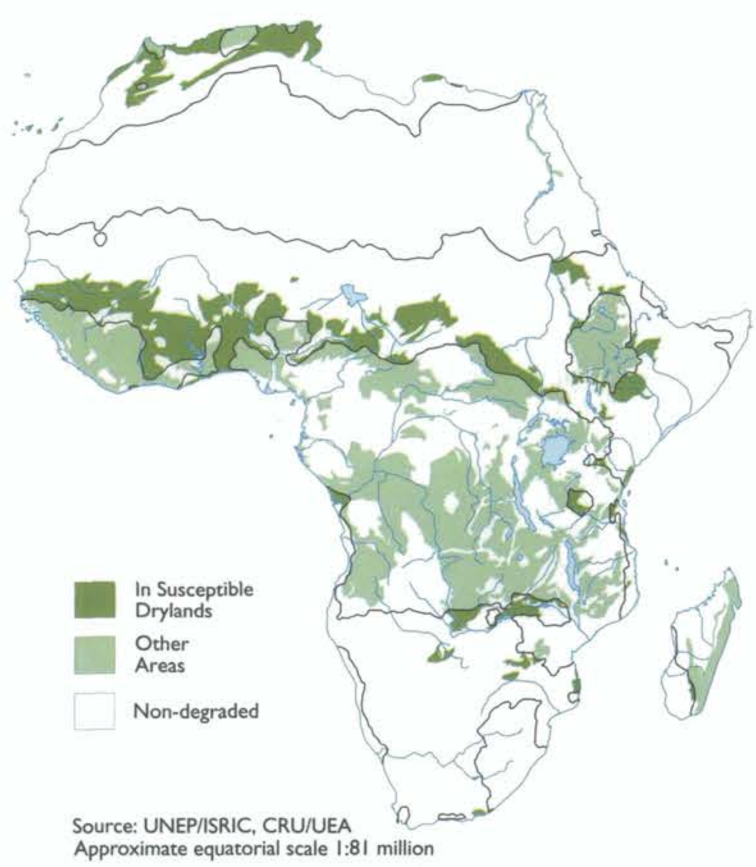
Map 2.11 Areas affected by agricultural activities



Map 2.12 Areas affected by overexploitation of vegetation



Map 2.13 Areas affected by deforestation



Maps 2.10–2.13 show areas where a particular cause has been identified as important in the soil degradation process, although they give no indication as to their relative importance. As the maps show, many areas are under multiple pressures and attributing degradation to any single cause can be difficult. Trees may be cleared from a mixed savanna, for example, to make way for cultivation, but the trees may also be used for firewood. Additionally, the savanna may be already stressed through grazing pressure.

Overgrazing

Overgrazing is the most widespread cause of soil degradation in Africa (see Map 2.10), affecting more than half of all degraded susceptible dryland soils (Table 2.14). It is largely a problem of the arid and semiarid zones. Pastoralists traditionally respond opportunistically to the inherently variable dryland range, but the success of this dynamism can be hampered by a range of external factors. The reasons for concentrating too many livestock in certain areas, leading to loss of vegetation cover and trampling of soil surfaces, can be cultural, socio-economic or political, or they may have their roots in environmental factors such as drought and the distribution of vector-borne diseases. Overgrazing around settlements in North Africa and the Sahel is often related to the sedentarisation of nomadic herders. In Algeria and Tunisia, where the transition of herders from a nomadic lifestyle to a more settled one has been taking place for some decades, expansion of cultivation and disruption of trade routes has undermined the traditional north–south seasonal migration of herders, who also performed important trading functions across the central steppe zone. The settlement of these former nomads has meant that their herds have been concentrated onto grazing around their new homes (Sghaier and Seiwert 1993).

Drought conditions have forced herders to concentrate their animals in the arid and semiarid Mauritanian Sahel, causing the complete disappearance of the herbaceous cover in many places, particularly around boreholes, with consequent windblown loss of topsoil and reactivation of ancient sand dune deposits. High mortality rates among cattle, sheep and goats in Mauritania during the 1980s was generally due to insufficient grazing rather than a lack of water (Middleton 1987). In the Butana region of the Sudan, the effects of drought, combined with the abolition of traditional rights of land use, have created similar problems. The resulting disorganised utilisation of grazing lands and the self-generated sedentarisation of many formerly nomadic groups has led to accelerated development of dunes and badlands after severe vegetation transformation in areas with permanent water supply or with sandy soils (Akhtar and Mensching 1993). In many parts of the Sahel, expanding areas of sorghum and millet cultivation have also been primary factors responsible for a major decrease in the availability of range, as Ringrose and Matheson (1992) identified in west-central parts of the area. The position of herders at the margins of society in the eyes of many central governments has often meant that they are situated at the end of a chain of events that sees the expansion of irrigated land for cash-cropping displacing rainfed subsistence cultivators who encroach into traditional grazing grounds, forcing herders into smaller ranges. This situation is described by Janzen (1994) in southern Somalia where expansion of irrigated agriculture on the Jubba and Shabelle rivers has forced small farmers to clear large areas of bushland for cultivation. For nomadic herders, this savanna zone and the river valleys themselves were important grazing lands during the dry season. Resultant intensification of grazing pressure into smaller areas has also been driven by the sedentarisation of some nomadic groups, a trend encouraged by government policy in the 1970s, and accelerated more recently by drought. The issue of government-sponsored sedentarisation continues in many other African countries. Not all of the examples of encroaching cultivation depict nomadic pastoralists as helpless victims, however, since such groups are inherently flexible and adaptable to changing circumstances, as Kohler-Rollefson *et al.* (1991) show for the Rashaida camel-breeders in the Kassala region of the Sudan.

Socio-economic factors can explain the increasing grazing pressures in the tribal areas of Hereroland and Damaraland in Namibia and some of the former 'homelands' within South Africa. Overgrazing in these regions is due to high growth rates in both human and livestock populations and a lack of alternative grazing lands to expand into (Seeley and Jacobson 1994, Dean et al. 1995). Excessive use of rangeland during the early stages of drought periods by increasing human and livestock populations is thought to be particularly important in explaining degradation in central Botswana (Sefe *et al.* 1996).

Table 2.14 Main causes of soil degradation in Africa by aridity zone (million ha)

	Region			
Cause	*Arid*	*Semiarid*	*Dry subhumid*	*Total*
Overgrazing	119.9	61.9	12.6	194.4
Agricultural activity	11.1	33.8	15.5	60.4
Overexploitation	42.0	11.7	1.8	55.5
Deforestation	3.9	7.6	10.5	22.0
Total	176.9	115.0	40.4	332.3

Source: GLASOD

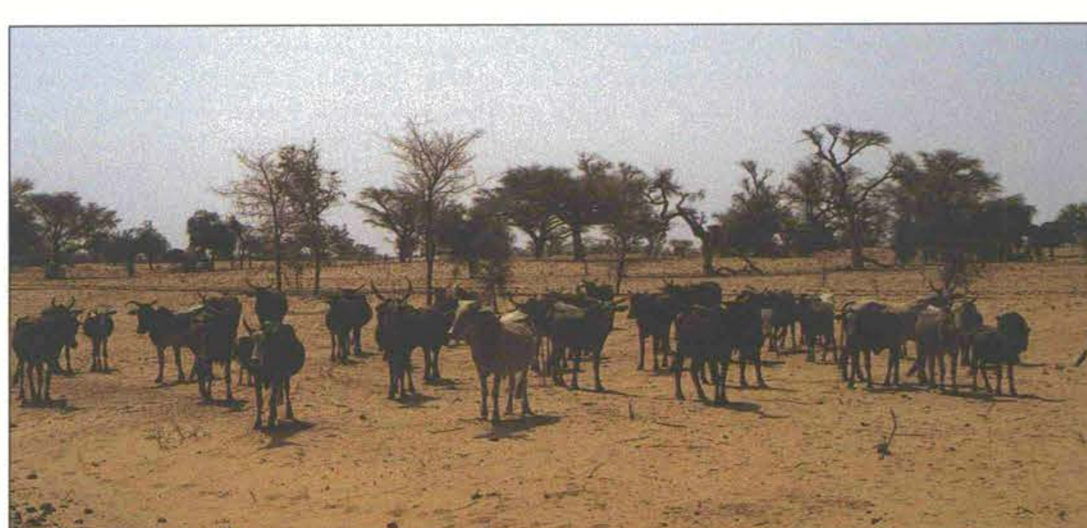


Figure 2.2 Intensive grazing by livestock has long been thought to be the primary cause of desertification in African drylands, as in this picture of Niger. However, the simple assumptions behind this viewpoint are being questioned and many researchers now believe that rainfall variability is a more important determinant of rangeland conditions (N Middleton)

The primary position of overgrazing as a cause of dryland degradation indicated in this survey and many previous ones (UN 1977b, UNEP 1984) has been intensely scrutinised in recent years, however. In the light of changes in the understanding of rangeland ecology, the relative importance of intense grazing and natural stresses are being reassessed (Figure 2.2). Many authorities now believe that rainfall variability is a more important determinant of the health of rangeland and its soils than overgrazing (Behnke *et al.* 1993). This change in understanding of dryland ecology is an important development because if natural environment factors are the major determinant of available rangeland resources, this has major implications for pastoral management.

Table 2.15 Agricultural land use in three areas of Mali interpreted from aerial photography, as a percentage of the total image area (IGN 1992)

Land use		*Area*		
		Nara (%)	*Mourdiah (%)*	*Yanfolila (%)*
Crops in 1950s	C1	4.1	6.4	4.3
Crops in 1987	C2	7.3	15.2	10.6
All agricultural land (crops plus fallow) in 1950s	T1	28	65	73
All agricultural land (crops plus fallow) in 1987	T2	55	71	72
Crop area for the year as a	C1/T1	14.7	13.3	9.9
proportion of all agricultural land	C2/T2	21.4	5.9	14.8

Agricultural activities

Degradation due to poor agricultural management (see Map 2.11) is largely concentrated in the semiarid and dry subhumid zones (Table 2.14) since these are the areas most suitable for dryland crops, although degraded soils on irrigated agricultural lands may also be located in more arid regions. Overirrigation and inadequate drainage are the most common problems leading to soil salinization and waterlogging in these areas. These problems are highlighted in the irrigation schemes in the Nile basin, along the lower reaches of the Senegal River, the Jubba and Shabelle rivers in southern Somalia, the Orange River in South Africa and the Limpopo River in Mozambique. Salinization is also one of the principal types of soil degradation in the Canary Islands; the others being water and wind erosion. Rodriguez *et al.* (1993) note that the main forms of mismanagement on the islands are all agricultural: overexploitation of aquifers, irrigation with water having a high salt and/or sodium content, intensive monoculture, and excessive and indiscriminate use of chemical fertilizers and other agrochemicals.

Inappropriate management of dryland crops stems from a number of driving forces. Rainfed farming in Algeria and Tunisia has been pushed into increasingly marginal areas since the nineteenth century, using European agricultural machinery inappropriate to dryland ecosystems. Dry cereal cropland continues to expand into the steppe using tractors and multidisc ploughs with consequent degradation largely due to wind action. In 1983, the Algerian Government passed legislation positively encouraging the cultivation of marginal lands in the Sahara and in the country's high plateau region in an effort to expand the agricultural resource base, to increase food supply, to combat the exodus of peasants to urban areas and to counterbalance coastal urban development. This homesteading programme was part of the 'new lands' scheme, a plan that also involved the reduction of fallow in traditional crop rotation systems. The extensification of cropland into the desert margins of neighbouring Morocco also proceeded apace in the 1980s, in this case driven by a doubling of prices paid to barley and wheat producers and relatively good rainfall totals. The average annual area under cereals grew from just over 4.4 million ha in 1980–84 to 5.5 million ha by 1990 (Swearingen 1994). In addition to the resulting degradation in these regions, such marginal cropland is almost by definition also severely prone to the affects of drought.

Commonly quoted reasons for traditional rainfed farming practices becoming unsustainable are the pressure from a growing population which needs more food and the expansion of cash cropping which pushes traditional farming into more marginal areas (Le Houérou 1996). The expansion of groundnut cultivation in Niger and the Sudan, and cotton cultivation in parts of Chad have pushed subsistence crops into areas whose sensitivity has been exposed by drought. Prolonged drought during the 1980s in the summer rainfall zone of southern Africa has also exposed poor cultivation practices in parts of the Cape, Botswana's Kalahari and eastern Zimbabwe. Declining crop yields during periods of drought may be one reason for the shortening of fallow periods, as Khogali (1991) describes for the Umm Ruwaba district of the Sudan's Kordofan region. Another reason might be because of population pressure and the decline and fragmentation of land holdings (Thébaud 1995). Whatever the cause, fallow periods have been declining in many parts of Africa's drylands. In a comparison of land uses between the 1950s and 1987 in three areas of Mali covered by an aerial photography transect (IGN 1992), the fallow period was approximately halved over the period at two sites (Table 2.15: compare C1/T1 and C2/T2 for Mourdiah and Yanfolila).

Overexploitation of vegetation for domestic use

Soil degradation due to the overuse of vegetation (see Map 2.12) for such domestic purposes as fuelwood, charcoal-making, fencing and construction is almost exclusively confined to the Sahel west of Ethiopia, and within this region very largely concentrated in the arid zone (Table 2.14). This pattern is probably due to the simple fact that vegetation in the arid zone is more sparse than in moister areas and thus a certain level of use will lead more quickly to degradation problems in a finely-balanced environment. Fuelwood collection is probably the most important domestic reason in Sahelian countries where imported fossil fuels are prohibitively expensive. Woody biomass constitutes the main domestic fuel in Sub-Saharan Africa. It is principally used in households for cooking, but is also an important fuel for certain rural and small industries such as beer brewing, fish smoking, brickmaking and commercial baking. Growing human populations in many areas have led to wholesale tree cutting in place of the collection of dead wood, but the Sahelian 'fuelwood crisis' that was widely feared during the 1970s and 1980s (e.g. World Bank 1985) has not come about. Poor data and inappropriate methodologies for assessing the fuelwood deficit, by comparing contemporary woodfuel consumption with current stocks and annual tree growth, have been criticised by many researchers (e.g. Leach and Mearns 1988), and more recent estimates of Sahelian woody biomass stocks indicate that for the region as a whole demand does not exceed supply (Millington *et al.* 1994).

Table 2.16 Major urban woodfuel markets in four Sahelian countries in 1992 (after RPTES 1996)

Urban area	*Fuelwood (thousand tonnes)*	*Charcoal (thousand tonnes)*	*Woodfuel equivalent (thousand tonnes)*	*Estimated population (thousands)*
Senegal				
Dakar-Thiès	54	176	1032	1890
St Louis	24	23	152	190
Kaolack	28	17	122	200
Ziguinchor	21	18	121	164
Burkina Faso				
Ouagadougou	152	16	230	634
Bobo Diolasso	87	2	97	269
Niger				
Niamey	146	–	146	500
Mali				
Bamako	305	15	388	712
Ségou	79	2	90	95

Table 2.17 Main causes of soil degradation in Africa by region (million ha)

	Region				
Cause	*North*	*Sahel*	*Southern*	*Others*	*Total*
Overgrazing	27.7	118.8	44.0	3.9	194.4
Agricultural activity	8.6	34.8	12.8	4.2	60.4
Overexploitation	0.2	54.2	1.1	0.0	55.5
Deforestation	4.3	16.3	0.7	0.7	22.0
Total	40.8	224.1	58.6	8.8	332.3

None the less, the loss of trees has become critical on the periphery of many urban areas where collection of woody vegetation leads to its complete clearance for many kilometres (e.g. Dakar, Ouagadougou, Niamey and Khartoum). Many Sahelian cities have experienced extremely rapid population growth since the 1950s (Michel *et al.* 1992), largely due to the influx of migrants whose traditional rural livelihoods have been rendered impossible by drought. Mauritania's capital, Nouakchott, was little more than a village of about 4000 people in 1959, but is now a city of more than 500 000 people. City dwellers in general use more fuelwood per head than their rural counterparts and the size of some urban markets in the Sahel is indicated in Table 2.16.

In some areas fuelwood is still only collected from dead trees, as Benjaminsen (1993) reports from the Gourma region in Mali. But in Gourma, as elsewhere, collection distances are getting longer; so people need to spend more time collecting wood and/or more of their limited incomes on buying it. In some countries such as Ethiopia and Somalia, apparently not suffering from domestic overexploitation of vegetation, the chopping of wood which is subsequently used for fuel is indicated in the deforestation map since the primary reason for clearance is to expand cultivated area. This may also reflect the fact that most suitable woody vegetation has already been cleared in the dryland areas.

Deforestation and removal of natural vegetation

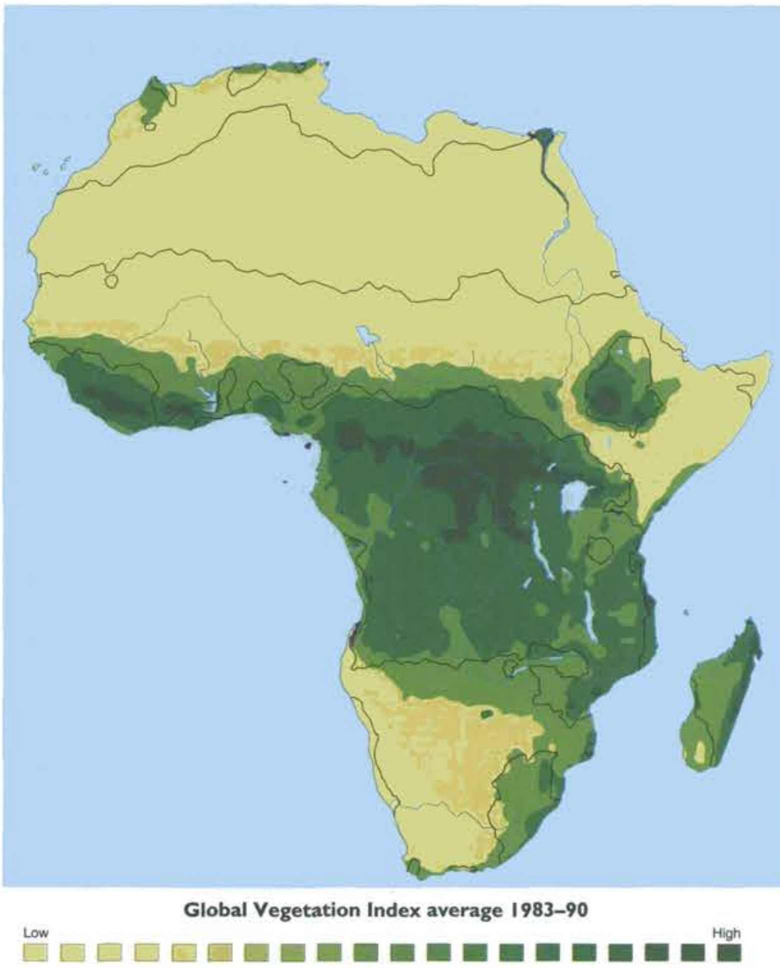
Complete removal of the vegetation cover (see Map 2.13) as a cause of African soil degradation is largely confined to the Sahel region and the region north of the Sahara (see Table 2.17). Within these regions it is predominantly a problem of the semiarid and dry subhumid zones. The expansion of agriculture is a prime cause of deforestation in Burkina Faso, where an estimated 50 000 ha of woodland was being cleared every year in the early 1980s. Similarly, widespread replacement of tree savanna by cultivation was reported over the period 1957–87 from the Nara area on the Mali/Mauritania border covered by IGN's (1992) aerial photography transect. The agricultural area virtually doubled over the period (Table 2.15: T1 to T2). Forest clearance for irrigated agriculture has been a factor leading to degradation along the Niger River south of Niamey and to make way for the Bakolori Agricultural Project in north-western Nigeria. Continuing deforestation in Niger is also the most serious threat to West Africa's last remaining population of giraffes, currently numbering less than 100 individuals (Ciofolo 1995).

Expansion of irrigation schemes in the Sudan, along the Blue Nile downstream of the Roseires Dam and in the existing cotton-growing schemes south-east of Khartoum, have pushed traditional farmers and herders into increasingly marginal savanna woodland areas. Deforestation for expanding grain cultivation in the semiarid uplands east of Benghazi in Libya is the prime cause of soil degradation by water erosion, and deforestation also plays a contributory role in parts of the Atlas Mountains of Tunisia, Algeria and Morocco where fluvial activity is again the main soil degradation process.

Another factor worthy of mention in discussing the clearance of natural vegetation is the role of fire. The burning of bush and grasses is a long-established management technique in the savannas of Africa, used to encourage tender green shoots from perennial grasses for livestock to feed on. Although savanna fires are often sparked by natural forces such as lightning strikes, the scale of human-induced burning can be very large: Parnot (1988) estimated that 30% of the land area of Burkina Faso, some 120 000 km^2, was burnt during the 1986–87 dry season. If carefully managed, fire at moderate temperatures and at the right time is thought to be an appropriate tool for rangeland management (Penning de Vries and Djeteyé 1982). Under certain circumstances, however, large losses of organic matter and nutrients probably result from these savanna fires, and exposed soil is particularly susceptible to erosion. The exact impact of repeated burning is poorly understood and deserves further study to improve knowledge of the effects of this form of human-induced vegetation clearance (Bock and Bock 1992).

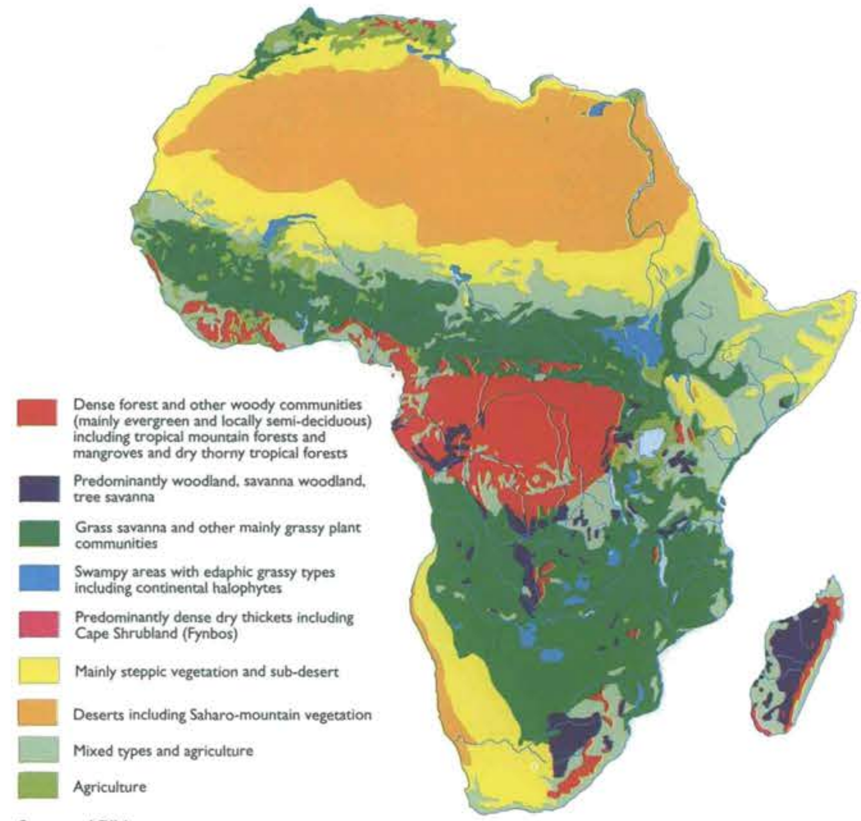
Vegetation

Map 2.14 Global Vegetation Index average



Source: NOAA, UNEP/GRID
Approximate equatorial scale 1:52 million

Map 2.15 Present vegetation communities



Source: ICIV
Approximate equatorial scale 1:81 million

Vegetation is an important factor in the occurrence of soil degradation as it can act as a buffer between the soil surface and processes that can cause degradation by soil displacement. It has been noted in the global section of this atlas (page 5) that vegetation can be characterised in many ways, including by plant community composition and biomass production, with the latter being used to examine the vegetation–degradation relationship at the global scale. Here, more detailed representation of degradation at the African scale allows vegetation to be considered in terms of both community composition and biomass.

GVI map of Africa

Map 2.14 shows the Global Vegetation Index (GVI) coverage of Africa, derived from 16 km x 16 km NOAA satellite data (see page 51). The map should only be interpreted in a qualitative manner because GVI values are not directly or quantitatively correlated with specific properties of the actual vegetation. The data used to develop the map have been averaged to even out seasonal variations in GVI values. In general, however, GVI does appear to relate to the ability of plants to photosynthesise and the relationship between canopy and evapotranspiration values (Tucker 1980, Justice *et al.* 1985), so that the map can be considered to be a representation of biomass.

The map cannot be directly compared with the representation of African vegetation in Map 1.20 in the global section, because that shows the relationship between GVI and soil degradation severity. Map 2.14 shows GVI alone. It is clear that biomass, as represented by GVI, generally varies in line with climate zones, with lowest GVI in hyperarid areas. More detailed variations, within individual regions such as the Sahara, are a function of changes in unspecified environmental and human factors, for example rainfall and land use, which cannot be determined without recourse to more specialised and local information. One important point of note is the occurrence of high GVI values in the valley and delta of the River Nile within the hyperarid zone. This clearly highlights the life-giving property of the Nile; it also indicates that GVI does not distinguish between natural vegetation and crops, as the high Nile values largely record irrigated cropland.

Vegetation community map of Africa

While the GVI map gives a useful general indication of vegetation cover, it gives no indication of the plant species and communities that make up the vegetation of a particular area. Map 2.15, which provides a simplified assessment of African vegetation communities, has been produced by Institut de la Carte Internationale de la Végétation (ICIV) at the Université Paul Sabatier at Toulouse, France. It is a modified version of the FAO-ICIV 'Digital map of the vegetation of Africa', produced in 1987. This is based on the analysis of Landsat Multi-Spectral Scanner (MSS) satellite imagery which has an 80 m x 80 m resolution, supplemented by NOAA satellite data.

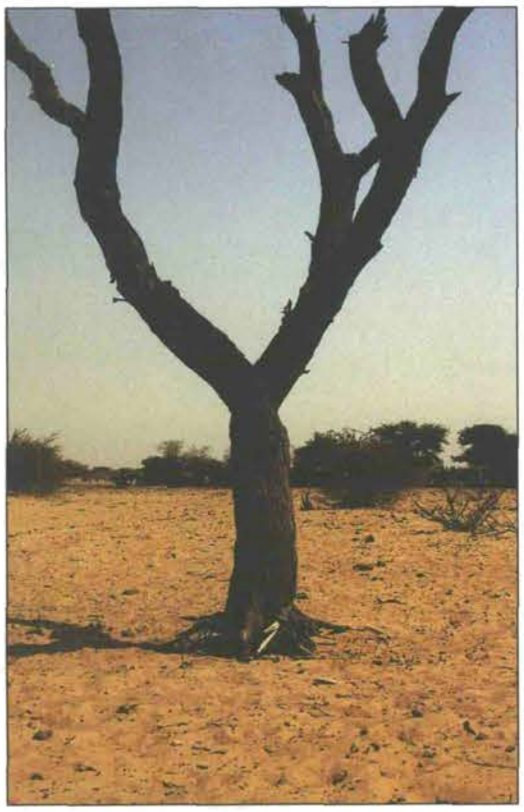
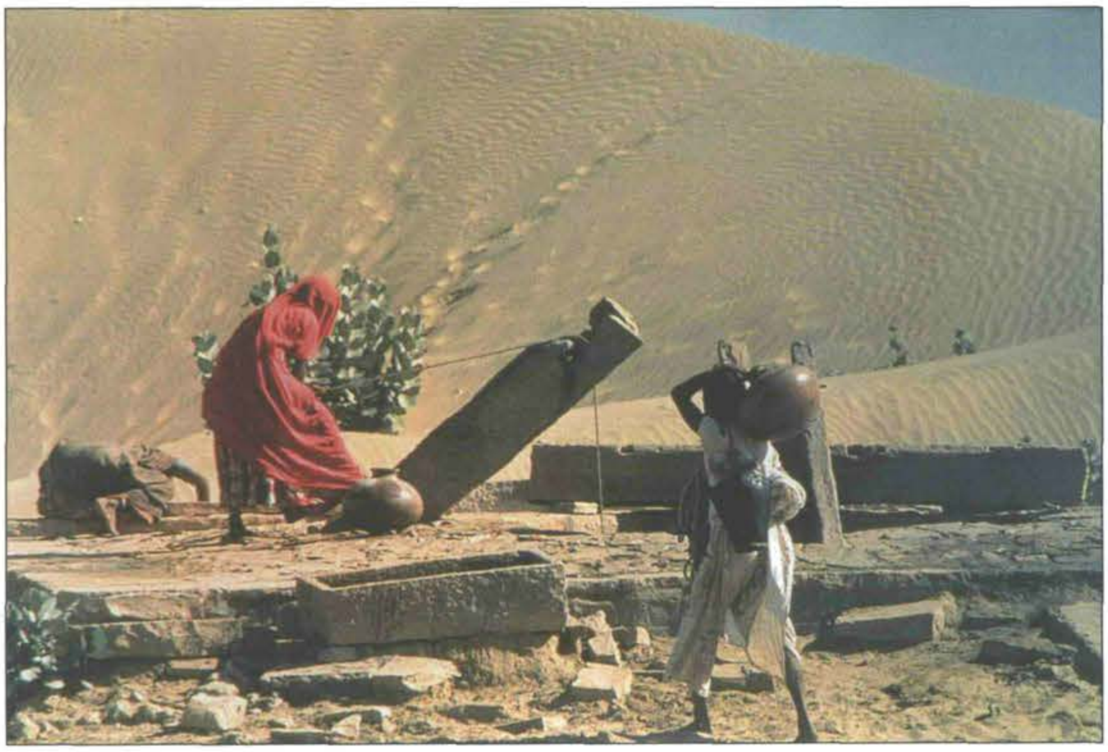


Figure 2.6 Virtually bare soil close to a borehole, a 'sacrifice zone', in the Kalahari (DSG Thomas)

points may become foci of devegetation and desertification, for example around some oases in Tunisia (Sghaier and Seiwert 1993).

Remote sensing studies using NDVI data for the Ferlo area of Senegal (Hanan *et al.* 1991) and Landsat MSS data for Kordofan Province, the Sudan (Hellden 1984) have suggested that rainfall variability accounts for most vegetation cover variability in these pastoral systems rather than livestock impacts, and that if an ecologically optimal borehole spacing is determined, the devegetated zones centred on water sources do not tend to expand and merge over time. While such studies highlight the general spatial patterns of change they do not indicate changes that may occur within plant communities, which require field-based investigations. One such study carried out in the borehole-based livestock systems in the eastern Kalahari of Botswana (Perkins and Thomas 1993a and b) highlights the more complex patterns of vegetation and soil change that can occur (Figure 2.5). Grazing-induced effects on vegetation occur within approximately 2 km of boreholes, beyond which livestock-use densities are relatively low. Within this distance a number of different vegetation community changes occur, while close to the borehole is a 'sacrifice zone' that may experience soil erosion by the wind (Figure 2.6). Superimposed upon these spatial patterns are temporal changes resulting from variations in rainfall and natural fires.

ASSOD: The New Assessment of Soil Degradation in South and South-East Asia



UNEP/ACHARYA SANJAY/TOPHAM

3

Following on from the experiences gained through the GLASOD project, a new assessment has been conducted of soil degradation in the countries of South and South-East Asia. This, the Assessment of the Status of Human-Induced Soil Degradation in South and South-East Asia (ASSOD), project, has again been conducted by the International Soil Reference and Information Centre (ISRIC). ASSOD incorporates a number of methodological improvements and changes in the manner in which data have been collected and processed. The maps that follow in this section illustrate the utility of the new approach which it is hoped will be applied in other areas and regions in the future. The ASSOD survey was not just confined to the susceptible dryland areas of the 17 countries in which it was applied. The total ASSOD database, and the maps that follow, have been analysed in order to extract the information relevant to the investigation of desertification. The result is that the subsequent considerations focus on the susceptible dryland areas of seven countries in the ASSOD region.

As ASSOD does have some marked technical differences compared to the surveys used for the compilation of the maps and data in Sections 1 and 2 of this atlas, it is first necessary to explain the nature of the ASSOD methodology.

Comparison between GLASOD and ASSOD

ASSOD has utilised a methodology and approach that has a number of underlying differences to that employed in GLASOD. These differences are summarised in Table 3.1, and are explained comprehensively in the remainder of this section. Given these differences, it is to be expected that the outputs in terms of degradation assessments may differ for any area depending on which database is being considered.

Geographical regions

ASSOD has involved the assessment of soil degradation in 17 countries in South and South-East Asia. Seven of these contain areas of susceptible drylands where by definition desertification is an actual or potential problem. The maps presented here from the ASSOD database focus on these susceptible dryland areas, in China, India, Myanmar, Nepal, Pakistan, Sri Lanka and Thailand (Map 3.1). The dryland areas have been delimited using the same climatic surfaces used for GLASOD (pages 2–7). For each of these countries, susceptible dryland areas have been input to the total ASSOD database at ISRIC in order to allow detailed data outputs that only pertain to the areas relevant to this atlas. In total 317 million ha, or 34% of China are susceptible drylands, 188.81 million ha (59.1%) of India, 2.33 million ha (3.5%) of Myanmar, 1.39 million ha (9.5%) of Nepal, 72.81 million ha (82.9%) of Pakistan, and 1.66 million ha (6.8%) of Sri Lanka.

Soil Degradation: The ASSOD Survey

ASSOD methodology

ASSOD recognises the same four main types of soil degradation as GLASOD: water erosion, wind erosion, chemical deterioration and physical deterioration. Within some of these, new subtypes have been added, or existing types modified (van Lynden and Oldeman 1997). These are:

- water erosion
  - new: *off-site effects of water erosion* – including reservoir sedimentation, flooding and pollution
- wind erosion: no changes
- chemical deterioration
  - new: *eutrophication* – an excess of soil nutrients, impairing plant growth
  - modified: *acidification* replaced by *dystrification* – the lowering of soil pH through increased acidic compounds in the soil
  - modified: *pollution* to distinguish 'contamination' which does not have significant negative effects from 'pollution' which impacts on productivity
- physical deterioration
  - new: *loss of productive function* – land taken out of productivity due to factors such as urban growth and mining
  - new: *aridification* – the decrease in average soil moisture content
  - modified: *compaction, crusting and sealing* clearly separated into compaction due to livestock and machinery impacts, and *crusting and sealing* due to the clogging of pore space leading to a fine impervious surface layer.

Additionally, land without human-induced degradation is divided into 'stable land', with no natural degradation occurring, and 'natural wasteland', where no or only natural degradation is occurring.

Impact on productivity is included in ASSOD as an assessment of significant human-induced degradation in terms of production systems. In other words, less importance is attached to change in its own right, and more to the actual effects of degradation on productivity. *Impact* in ASSOD replaces the *degree* of degradation used in GLASOD. Impact takes account of the interacting effects of the management practices employed in different areas and the levels of decreasing or increasing productivity that ensue from the combined effects of management and degradation.

Management levels have been divided into *high*, which is the maximum intervention that may be achieved through factors such as mechanisation and the application of fertilizers, pesticides and the use of improved crop varieties or livestock types; *medium*, an intermediate state; and *low*, which is indigenous or traditional management systems. Changes in

Map 3.1 Aridity zones

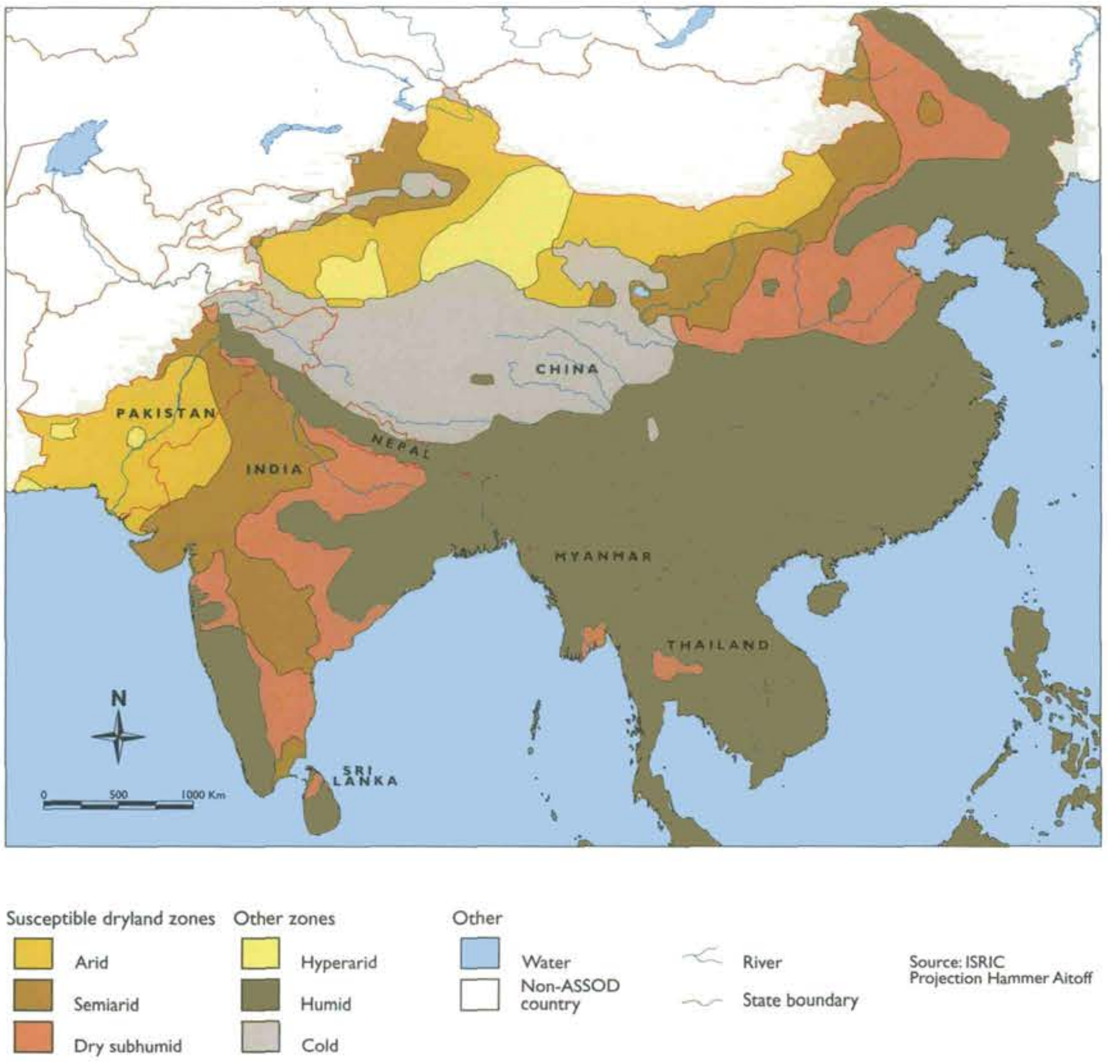


Table 3.1. Comparison of the main characteristics of the GLASOD and ASSOD methodologies

	GLASOD	*ASSOD*
Coverage	Global	South and South-East Asia
Mapping units (polygons)	Physiographic areas based on terrain	Physiographic areas including terrain and soils
Area basis	Physiographic only	Country boundaries added to physiographic map prior to data collection, so country data available
Dryland consideration	Dryland areas delimited using climate surface data	Dryland areas delimited using climate surface data. Drylands within countries delimited
Status assessment	Severity = degradation degree by extent per polygon	Severity = degradation impact by extent per polygon
Rate of degradation	Some limited data	Rate of degradation data included
Conservation	No data	Some data
Cartographic possibilities	Maximum 2 degradation types per polygon	No restrictions on number of degradation types per polygon
End product	Various maps and tables constructed from database	Various maps and tables constructed from database
Database	Digital information derived from initial map and input to GIS	Data input to GIS prior to map production
Data source	Individual experts	National institutions

Table 3.2. Impact of degradation: management levels and productivity change interactions

Level of production change	*Level of management*		
	High	*Medium*	*Low*
Large increase	Negligible	Negligible	Negligible
Small increase	Light	Negligible	Negligible
Unchanged	Moderate	Light	Negligible
Small decrease	Strong	Moderate	Light
Large decrease	Extreme	Strong	Moderate
Unproductive	Extreme	Extreme	Strong to extreme

production are expressed with regard to one of two states: either as the current average productivity in the area relative to a comparable, unaltered area, or as the current average productivity in the area relative to trends in production over the last 15–25 years.

Five classes have been employed to express degradation impact. The occurrence of a particular impact is a function of the combination of management and productivity change, as shown in Table 3.2. Thus the same magnitude of soil degradation may have a strong negative impact in an area subject to low levels of land management, but a lesser impact in an area subject to high levels of management; for example because artificial fertilizers are added to compensate for nutrient depletion. In another respect, a large decrease in productivity in an area of high management levels may be regarded as an extreme impact, since significant inputs, probably at great financial cost, are made but to no avail. The same decrease in productivity in an area of low management levels may be considered as having only a moderate impact since lesser – or even no – additional efforts have been taken to counter productivity declines. A *negligible* impact of degradation as assessed in ASSOD is not therefore synonymous with stable in the GLASOD assessment, as stable indicates no degradation, while negligible indicates degradation that does not affect productivity.

In ASSOD the extent of a polygon affected by soil degradation was assessed to the nearest 5%. For mapping purposes these data were classified into the same five classes used in GLASOD to determine the **extent of soil degradation** (see page 19). These define the percentage area of a polygon subject to a specific degradation type. The overall **severity of degradation** in ASSOD is the combination of degradation impact and degradation extent. In GLASOD a matrix was employed to combine degree and extent, and is shown on each GLASOD map in Section 1 of this atlas. In ASSOD maps, the combination of extent and impact is shown with regard to each of the four main degradation types.

Other components of the ASSOD data set

The factors considered above contribute to the degradation severity assessment in ASSOD, and are used in the generation of the main ASSOD maps and tables on the pages that follow. In addition to degradation severity the ASSOD database also contains information on degradation cause, rate of soil degradation and soil conservation measures.

Human activities causing soil degradation have been considered within the same five categories used in GLASOD, and are discussed on pages 92–94. The main database also incorporates information on any *soil conservation and rehabilitation practices* that have been used in both degraded and stable areas. These data were collected according to the principles of the WOCAT project that assessed soil erosion conservation, an example of which is given in Section 4 (pages 120–125). Four types of practice are recognised (van Lynden and Oldeman 1997): *plant management practices* that limit erosion, *land management practices* such as tillage and ploughing regimes, *structural practices* including slope terracing, and *other practices* that counter problems such as salinization. Data on conservation was not forthcoming for the majority of ASSOD polygons and so it is not specifically included in any of the maps that are presented here.

An improvement in ASSOD is a more detailed consideration of the recent *rate of soil degradation*. This is a useful addition, since the significance of degradation cannot be fully assessed by considering severity alone. For example, a severely degraded area may be relatively stable at present and therefore not showing a trend towards further changes that would damage productivity. Indeed, areas of severe degradation may show a natural trend towards stabilisation as new equilibrium conditions become established. On the other hand, an area with only light degradation today may be showing signs of a high rate of change. In this situation degradation may represent a substantial threat to future productivity. Rate of soil degradation has been assessed over 5 to 10 years, on a seven point scale from +3 which is rapidly increasing degradation, through 0 which is a constant rate of degradation to –3 where degradation is rapidly decreasing. Degradation rate must not be confused with the level of productivity change that contributes to the determination of degradation impact.

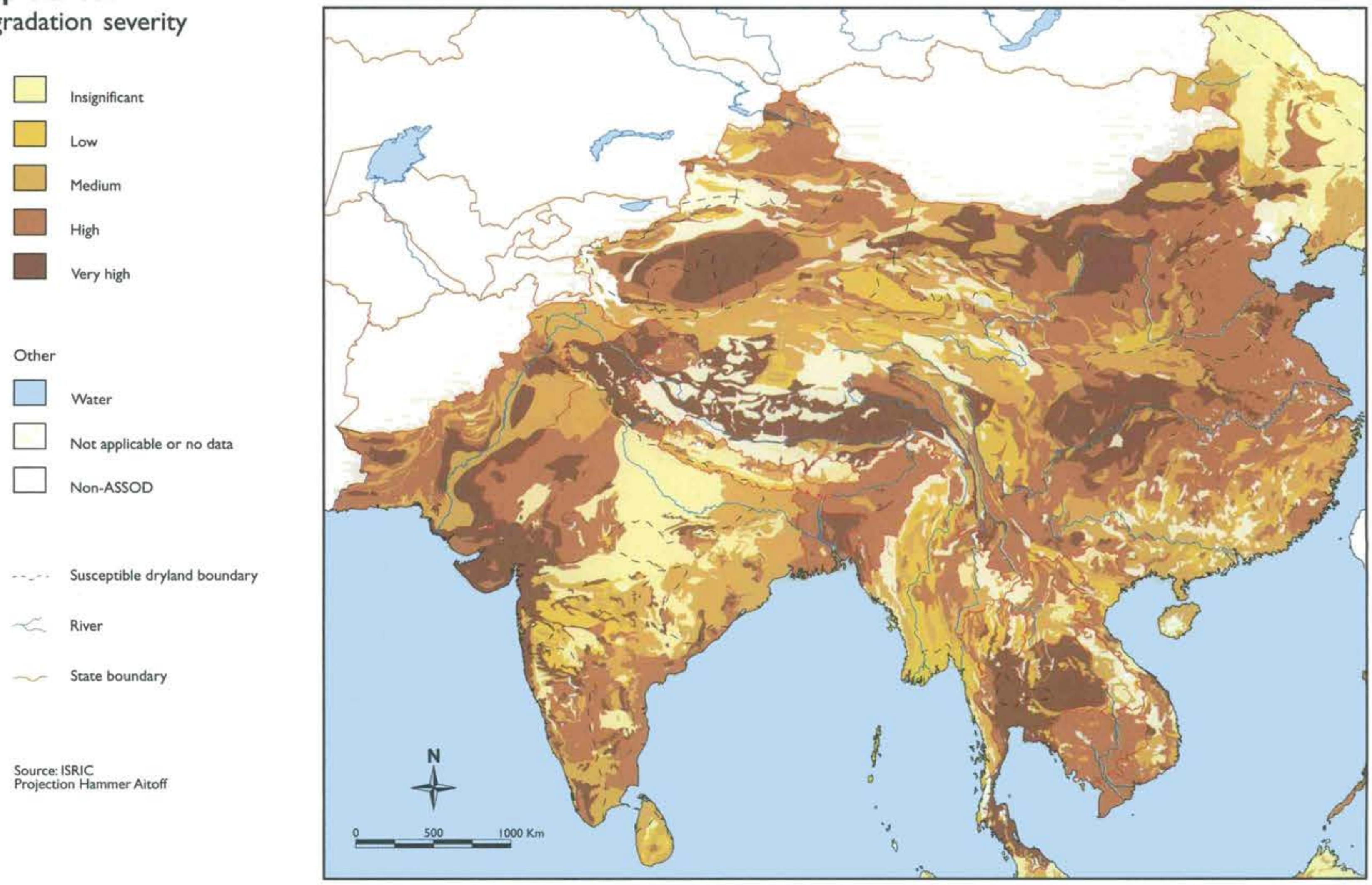
Interpreting the ASSOD database

The ASSOD survey was enacted through national institution members of the Asia Network on Problem Soils. Countries not participating in the network were represented by other relevant bodies, except for Cambodia. Actual degradation assessments were conducted for 4450 mapping units or polygons, giving a higher spatial resolution than the GLASOD survey, in which 320 polygons covered the same region. The GLASOD polygons were loosely based on natural physiographic regions. For ASSOD this approach has been developed such that polygons are based not only on terrain properties following the principles used in developing the SOTER methodology (see pages 114–119). The country dimension of ASSOD meant that many of the initial physiographic polygons were dissected by national boundaries, with separate assessments of degradation conducted by national institutions for their respective areas. In such situations the political boundaries were overlain on the original polygons to create additional mapping units.

The greater resolution of ASSOD compared to GLASOD in part accounts for the different representation in some susceptible dryland areas of degradation type and extent when the two surveys are compared. For example, the cartographic representation employed in GLASOD led to each individual polygon being shaded in terms of the dominant degradation type or severity found in that polygon, even if the occurrence of that degradation was spatially limited. By employing a greater resolution of polygons, an area that appeared as a single polygon in GLASOD, with one degradation type, may in the ASSOD survey be shown as several polygons, each perhaps experiencing a different dominant degradation type or severity, and some perhaps having no degradation at all. Examples of these differences are pointed out in the explanations on the following pages. While it is not intended that direct comparisons be made between GLASOD and ASSOD, it is useful to outline the major areas of similarity and departures of the ASSOD methodology from the earlier global assessment, while more detailed consideration is given on the relevant pages.

Soil Degradation

Map 3.2 Soil degradation severity



Introduction

There are over 350 million ha of desertified lands in ASSOD countries (Map 3.2, Table 3.3) which represents 52.9% of the total susceptible dryland area. When all impact levels of desertification are considered, 61.7% of dry subhumid, 39.55% of semiarid and 63.8% of arid areas are affected. The majority of degraded land is of negligible or light impact, when the level of land management and the effect of degradation on productivity are considered in conjunction with each other (Table 3.3). Over 120 million ha, however, are subject to desertification with a moderate or strong impact, and almost 5 million ha suffer from extreme impacts which usually make the land totally unproductive. Dry subhumid areas have experienced most extreme degradation, but overall it is perhaps the semiarid lands where production has been most affected, as the impact on production has been moderate or greater in over 40% (almost 50 million ha) of the area affected by desertification processes. Figure 3.1 shows the different levels of degradation impact in all ASSOD countries in terms of percentages of the total susceptible dryland area.

The distribution by aridity zone of the different types of soil degradation contributing to desertification in ASSOD countries is shown in Table 3.4. Water erosion affects 16.4% of susceptible drylands in the ASSOD area, wind erosion 17.3%, chemical deterioration 13.3% and physical deterioration 5.9%. It can be seen that wind erosion is dominant in arid areas, which is a function of the naturally lower soil moisture and vegetation covers that such areas have, making them more susceptible to aeolian processes (Thomas 1997a). Table 3.4 also shows that the ASSOD survey indicates that water erosion and physical deterioration affect lands in dry subhumid areas more than in other dryland climate zones. While it is obvious that water erosion, once the land is rendered susceptible to desertification, is dependant upon the availability of runoff, and this is greatest in the dry subhumid areas, some of the processes of physical deterioration, notably sealing and crusting, are also dependent to a large part on rainfall.

Severity and distribution of desertification

By combining the impact of soil degradation with its extent in individual mapping units, the overall severity of degradation can be assessed. This has been done for the whole of the ASSOD region, including areas outside the susceptible drylands, and is shown in Map 3.2. Unlike GLASOD, the ASSOD database allows precise assessments of soil degradation to be made on a country-by-country basis. Table 3.5 shows the data for soil degradation impact in the susceptible dryland areas of the ASSOD region, by country.

In susceptible dryland areas, soil degradation is most severe in areas of northern China, north-west India, Pakistan and Thailand (Map 3.2). In China, nearly 180 million ha, or 56%, of the susceptible drylands are affected by desertification, almost 20% of the country area (Table 3.5). A significant area of degradation is the 640 000 km^2 loess plateau, most of which is located in susceptible dryland areas (World Bank 1994). This includes the triangle of terrain between Lanzhou, Baotou and Taiyuan through which the Huang He (Yellow) River passes and which includes the arid to semiarid Tengger Desert, which experiences desertification where erosional processes are prevalent. Significant degradation also impacts upon the dry subhumid area to the east, which includes Beijing.

Table 3.3 Degradation impact by aridity zone (million ha)

	Negligible	*Light*	*Moderate*	*Strong*	*Extreme*	*Total degraded*	*Total non-degraded*	*Total*
Dry subhumid	46.37	49.51	17.03	4.70	3.09	120.70	74.93	195.63
Semiarid	15.68	45.02	29.00	18.97	1.70	110.37	168.81	279.18
Arid	10.82	61.69	19.68	33.16	0.03	125.38	74.21	199.59
Total	72.87	156.22	65.71	56.83	4.82	356.45	317.95	674.40

Note: column and row totals may not correspond due to rounding of decimals
Source: ASSOD

Table 3.4 Distribution of degradation types by aridity zone (million ha)

	Arid	*Semiarid*	*Dry subhumid*	*Total*
Water erosion	19.87	37.83	53.07	110.77
Wind erosion	70.00	39.40	6.94	116.34
Chemical	23.49	26.33	39.56	89.38
Physical	11.98	6.82	21.16	39.96
Total	125.34	110.38	120.73	356.45

Note: column and row totals may not correspond due to rounding of decimals
Source: ASSOD

Table 3.5 Desertification in susceptible drylands in each country (million ha)

	Arid	*Semiarid*	*Dry subhumid*	*Total*	% susceptible dryland area	% country area
China	64.82	44.54	69.81	178.87	56.41	18.61
India	8.36	52.63	43.63	108.62	57.53	32.62
Myanmar	0.00	0.00	0.23	0.23	9.87	0.35
Nepal	0.00	0.00	0.45	0.45	32.37	5.38
Pakistan	52.46	8.91	1.06	62.43	85.74	71.23
Sri Lanka	0.00	0.31	1.36	1.67	100.00	25.58
Thailand	0.00	0.00	4.18	4.18	100.00	8.17
Total	125.34	110.39	120.72	356.45		

Note: column and row totals may not correspond due to rounding of decimals
Source: ASSOD

The susceptible drylands of north-western India and Pakistan also show high and very high degradation problems. While the total desertified land areas are smaller than in China (Table 3.5), desertification in India affects over 57% of the susceptible dryland area, while in Pakistan this figure extends to over 85%. In Pakistan a further reminder of the significance of desertification is that while susceptible drylands account for the bulk of the country's area, of the remainder much is unproductive because it is hyperarid or mountainous (Map 3.1). The sheer spatial scale of desertification, and its implications for feeding the large populations of India and Pakistan, result in land and soil resource issues being given the highest priority of all resource and environmental issues in both countries (ADB 1994). In India, desertification is of high and very high severity in the Thar Desert and the Ran of Kutch where terrain is susceptible to erosion by the wind. The semiarid to dry subhumid lands of central and eastern India show variable severity of desertification, including large areas where it is low or insignificant. Medium to very high severity desertification, linked to physical deterioration processes, affects the heavily utilised lands that border the Indus River in Pakistan.

In Nepal lands susceptible to desertification are confined to the dry subhumid Terai area, which forms a long strip of alluvial deposits along the border with India (UNEP/EAP 1995a). Soil erosion is usually seen as a major problem in Nepal's mountainous areas, outside the susceptible drylands, where deforestation may be a contributing factor (Ives and Messerli 1989). Due to growing populations, including through migration, land use pressure in the Terai has dramatically increased since the 1960s, leading to almost total removal of natural forests and their replacement with subsistence agricultural practices (Basnet 1992). The area is at risk from degradation because the coarse alluvial deposits, which are an extension of the Ganges Plain, are very susceptible to water erosion (UNEP/EAP 1995a).

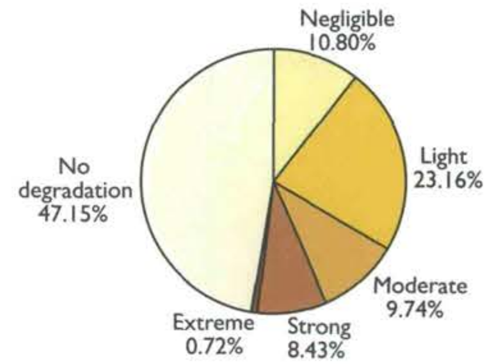


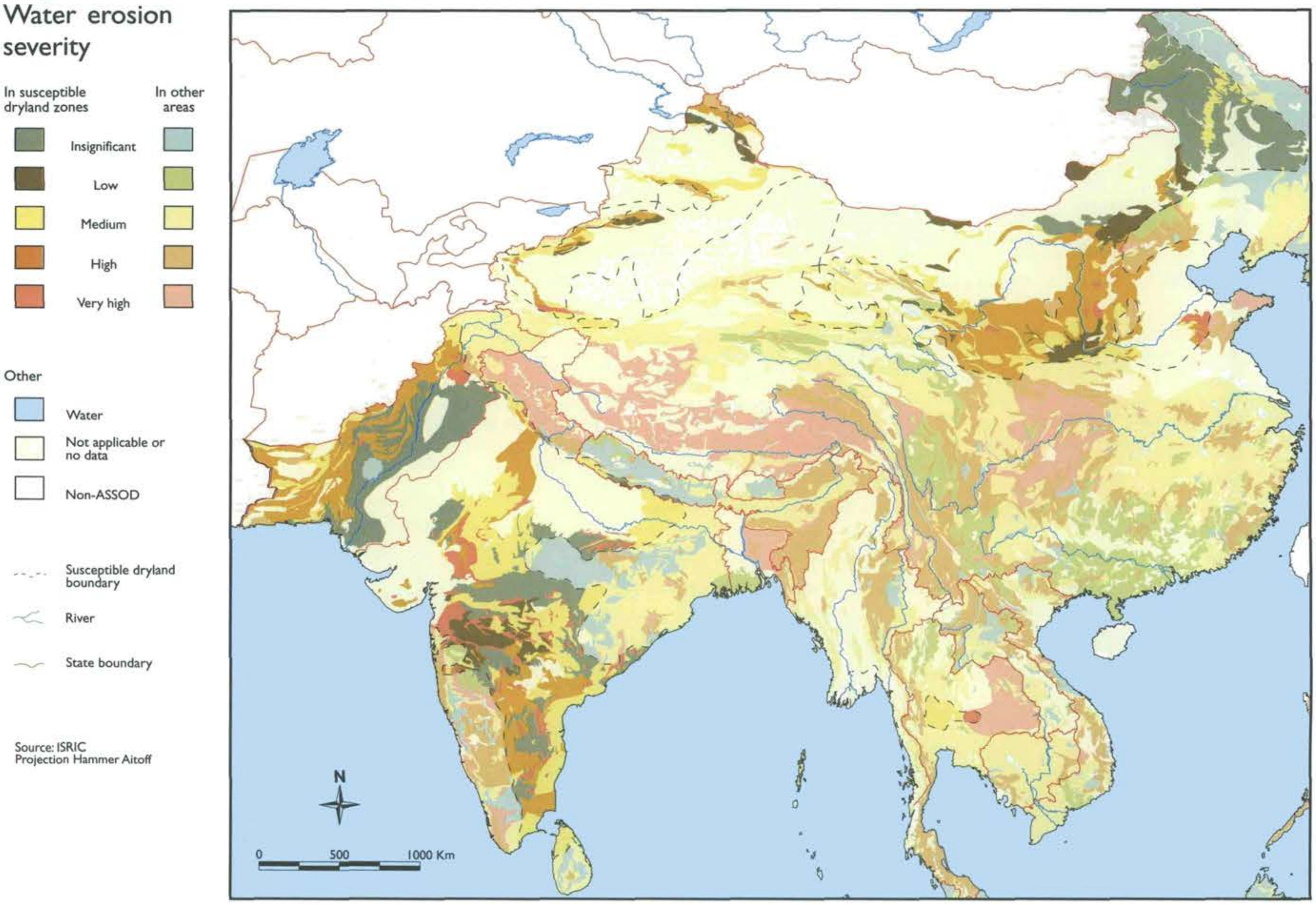
Fig 3.1 ASSOD susceptible drylands degradation impact. Source: ASSOD

The north–south-flowing Irawaddy is the major river in Myanmar, and its heavily cultivated floodplain is in the rain shadow of the Araka Yoma hills to the west (UNEP/EAP 1995b). It is, however, only the eastern part of this river's delta, and adjacent areas including Rangoon and Yungon Division, that is sufficiently arid to be classified as susceptible dryland. While desertification is recorded, it is of low severity and affects less than 250 000 ha. In neighbouring Thailand, very severe soil degradation is a problem in large areas of the country, and ASSOD records 100% of the susceptible dryland area as desertified, principally caused by salinization linked to irrigation and to overuse of groundwater (Ghassemi *et al.* 1995). Most of the country falls outside the susceptible drylands, but the problem of chemical deterioration is notably very severe in the dry subhumid area located in the flat, heavily cultivated south-central part of the country, where over 4 million ha are desertified (Table 3.5). All of Sri Lanka's northern dry subhumid to semiarid lands, some 1.6 million ha, experience desertification, but problems that are mainly attributed to water erosion and chemical deterioration do not attain more than medium severity.

As dryland areas constitute a substantial proportion of the total potential productive lands in China, India and Pakistan, the overall national impact of dryland degradation in these countries could be interpreted as greater than in Myanmar, Nepal, Sri Lanka and Thailand, where dryland areas represent a smaller proportion of the total land area. None the less, the national importance of dryland degradation may be significant even when countries are predominantly humid. In Thailand, for example, due to degradation being a severe problem in agricultural lands in dryland and humid areas, the importance of the dryland problem should not be underestimated.

Water and Wind Erosion

Map 3.3
Water erosion severity



Water and wind erosion together account for desertification in nearly 230 million ha of susceptible drylands in ASSOD countries. The ASSOD survey recognised both on- and off-site effects of water and wind erosion, which illustrates how a degradation problem in one location can lead to outcomes that have negative impacts elsewhere.

Water erosion

Map 3.3 shows the severity and distribution of water erosion in the ASSOD region. Desertification resulting from water erosion occurs in six of the seven ASSOD countries that contain susceptible dryland areas, Myanmar being the exception (Table 3.6). In total, water erosion impacts on 16% of ASSOD susceptible drylands (Figure 3.2). On-site water erosion directly affects almost 110 million ha, through the loss of topsoil and terrain deformation such as gullying and rilling. A further 1 million ha experience the impact of water erosion through off-site effects, where sediments removed through erosion contribute to siltation in reservoirs, enhanced flooding and pollution.

Water erosion is a major occurrence in India's susceptible drylands, where almost 50 million ha, or a quarter of the susceptible drylands, mainly used for rainfed agriculture, are affected. While 4.5 million ha of the subhumid and semiarid zones suffer water erosion with an extreme impact, Table 3.7 indicates that most water erosion in India's susceptible drylands has negligible or light impacts. This means that under current management practices in these areas, agricultural outputs have not to date declined, or may even have increased due to management initiatives offsetting desertification effects. Degradation impact combined with the spatial extent of water erosion in each polygon is shown as severity in Map 3.3. Large areas appear as insignificant or low severity (shown as turquoise or green in the map), for example in the large area of Madhya Pradesh in the centre of the country.

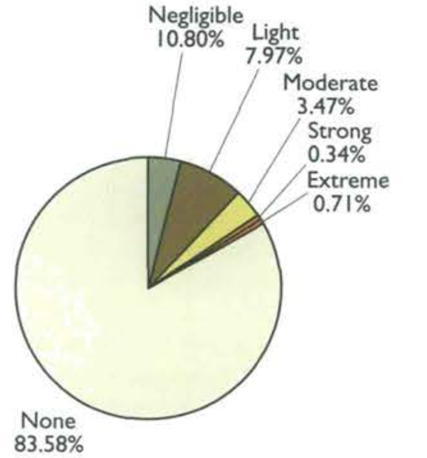


Figure 3.2 Water erosion (on-site and off-site) impact in ASSOD susceptible drylands. Source: ASSOD

Table 3.6 Desertification due to water erosion in ASSOD countries

	On-site in susceptible drylands			*Off-site in susceptible drylands*		
	Million ha	*% susceptible dryland area*	*% country area*	*Million ha*	*% susceptible dryland area*	*% country area*
China	44.67	14.09	4.83	0.56	0.18	negl.
India	48.08	25.46	15.09	0.12	0.06	negl.
Nepal	0.27	19.42	1.83	0.13	7.19	0.88
Pakistan	15.69	21.55	17.88	0.00	0.00	0.00
Sri Lanka	0.42	25.30	6.41	0.42	25.30	6.38
Thailand	0.57	16.38	1.11	0.00	0.00	0.00
Total	109.70			1.23		

Note: column and row totals may not correspond due to rounding of decimals
Source: ASSOD

Table 3.7 On-site water erosion impacts (million ha)

		Impact					
	Country	*Negligible*	*Light*	*Moderate*	*Strong*	*Extreme*	*Total*
Arid	China	0.26	5.29	1.16	0.11	0.00	6.82
	India	0.77	0.19	0.00	0.00	0.00	0.96
	Pakistan	3.06	0.94	8.09	0.00	0.00	12.09
Arid Total		4.09	6.41	9.26	0.11	0.00	19.87
Semiarid	China	1.51	10.22	1.06	0.00	0.00	12.79
	India	4.12	9.98	4.53	1.06	1.66	21.34
	Sri Lanka	0.00	0.08	0.00	0.00	0.00	0.08
	Pakistan	0.83	0.65	1.75	0.00	0.00	3.24
Semiarid Total		6.46	20.93	7.34	1.06	1.66	37.45
Dry subhumid	China	6.13	16.08	2.53	0.33	0.00	25.06
	India	9.19	9.39	3.62	0.48	3.09	25.78
	Sri Lanka	0.01	0.33	0.00	0.00	0.00	0.34
	Myanmar	0.00	0.00	0.00	0.00	0.00	0.00
	Nepal	0.00	0.15	0.00	0.00	0.00	0.16
	Pakistan	0.06	0.16	0.13	0.00	0.00	0.36
	Thailand	0.00	0.00	0.27	0.30	0.00	0.57
Dry subhumid Total		15.39	26.12	6.55	1.10	3.09	52.26
Grand Total		25.94	53.46	23.16	2.27	4.76	109.59

Note: column and row totals may not correspond due to rounding of decimals
Source: ASSOD

Table 3.8 Off-site water erosion impacts (million ha)

		Impact					
	Country	*Negligible*	*Light*	*Moderate*	*Strong*	*Extreme*	*Total*
Semiarid	China	0.06	0.02	0.22	0.00	0.00	0.30
	Sri Lanka	0.08	0.00	0.00	0.00	0.00	0.08
Semiarid Total		0.13	0.02	0.22	0.00	0.00	0.38
Dry subhumid	China	0.11	0.14	0.02	0.00	0.00	0.26
	India	0.00	0.06	0.00	0.05	0.00	0.12
	Sri Lanka	0.34	0.00	0.00	0.00	0.00	0.34
	Nepal	0.00	0.09	0.00	0.00	0.04	0.13
Dry subhumid Total		0.45	0.29	0.02	0.05	0.04	0.85
Grand Total		0.58	0.31	0.23	0.05	0.04	1.22

Note: column and row totals may not correspond due to rounding of decimals
Source: ASSOD

Very high severity water erosion does occur in some Indian susceptible dryland areas, for example along parts of the Narmada River valley and north from the city of Ujjain to Jaipur in Rajasthan. This area includes the Aravalli Hills, where recent vegetation clearance rates are amongst the highest in the whole of India (Srivastava and Kaul 1995). In the Ganges river system, some steep terraced slopes experience water erosion due to gullying particularly in the valleys of the Jumna and Chambal rivers (FAO 1994). This is in the area shown as having high severity water erosion in Map 3.3. In Gujurat Province in the extreme west of the country, several areas of the Saurashtra region are mapped as having high severity water erosion. It has been recognised since the late 1970s that inadequate soil conservation practices have contributed to high runoff rates and erosion in some of this state's 8 million ha of rainfed cropland, and that the problems of erosion grew dramatically as a consequence of attempts to mechanise and increase production during the Green Revolution of the 1960s (Choksi and Dyer 1996).

A number of integrated watershed management projects have been set up in different susceptible dryland areas in India. These address degradation problems in a manner that deals not only with soil loss, but attempts an integrated, community-based approach to sustainable land use (World Bank 1990). Singh (1995) outlines a number of projects that have been successful, for example at Sheetalpur in Madhya Pradesh, where land reclaimed by gully plugs is yielding a 66% increase in crop production. In the same watershed the construction of contour trenches on hillsides has reduced runoff, enhanced soil moisture and improved the survival rate of trees that have been planted as part of the overall programme of land restoration. In the Aravalli Hills, the Rehabilitation of Common Lands Project was launched by the Government of Haryana in 1990 in an attempt to revegetate, with community participation, lands that are degrading rapidly (Srivastava and Kaul 1995).

Water erosion contributes to desertification in 45 million ha of dryland China (Table 3.6). As in India, in the majority of situations impacts are negligible (Table 3.7), but ASSOD data show that over 400 000 ha experience desertification due to water erosion that has a strong impact and in a further 4.8 million ha the impact is moderate. Map 3.3 indicates a significant area affected by very high severity water erosion in Shandong Province, southeast of the Huang He River, and other areas where the problem is very severe are the steep lands of Shanxi Province, north and south of the city of Taiyuan. These form pockets within an extensive area of high severity water erosion

Table 3.9 Desertification due to wind erosion in ASSOD countries

	On-site In susceptable drylands			*Off-site In susceptable drylands*		
	Million ha	*% susceptible dryland area*	*% country area*	*Million ha*	*% susceptible dryland area*	*% country area*
China	75.70	23.87	8.67	5.36	1.69	0.58
India	16.56	8.77	5.19	3.59	1.90	1.10
Nepal	0.12	8.63	0.85	0.00	0.00	0.00
Myanmar	0.00	0.00	0.00	1.85	79.39	2.10
Pakistan	8.67	11.91	9.87	0.00	0.00	0.00
Sri Lanka	0.00	0.00	0.00	0.00	0.00	0.00
Thailand	0.00	0.00	0.00	0.00	0.00	0.00
Total	101.05			10.8		

Source: ASSOD

that occurs throughout the catchment of the Huang He, in the Loess Plateau. This plateau comprises thick deposits of wind-deposited dust, or loess, that are naturally susceptible to erosion by both running water and deflation (Derbyshire and Goudie 1997). The natural erosive effects of the Huang He (the Yellow River, so-called because of its high sediment load) and its drainage system are, however, enhanced by the effects of intensive cultivation, often on steep slopes. It is estimated that the annual loss of soil in Yulin county, in the Huang He catchment, was over 500 million tonnes per year in the mid-1980s (Zhao 1996), while one of the most severely affected areas is in the catchment of the Dali River, a tributary of the middle Huang He (Mainguet 1991). According to Mou and Meng (1980), each year an average of 25 000 tonnes of soil are lost per square kilometre by water erosion from a catchment with an area of 96 km^2.

It is estimated that topsoil erosion leads to the loss of nutrients equivalent to the total national production of chemical fertilizers, with the erosion problem greatest in the Huang He system (World Bank 1994). Erosion and declining livestock and crop yields in parts of the Loess Plateau have been strongly linked to poverty, not least because rural population densities are high: commonly 100–200 people per ha and often above 400 people per ha (World Bank 1994). Indeed, agricultural incomes in China's semiarid areas where desertification is most severe are only one-third of industrial incomes (Zhao 1996). Integrated programmes of watershed management, including tree planting, the terracing of steep slopes (Figure 1.16) and the construction of sediment control dams to counteract the effects of highly erosive intense storms, and developments in agricultural practices, are seen as an appropriate route to tackling both human and environmental aspects of desertification simultaneously (World Bank 1994).

Water erosion is a very significant desertification process in Pakistan, where ASSOD shows nearly 16 million ha or 22% of the susceptible drylands, to be affected. The majority of this, some 10 million ha, is in the moderate impact category. The area most widely affected by water erosion occurs to the west of the Indus Valley, in the hills of Baluchistan. Map 3.3 shows that in this region high severity erosion occurs. In the Punjab, on the Potwar Plateau to the east of the Indus, the severity of water erosion, both by sheet wash and through the development of gullies, is high in the districts of Jhelum, Rawalpindi and Attock (Chaudhari 1995). The clearance of vegetation, especially for fuelwood which is nationally in short supply, and for timber, is a major contributory factor towards desertification by water erosion in Pakistan (World Bank 1992). Pastoralism is a major land use in Baluchistan and this may in some case contribute to water erosion when pressure on vegetation is excessive, particularly in areas of steep slopes.

Table 3.8 shows that ASSOD reports only limited off-site impacts of water erosion in the susceptible drylands, with Sri Lanka and China having the greatest reported occurrences.

Wind erosion

Wind erosion occurs in the susceptible drylands of four ASSOD countries, China, India, Nepal and Pakistan (Map 3.4), impacting upon 17% of ASSOD susceptible drylands (Figure 3.3). In Nepal, wind erosion is a relatively limited problem but it attains great significance in the other three countries. On-site effects, which are the deflation of topsoil and terrain deformation including sand dune development, occur in over 100 million hectares (Table 3.9). The efficiency of aeolian processes in dry environments means that, at 10 million ha, the area affected by off-site wind erosion impacts, notably the burial of land with windblown material derived from other localities, is 10 times greater than for water erosion. Once desertification processes have rendered surfaces susceptible to aeolian processes, dryness provides conditions that

Table 3.10 On-site wind erosion impacts (million ha)

		Impact					
	Country	*Negligible*	*Light*	*Moderate*	*Strong*	*Extreme*	*Total*
Arid	China	0.82	26.20	1.28	23.23	0.00	51.82
	India	0.00	5.66	0.16	0.14	0.00	5.96
	Pakistan	0.03	0.64	1.49	6.50	0.00	8.66
Arid Total		0.85	32.50	2.93	29.88	0.00	66.45
Semiarid	China	0.02	10.41	0.86	12.58	0.00	23.87
	India	0.00	1.32	9.26	0.00	0.00	10.58
	Pakistan	0.00	0.00	0.01	0.00	0.00	0.01
Semiarid Total		0.02	11.73	10.12	12.58	0.00	34.45
Dry subhumid	China	0.00	1.19	0.41	3.06	0.00	4.67
	India	0.00	0.00	0.17	0.00	0.00	0.17
	Nepal	0.00	0.08	0.00	0.00	0.00	0.12
Dry subhumid Total		0.00	1.28	0.59	3.06	0.00	4.97
Grand Total		0.87	45.51	13.64	45.44	0.00	105.46

Note: column and row totals may not correspond due to rounding of decimals
Source: ASSOD

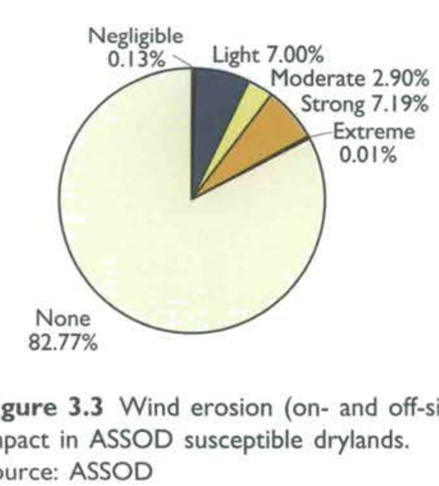
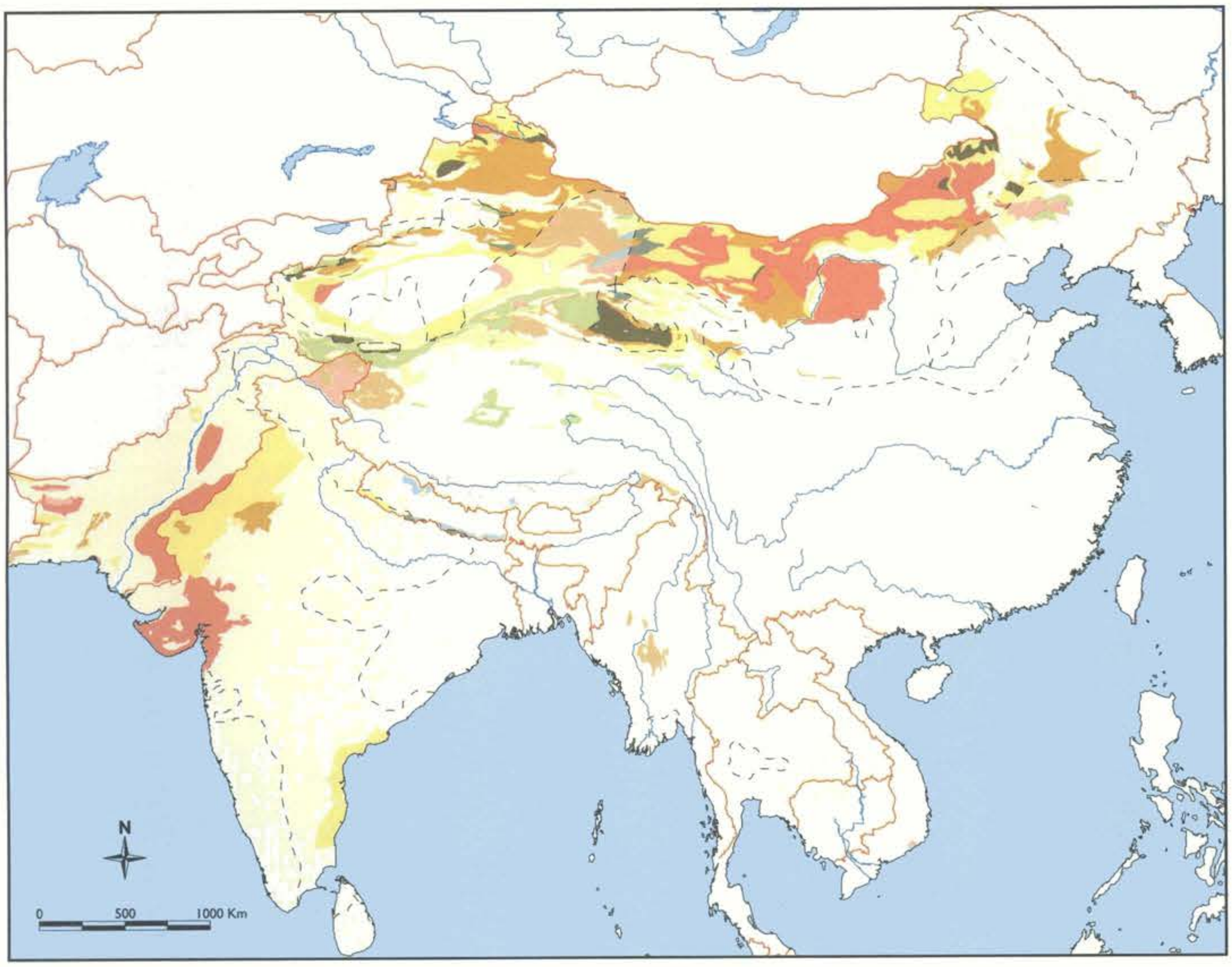


Figure 3.3 Wind erosion (on- and off-site) impact in ASSOD susceptible drylands.
Source: ASSOD



Map 3.4 Wind erosion severity

favour their effective operation. As Table 3.10 shows, wind erosion therefore attains its greatest impact in the arid regions of the susceptible drylands of the ASSOD region.

The general aridity of the country as a whole means that Pakistan is particularly susceptible to desertification by wind erosion, which mainly has a strong impact in the areas in which it occurs (Table 3.9). Although the total area suffering from this problem is less than in both China and India, it does represent nearly 10% of the total country land area of Pakistan.

Three areas in Pakistan are most affected by wind erosion. In the west, Baluchistan shows two areas of very high severity, notably around the depression of Hamün-r-Mashkel near the border with Iran, and other areas where severity is medium and high. Grazing pressure is seen as a major contributary factor in this area (World Bank 1992) and indeed in the wind-erosion-affected areas of the country as a whole (ADB 1992). To the east of the Indus River, in Sindh and Punjab Provinces, the western area of the Thar Desert and the Cholistan Desert show very high severity wind erosion. The naturally sandy soils, including both old desert sands and Pleistocene river terraces (Baig *et al.* 1980, Mian and Syal 1986) are susceptible to deflation. High population pressures – which continue to grow – have led to increased sedentarisation of previously nomadic peoples (Arshad and Rao 1995). This has contributed to intensification and over-use of plants, not only for grazing but for a range of economic activities. Some of these are very specialised, for example the extraction of caustic soda from *Haloxlon recurvum* (Arshad *et al.* 1995). The third area, the Thal Desert, is located further north in Punjab and also experiences very high severity wind erosion.

In India, the impact of on- and off-site wind erosion affects 11% of susceptible drylands, largely in the light category (Table 3.10). Map 3.4 shows that when severity is considered, which combines impact and extent, medium severity wind erosion occurs both in the mainly dry subhumid coastal areas of the Bay of Bengal and in the north-western part of the country from Rajasthan up to Delhi. In Rajasthan, which includes most of the arid to semiarid Thar Desert, human population doubled between 1921 and 1961 and doubled again up to 1991 (Dhir 1995). The potential for human-induced degradation in this drought-susceptible area is therefore considerable.

In the Thar Desert, the abrupt change from medium to very high severity wind erosion apparent in Map 3.4 is coincident with the Pakistan-India border. There are several reasons that could explain this sharp change. First, it may be an artefact of the assessments by different national organisations contributing to ASSOD. Second, it may be because the impact component of the severity calculation records that wind erosion does not everywhere have an undue effect on productivity. Singh *et* *al.* (1992) note how the sediments eroded by the wind in parts of Rajasthan have low nutrient contents, a result of poor natural soil fertility. Though some loss of productivity does occur after wind erosion events, both through topsoil loss and surface instability, recovery can be rapid (Dhir 1995) and the overall effect on productivity may therefore not be as high as might be expected. Third, it may be a result of chemical degradation problems being greater than wind erosion on the Indian side of the border in this area. Since the construction of the Indira Gandhi Canal in the northern part of the Indian Thar, irrigated cultivation has been replacing other more traditional land uses (Dhir 1995), including those that may lead to wind erosion. None the less, in the border area pastoralism is still the major land use type and many experts regard wind erosion as a real desertification problem in this area of light sandy soils (Gupta *et al.* 1981, Abrol and Venkateswarlu 1995). Table 3.11 shows that 90 000 ha in India are affected by strong impact off-site effects of wind erosion. Dhir (1995) notes how cultivation in Rajasthan can be hampered by the accumulation in fields of blowing sand. Irrigated agriculture, which is expanding in this area, may also become hindered as water transfer canals and channels can become clogged by blowing sand.

Table 3.11 Off-site wind erosion impacts (million ha)

		Impact					
	Country	*Negligible*	*Light*	*Moderate*	*Strong*	*Extreme*	*Total*
Arid	China	0.00	0.44	1.33	0.11	0.00	1.87
	India	0.00	0.00	0.00	0.09	0.03	0.13
	Pakistan	0.00	0.00	1.85	0.00	0.00	1.85
Arid Total		0.00	0.44	3.17	0.20	0.03	3.85
Semiarid	China	0.00	1.19	0.83	0.00	0.00	2.02
	India	0.00	0.00	0.09	2.84	0.00	2.93
Semiarid Total		0.00	1.19	0.92	2.84	0.00	4.95
Dry subhumid	China	0.02	0.07	1.38	0.00	0.00	1.47
	India	0.00	0.00	0.49	0.05	0.00	0.53
Dry subhumid Total		0.02	0.07	1.86	0.05	0.00	2.01
Grand Total		0.02	1.70	5.95	3.08	0.03	10.78

Note: column and row totals may not correspond due to rounding of decimals
Source: ASSOD

Map 3.4 shows very high severity wind erosion to occur in a large area of Gujarat, including the Ran of Kutch. Pastoralism is the traditional land use activity here (Choksi and Dyer 1996) and, as in other arid dryland areas, is a very appropriate land use. When desertification occurs in such regions, it is common to attribute blame on overgrazing pressures. However, the expansion of other land use activities in Gujarat, notably modernised cultivation, has effectively marginalised traditional nomadic pastoralism by making fodder a scarce resource (Vira 1993). Wind erosion in this area may well in some localities be the result of pastoral pressure, but activities of livestock owners are not the root cause of the degradation. In many parts of Gujarat wind erosion is a result of cultivation which has expanded spatially and intensfied in recent times (Choksi and Dyer 1996).

Over 25% of China's susceptible drylands are affected by wind erosion. Off-site erosion affects nearly 4 million ha (Table 3.11). Eighty million ha experience on-site wind erosion impacts; in 40 million of these the impact is strong (Table 3.10). Well over half of China's wind-erosion-affected lands are in areas with arid climates, mainly in 13 provinces in the north of the country. High and very high severity wind erosion (Map 3.4) occurs in areas mainly in Inner Mongolia, Shanxi, Shaanxi, Ningxia and Gansu Provinces (Zhao 1996). Medium severity wind erosion includes the lands surrounding the natural Taklamakan Desert in the northwest of China.

Some of the worst affected areas are in Inner Mongolia (Lin *et al.* 1983, Sheehy 1992), particularly on the Ordos Plateau (or Mu Us Desert) within the 'big bend' of the Huang He River. Remote sensing surveys by Luk and Kalinauskas (1982) have shown how considerable deterioration of the natural vegetation cover has rendered silty-sandy loessic soils susceptible to deflation by strong winter winds. Again, pastoralism appears to be a significant factor that is interwoven with desertification pressures. Population growth, in part through government directed in-migration during the last 30 years (Zhao 1996), has increased the number of small stock owners. At the same time, farmers have been encouraged to increase the area of grain cultivation on marginal lands as part of a national food self-sufficiency programme (World Bank 1994). This has reduced the land area available for grazing. Sheehy (1992) reports that in one area livestock numbers increased by 330% between 1949 and 1964 while at the same time grazing lands fell by 26%. Even though livestock numbers have since fallen, so too has the area of pasture land.

While wind erosion is a severe desertification problem in China, there are notable examples where actions have been taken to stabilise newly developed mobile sands or restabilise disturbed surfaces. Tree planting has occurred extensively (Yang 1990, Zhu *et al.* 1992) within semiarid and arid areas, including as part of China's 'Green Wall' project (Guo *et al.* 1989). Checker boards (Figure 1.19) are extensively used as a means of first stabilising shifting dunes, allowing plants and trees to gain a permanent foothold. A widely cited example of the successful use of this technique comes from Shapotou, in the high severity wind erosion area of the Tengger Desert on the northern bank of the Huang He. Here dunes that were continually encroaching on a major railway line have been stablised by a combination of bulldozing, checkerboards, and tree planting (Zhu *et al.* 1992, Feng *et al.* 1994, Fullen and Mitchell 1994).

Chemical deterioration

About 90 million ha of soils in the susceptible drylands of the ASSOD countries are degraded by chemical deterioration (Table 3.12), an area that equates to about 5.5% of the total area of the seven ASSOD countries containing susceptible drylands. As a proportion of these countries' susceptible drylands, chemical deterioration affects just over 13%, most of it in the negligible and light impact categories (Figure 3.4). The problem reaches very high severity in parts of Pakistan, India, China and Thailand (Map 3.5). Low severity deterioration occurs across the dryland zone of Myanmar, the impact on 60 000 ha of drylands in Nepal is light, and a similar level of impact is recorded on about 70 000 ha in northern Sri Lanka.

The chemical deterioration problem is most widespread in Pakistan, where it affects 29% of all the country's land area, and about 31% of its susceptible drylands. Chemical deterioration is of very high severity in two parts of the Sind: the Indus delta and an area between Karachi and Hyderabad; along the Dasht River in the Makran region of Baluchistan, and in the northern Punjab immediately south of Islamabad: the Potwar Plateau and, south of this, the Salt Range. High severity chemical deterioration is recorded in north-eastern Sind, several parts of northern Baluchistan, and west and north of Peshawar in North West Frontier Province.

Much of the affected area is cropland, part of the Indus irrigation system, the largest single irrigation system in the world (Ghassemi *et al.* 1995). The most insidious form of chemical deterioration in these areas is salinization (Map 3.6), a problem affecting 8.86 million ha, most of these in the susceptible drylands (Table 3.13). Although soils in parts of the Indus plain and elsewhere in Pakistan are naturally saline, secondary salinization problems are widespread in irrigated areas. This is the result of either accelerated redistribution of salts in the soil profile due to high water-tables, caused by many years of excessive irrigation or, in areas with lower water-tables, the use of insufficient water to leach salts out of the soil.

The relatively less severe secondary salinization problems of the Punjab are due mainly to Pakistan's Salinity Control and Reclamation Projects (SCARP), the first of which began in the 1950s. The area of waterlogged and saline

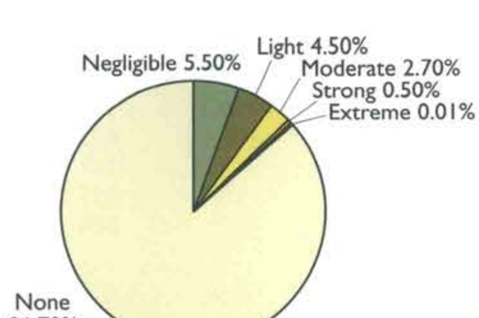


Figure 3.4 Chemical deterioration impact in ASSOD susceptible drylands. Source: ASSOD

Map 3.5 Chemical deterioration severity

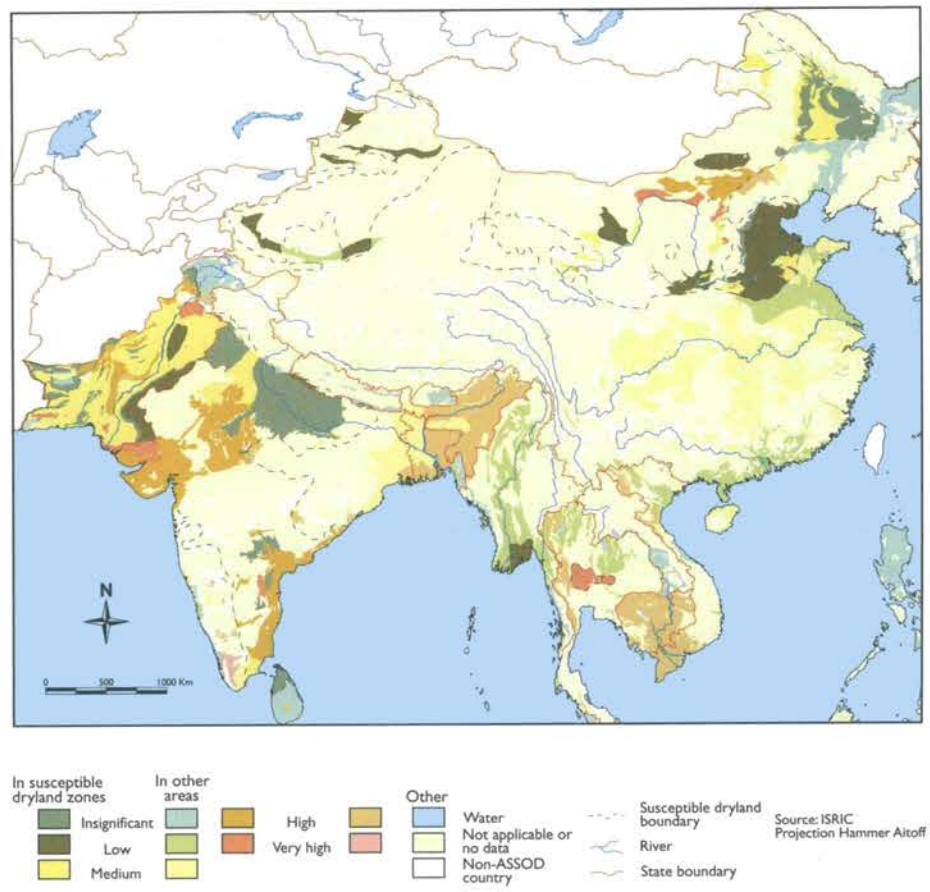


Table 3.12 Impact of chemical deterioration by climate zone (million ha)

		Impact					
	Country	*Negligible*	*Light*	*Moderate*	*Strong*	*Extreme*	*Total*
Arid	China	0.00	2.96	1.26	0.00	0.00	4.21
	India	0.00	0.09	0.08	0.56	0.00	0.73
	Pakistan	3.08	14.04	0.52	0.91	0.00	18.55
Arid total		3.08	17.09	1.86	1.47	0.00	23.49
Semiarid	China	0.93	3.69	0.71	0.00	0.00	5.33
	India	6.59	1.98	7.66	1.23	0.04	17.50
	Sri Lanka	0.14	0.00	0.00	0.00	0.00	0.14
	Pakistan	0.03	1.87	1.42	0.04	0.00	3.36
Semiarid		7.68	7.54	9.80	1.27	0.04	26.34
Dry subhumid	China	17.57	5.43	0.70	0.00	0.00	23.70
	India	8.11	0.12	3.22	0.44	0.00	11.90
	Sri Lanka	0.61	0.00	0.00	0.00	0.00	0.61
	Myanmar	0.00	0.23	0.00	0.00	0.00	0.23
	Nepal	0.00	0.06	0.00	0.00	0.00	0.07
	Pakistan	0.15	0.11	0.23	0.00	0.00	0.49
	Thailand	0.00	0.00	2.57	0.00	0.00	2.57
Dry subhumid Total		26.45	5.94	6.72	0.44	0.00	39.57
Grand Total		37.21	30.57	18.38	3.18	0.04	89.40

Note: row and column totals may not correspond exactly due to rounding of decimals
Source: ASSOD

land in Pakistan's Punjab rose from 61 000 ha in 1960 to 68 000 ha in 1966, but by 1985 the area had been reduced to 23 000 ha (Chopra 1989, see also below). Fertility decline is reported to be a less widespread problem in Pakistan, but it still affects over 15.5 million ha, nearly 21% of all the country's soils (Table 3.14). The phenomenon occurs largely west of the Indus, with the major exception of the Potwar Plateau in northern Punjab (Map 3.7).

In India, the worst-affected area of very high severity chemical deterioration lies in northern Gujarat, while in most of the rest of the state the problem occurs with a high severity. Areas of eastern Rajasthan and a broad swath of largely dry subhumid land along the eastern coast of the country are also affected to a high severity. Soils in the area west of the Namalla Hills in southern Andhra Pradesh are affected to a very high severity in the southern part of the country.

Gujarat, like the neighbouring Pakistan province of Sind, is a major agricultural state. While 80% of the cropland in Gujarat is rainfed, the construction of several major reservoirs, such as the Mahi, Shetrunji and Ukai, has provided a large perennial water supply that has been used in four major irrigation projects: the Kakrapar, Ukai, Mahi and Dantiwada. The Kakrapar and Mahi particularly have suffered problems of salinization. Much of the state's long coastline has also experienced salinization as overpumping of fresh groundwater has led to seawater intrusion into aquifers (Mistry 1989).

Salinization appears as a relatively minor problem on the arable land of the Ganges Plains in Uttar Pradesh, where a significant decrease in the area of salt-affected soils has been noted in remote sensing studies from 1975 and 1990 (Dwivedi 1994). Large areas of salt-affected soils have been reclaimed in recent years by government agencies and farmers. A study in one district of Uttar Pradesh, comparing survey maps from 1956 with aerial photographs for 1972 and Landsat TM images for 1986, showed that the average increase in cultivated area due to reclamation within salt-affected soil blocks during 1956–86 was 22%. Increased canal irrigation in the area, however, was also found to be leading to new salinization elsewhere. During 1972–86, an increase in the extent of salt-affected soils on the periphery of reclaimed blocks was quantified at 3% (Singh 1994).

Although loss of nutrients affects 18.2 million ha of India's susceptible dryland soils, Map 3.7 indicates that this form of chemical deterioration is not particularly widespread in India, despite reports to the contrary in the acade-

Map 3.6 Salinization severity

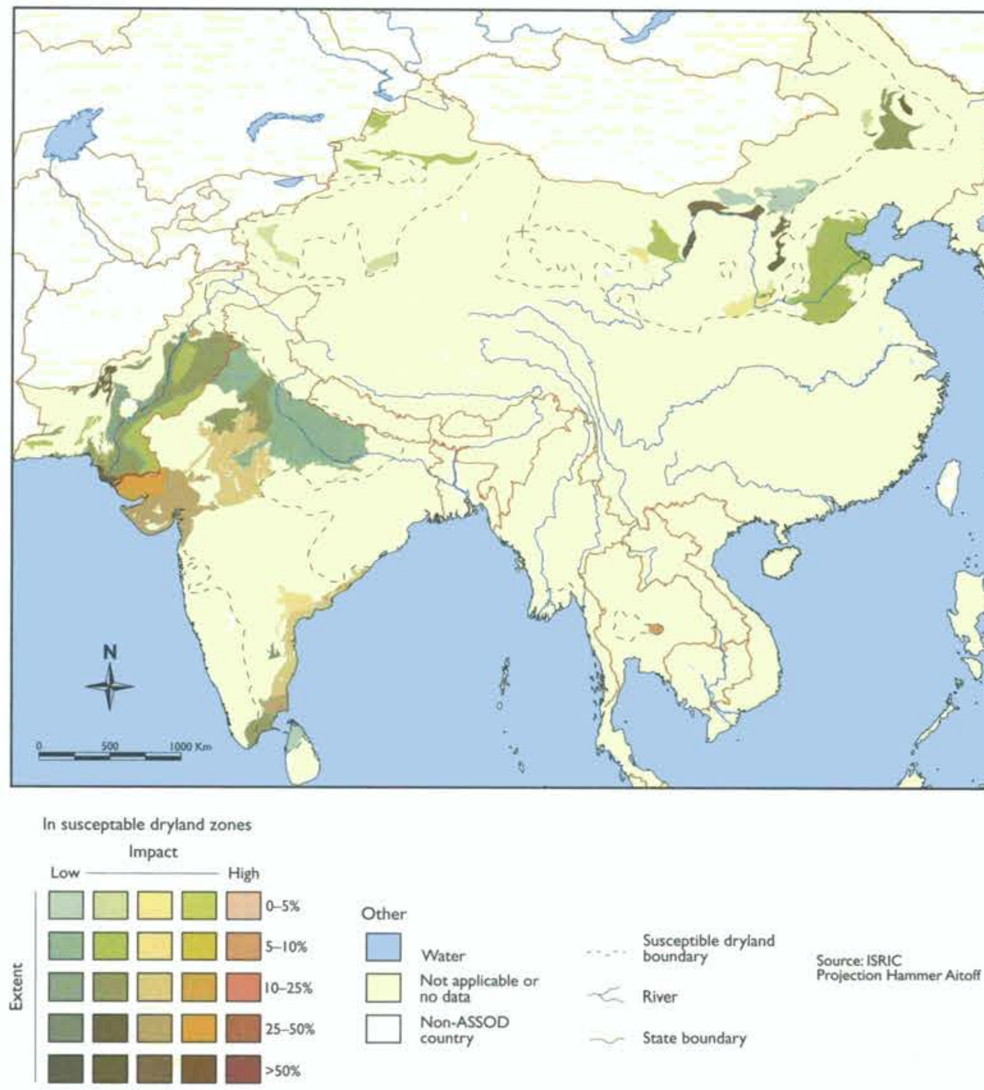


Table 3.13 Impact of salinization by climate zone (million ha)

		Impact					
	Country	Negligible	Light	Moderate	Strong	Extreme	Grand Total
Arid	China	0.13	0.41	1.26	0.00	0.00	1.80
	India	0.00	0.09	0.08	0.56	0.00	0.73
	Pakistan	1.09	5.21	0.03	0.91	0.00	7.24
Arid Total		1.22	5.71	1.37	1.47	0.00	9.77
Semiarid	China	0.14	0.98	0.71	0.00	0.00	1.84
	India	1.62	1.90	7.45	0.87	0.00	11.84
	Sri Lanka	0.00	0.00	0.00	0.00	0.00	0.00
	Pakistan	0.00	1.23	0.20	0.04	0.00	1.47
Semiarid Total		1.76	4.11	8.37	0.91	0.00	15.15
Dry subhumid	China	0.09	3.47	0.52	0.00	0.00	4.08
	India	1.73	0.03	2.16	0.08	0.00	4.00
	Sri Lanka	0.01	0.00	0.00	0.00	0.00	0.01
	Pakistan	0.00	0.11	0.04	0.00	0.00	0.15
	Thailand	0.00	0.00	0.00	0.00	0.06	0.06
Dry subhumid Total		1.83	3.60	2.73	0.08	0.06	8.30
Grand Total		4.81	13.42	12.47	2.46	0.06	33.22

Note: row and column totals may not correspond exactly due to rounding of decimals
Source: ASSOD

Map 3.7 Fertility decline severity

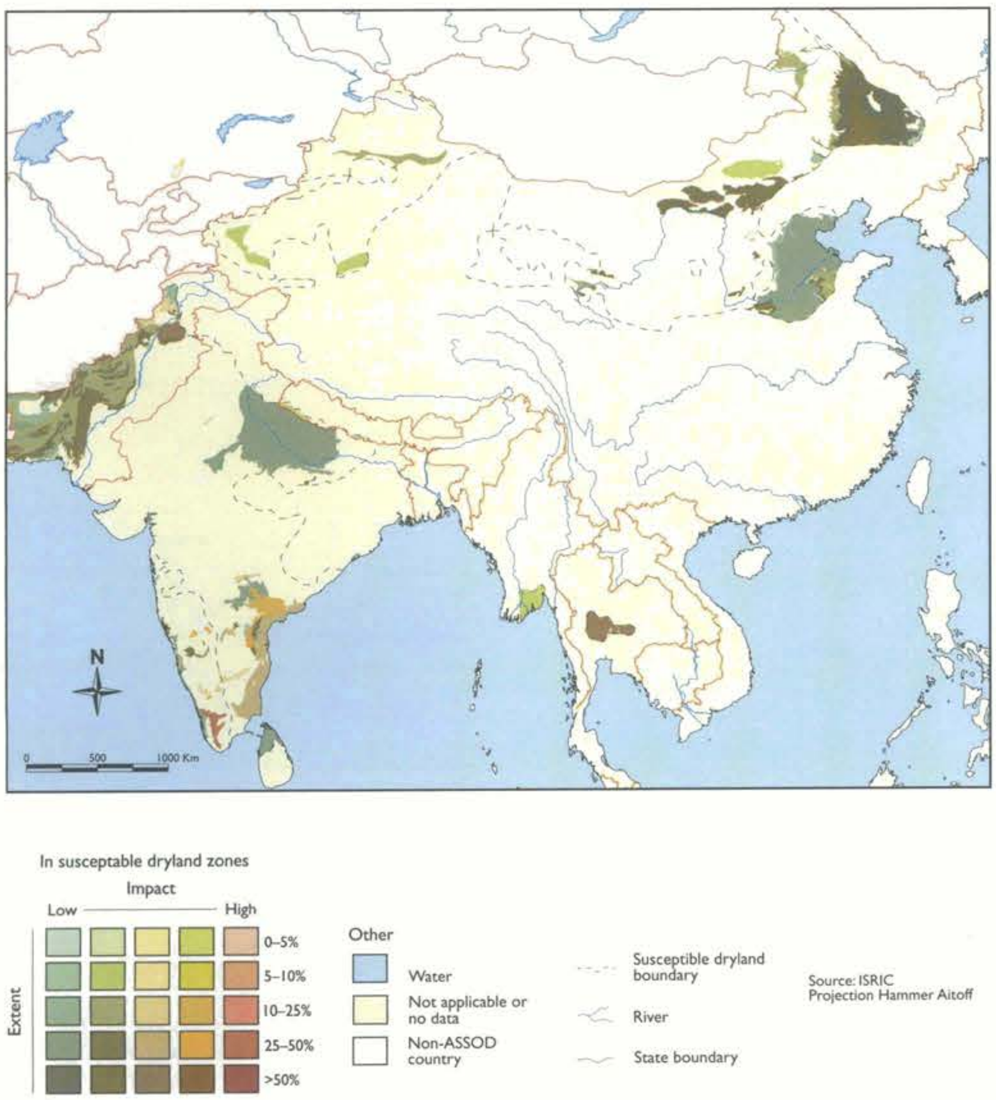


Table 3.14 Impact of fertility decline by climate zone (million ha)

		Impact					
	Country	*Negligible*	*Light*	*Moderate*	*Strong*	*Extreme*	*Grand Total*
Arid	China	0.00	3.42	0.00	0.00	0.00	3.42
	Pakistan	2.85	9.71	0.52	0.00	0.00	13.09
Arid Total		2.85	13.13	0.52	0.00	0.00	16.51
Semiarid	China	0.90	3.23	0.00	0.00	0.00	4.13
	India	5.95	0.07	1.11	0.37	0.04	7.53
	Sri Lanka	0.14	0.00	0.00	0.00	0.00	0.14
	Pakistan	0.03	0.65	1.42	0.00	0.00	2.10
Semiarid Total		7.01	3.95	2.53	0.37	0.04	13.90
Dry subhumid	China	17.57	4.97	0.17	0.00	0.00	22.71
	India	7.94	0.09	2.27	0.35	0.00	10.67
	Sri Lanka	0.61	0.00	0.00	0.00	0.00	0.61
	Myanmar	0.00	0.23	0.00	0.00	0.00	0.23
	Nepal	0.00	0.06	0.00	0.00	0.00	0.07
	Pakistan	0.15	0.00	0.23	0.00	0.00	0.38
	Thailand	0.00	0.00	2.57	0.00	0.00	2.57
Dry subhumid Total		26.28	5.34	5.24	0.35	0.00	37.24
Grand Total		36.14	22.42	8.29	0.72	0.04	67.65

Note: row and column totals may not correspond exactly due to rounding of decimals
Source: ASSOD

mic literature. Relatively low-impact deterioration affects 25–50% of mapping units in Uttar Pradesh, but medium to high impacts only affect mapping units on the eastern seaboard. This pattern contrasts with reports of nutrient depletion from all 15 agro-climatic regions of India (Biswas and Tewatia 1991). These differences are probably a reflection of differences in methodology and interpretation. While chemical deterioration in the ASSOD survey, as in the GLASOD study, refers specifically to *in situ* degradation, nutrients can also be removed from a field by erosion and in some areas erosive degradation may have been recorded.

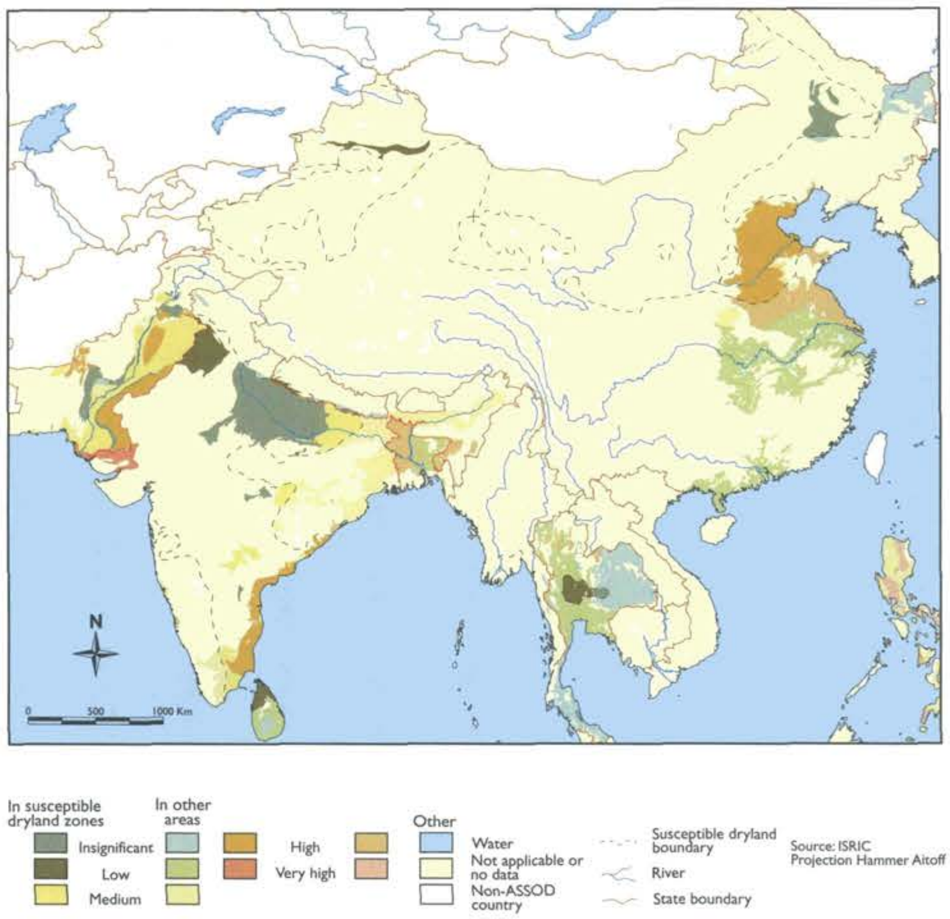
Very high severity deterioration is prevalent across virtually the entire dryland area of Thailand, an area that stretches from the country's Central Plain across the Central Highlands to include part of the north-eastern Khorat Plateau. Fertility decline affects more than half of all mapping units in this dryland zone and moderate impact is reported from 2.57 million ha due to leaching (Potisuwan 1994). Primary and secondary salt-affected soils are widespread on the Khorat Plateau. They are generally sandy, with a low fertility and high sodium and chloride contents.

Soils in the susceptible drylands of China badly affected by chemical deterioration are located along the banks of the Huang He's 'elbow' section: the northernmost rim of the Ordos Plateau to the south of the river and more extensive areas elsewhere in Inner Mongolia to the north of the Huang He, including the Hetao Plain on the north-west of the elbow. Larger areas of Inner Mongolia to the east are affected to a high severity.

Fertility decline affects more than 30 million ha in China's susceptible drylands, much of this area in Inner Mongolia, on the Huang-Huai-Hai Plain, formed by the alluvial deposits of the Huang He, Huai He and Hai He rivers, and in Heilongjiang in the north-east. This pattern largely confirms analysis of soil-profile data over a 50-year period (1930–80) indicating that organic matter and nitrogen, though not phosphorous or potassium, have declined over broad areas of the North since the 1950s (Lindert *et al.* 1996).

Salinization is the most prevalent problem in the areas along the Huang He River. All cultivated land on the Hetao Plain is irrigated with water from the river, but drainage is poor, water-tables are frequently close to the surface and salinization is a major limiting factor for crop yields. Although irrigation has been practised here for many centuries, both the irrigated area and the proportion experiencing salinity problems have increased in recent decades: 73% of the 230 000 ha of

Map 3.8 Physical deterioration severity



irrigated land was affected in 1979 (Dregne *et al.* 1996). Salinity is also a serious problem on the Ningxia Plain, on the western banks of the northward-flowing bend of the Huang He. Excessive amounts of water are applied to the fields, irrigation canals leak and drainage is poor on the flat topography, where more land is affected in the north of the plain than in the south (Xiong *et al.* 1996). Many areas in the Huang-Huai-Hai Plain bordering the Bo Hai and Yellow Sea are affected by light-impact human-induced salinization due to high water-tables and sea water intrusion in the coastal areas. In the north-west of the country, salinization affects isolated oasis settlements on the southern rim of the Taklamakan Desert, but in some of these areas revegetation with Tamarix trees has proved successful in rehabilitating degraded soils (see page 166). Salinity problems have also been experienced on new irrigation schemes in Dzungaria (Gruschkke 1991).

Table 3.15 Impact of physical deterioration by climate zone (million ha)

	Country	*Negligible*	*Light*	*Moderate*	*Strong*	*Extreme*	*Total*
Arid	China	0.00	0.10	0.00	0.00	0.00	0.10
	India	0.00	0.00	0.00	0.58	0.00	0.58
	Pakistan	2.80	5.14	2.46	0.91	0.00	11.31
Arid Total	2.80	5.25	2.46	1.50	0.00	12.00	
Semiarid	China	0.15	0.08	0.00	0.00	0.00	0.23
	India	1.07	1.54	0.49	1.18	0.00	4.28
	Sri Lan	0.00	0.01	0.00	0.00	0.00	0.01
	Pakist	0.17	1.98	0.11	0.04	0.00	2.30
Semiarid Total	1.39	3.61	0.60	1.22	0.00	6.82	
Dry subhumid	China	1.08	13.56	0.00	0.00	0.00	14.65
	India	1.90	1.97	1.26	0.00	0.00	5.14
	Sri Lan	0.00	0.07	0.00	0.00	0.00	0.07
	Nepal	0.00	0.06	0.00	0.00	0.00	0.09
	Pakist	0.04	0.15	0.02	0.00	0.00	0.21
	Thai	1.04	0.00	0.00	0.00	0.00	1.04
Dry subhumid Total		4.06	15.81	1.29	0.00	0.00	21.19
Grand Total		8.25	24.67	4.35	2.72	0.00	40.01

Note: row and column totals may not correspond exactly due to rounding of decimals
Source: ASSOD

Physical deterioration

Physical deterioration affects about 40 million ha of susceptible drylands in the ASSOD countries (Table 3.15). Such problems are of low or insignificant severity in the susceptible drylands of southern Nepal, northern Sri Lanka and Thailand, and do not affect the dry subhumid part of Myanmar. The main susceptible dryland areas of ASSOD countries affected are on the Indo-Gangetic Plains of Pakistan and India, the south-eastern coast of India and on the Huang-Huai-Hai Plain in China (Map 3.8). Altogether physical deterioration affects nearly 2.5% of the total area of the seven ASSOD countries containing susceptible drylands. This equates to nearly 6% of the susceptible drylands themselves (Figure 3.5).

Waterlogging has been recognised as a problem on Pakistan's irrigated cropland since 1841 (Shafique and Skogerboe 1984) and today the problem is of medium severity along the whole length of the Indus. In total, some 13.62 million ha or about 19% of Pakistan's susceptible drylands are affected (Table 3.16). Physical deterioration by waterlogging reaches its highest severity in the irrigated areas at the lower end of the Indus River system in southern parts of Sind province where the water-table is particularly shallow. Its depth below

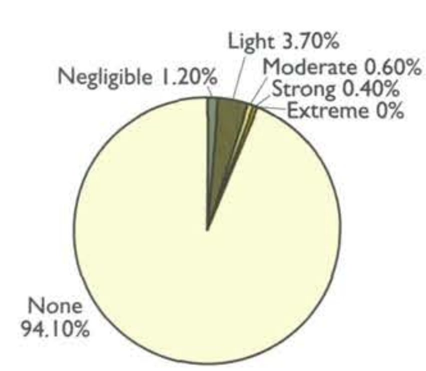


Figure 3.5 Physical deterioration impact in ASSOD susceptible drylands. Source: ASSOD

Table 3.16 Areas affected by waterlogging by climate zone (million ha)

Country	Arid	Semiarid	Dry subhumid	Non-drylands	Total
	Climate zone				
China	0.00	0.15	1.08	2.61	3.84
India	0.58	4.19	4.89	8.27	17.93
Sri Lanka	0.00	0.00	0.01	0.04	0.05
Myanmar	0.00	0.00	0.00	0.04	0.04
Nepal	0.00	0.00	0.09	0.11	0.19
Pakistan	11.31	2.13	0.17	0.64*	14.26
Thailand	0.00	0.00	0.00	0.61	0.61
Total	11.90	6.47	6.25	13.15	37.77

*includes 0.59 million ha of waterlogged land in the hyperarid zone of Pakistan
Note: row and column totals may not correspond exactly due to rounding of decimals
Source: ASSOD

ground surface varies with the seasons, but is on average less than 1.5 m (Ghassemi *et al.* 1995). High severity physical deterioration is recorded in the Quetta area of Baluchistan and east of the Indus in parts of Sind and Punjab. Not all of these areas are on irrigation schemes, however: waterlogging is also a problem on rainfed cropland in Baluchistan (Rees *et al.* 1991).

The longstanding problems of waterlogging and salinization in Pakistan have been addressed with some success in certain irrigated areas. Reclamation has taken place under the Salinity Control and Reclamation Projects (SCARP). The first SCARP, which began in 1956 and ended in 1963, extended over an area of nearly 0.5 million ha in the Rechna Doab area near Lahore in Punjab. It involved sinking more than 2000 tube-wells to lower the water-table and to provide more water for agriculture; reducing the salinity hazard by leaching and adding amendments, and helping farmers with technical information and economic support. About 73% of the area, some 360 000 ha, had water-tables shallower than 3 m in 1959, but this area had been reduced to about 38% or approximately 160 000 ha by 1977–78. This success in reducing the prevalence of waterlogging, combined with the overall reduction in the area of soils affected by salinity, had a dramatic effect on agricultural productivity. Estimated to be about 53% in 1959, the productivity of the area had increased to 80% by 1977-78 (Awan and Latif 1982, Ghassemi *et al.* 1995). SCARP has been largely responsible for the significant decline in areas with shallow (<1.5 m) water-tables in Punjab over the period 1979–86, while in Sind and Baluchistan this problem has become more widespread over the same period (Zia *et al.* 1994)

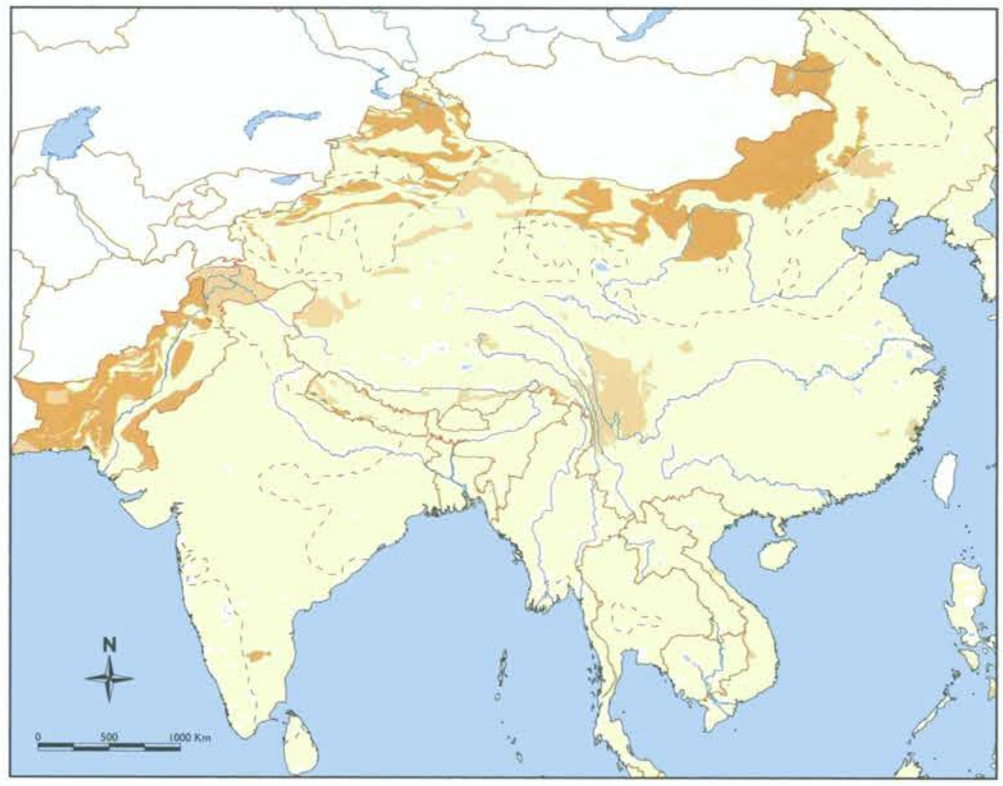
Waterlogging also affects nearly 10 million ha of India's susceptible drylands. Northern parts of Gujarat are particularly affected by physical deterioration, and this is mainly in the form of waterlogging. Water-tables in the area have steadily risen since the widespread shift from rainfed to irrigated agriculture which took place in the late 1950s (see above).

The largely dry subhumid Huang-Huai-Hai Plain is an important agricultural region of China. Rice, wheat and cotton are the main crops cultivated on 20 million ha of land, about 64% of which is irrigated. The water-table across most of the region is shallow, ranging from 2–4 m deep in the alluvial plain, and less than 2 m deep in coastal areas and some depressions (Zhu and Zheng 1983). High sediment loads brought from the Loess Plateau have accumulated in the lower Huang He River so that its bed is 3–10 metres higher than the surrounding land surface. Consequently the water-table has been raised due to lateral seepage of river water (Hseung *et al.* 1981). Daily rainfall totals can be as high as 100–300 mm in the summer rainy season, often resulting in flooding and waterlogging. Attempts to ameliorate water scarcity due to the lack of rainfall in spring and autumn concentrated on irrigation during the 1950s. Many reservoirs were built on the Plain and irrigation systems were constructed without adequate drainage, causing water-tables to rise further and exacerbating salinization and waterlogging problems.

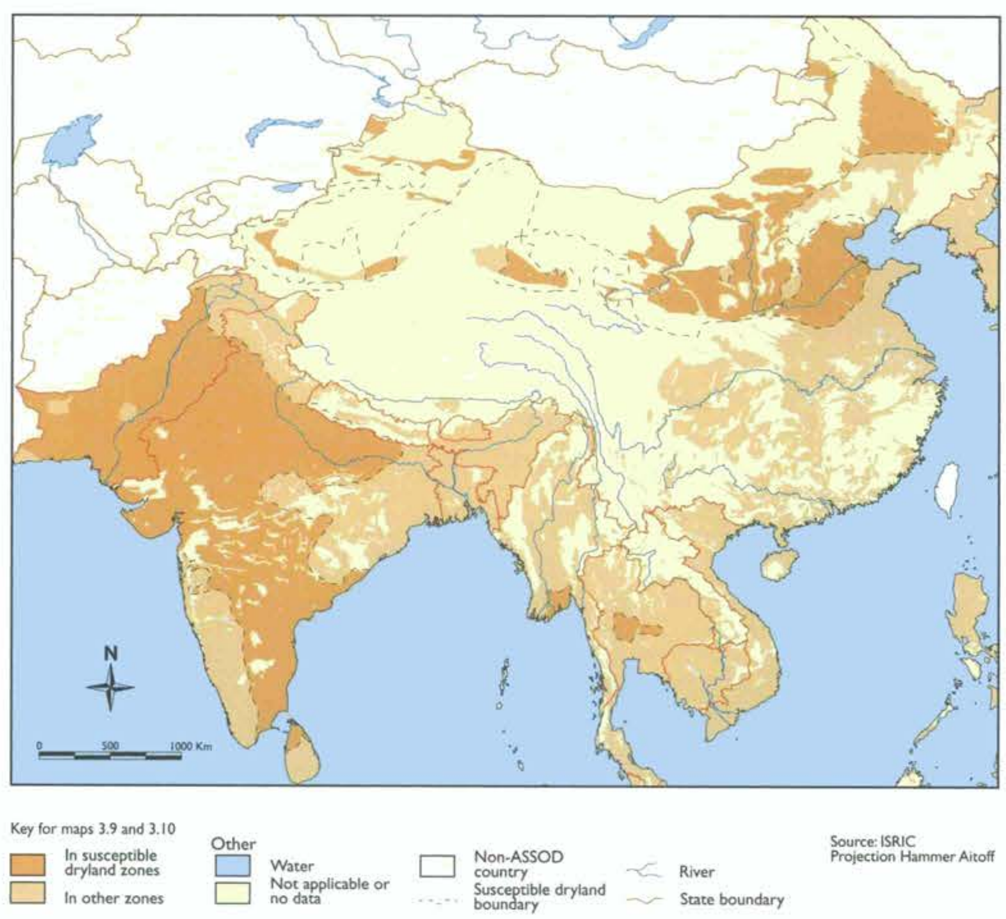
Causes of Soil Degradation

The human activities considered to be causing desertification by soil degradation in the ASSOD survey have been identified using the same five categories used in GLASOD. (Bio)industrial activities were not identified as a cause of degradation in any part of the ASSOD susceptible drylands. Maps 3.9–3.12 show the areas affected by the four main causes and comparison of the maps indicates that many areas where soil degradation is occurring experience multiple human-induced pressures. Table 3.17 summarises the major causes of degradation by susceptible dryland climate zone. Agricultural activities are the most widespread main cause of soil degradation in the susceptible drylands, where they are the prime cause on nearly 90 million ha in total. This factor dominates in the dry subhumid and semiarid zones, resulting in soil degradation in about 21% and 9% of these climate zones respectively. Overgrazing is seen as the main cause of soil degradation in arid areas, where it is the primary agent on about 15% of the territory.

Map 3.9 Areas affected by overgrazing



Map 3.10 Areas affected by agricultural activities



Overgrazing

Excessive grazing pressure is a significant cause of soil degradation in the susceptible drylands of China, Nepal and Pakistan (Map 3.9). It is not recorded as a cause in the susceptible drylands of Myanmar, Thailand or Sri Lanka, and accounts for soil degradation in only small areas of Indian susceptible drylands. The relative absence of overgrazing as a cause of soil degradation in India contrasts with the reports of the GLASOD survey (see Map 1.16) and with the views of several authors (e.g. Gupta and Saxena 1971, Kumar and Bhandari 1993, Srivastava and Kaul 1995). The recent shift in ecological thinking on the role of livestock in rangeland degradation and the subsequent reassessment of many areas previously thought to have been overgrazed (see page 50), lies behind this apparent contradiction in reporting.

Large parts of China's northernmost regions – Xinjiang, Gansu and Inner Mongolia – are under severe grazing pressure. In Xinjiang, the northern and eastern rim of the Taklamakan Desert are affected and the northern arid portion of the corridor through the Taklamakan formed by the ephemeral Hotien He River, as well as areas in Dzungaria north of the Tien Shan Mountains. Further east, much of the Ordos Plateau south of the Huang He River elbow is pastureland based on easily disturbed Quaternary deposits. Degradation problems caused by excessive grazing pressure, largely in the form of wind erosion and dune activation, have become increasingly serious since the late 1950s (Hong Jiang *et al.* 1995). These authors point out that although overall population densities in the area are low in comparison with other dryland parts of the world, rising human population is none the less the underlying driving force behind soil degradation on the Ordos Plateau. Increasing herd sizes have also been responsible for widespread wind erosion in the Kerqin Sandy Lands of Inner Mongolia (Takeuchi *et al.* 1995).

Table 3.17 Dominant causes of soil degradation (as highest severity per polygon) by susceptible dryland climate zone (million ha)

Climate zone	*Overgrazing*	*Agriculture*	*Overexploitation*	*Deforestation*	*Total*
Arid	29.32	23.77	17.00	12.52	82.61
Semiarid	19.28	25.33	16.88	5.00	66.48
Dry subhumid	3.85	40.63	9.23	5.66	59.36
Total	52.45	89.73	43.11	23.18	208.4

Source: ASSOD

Overgrazing is also identified as a serious cause of soil degradation in many parts of Pakistan outside the cultivated areas on the Indus River. In Baluchistan, where the grazing rights to practically all rangeland are owned by tribal groups, traditional management systems have broken down in many areas under increasing human and livestock populations and exposure to outside influences. In the past most rangeland was closed to grazing during the rainy season to allow pastures to regenerate, but greater livestock numbers and a weakening of tribal authority in some areas has resulted in year-round grazing in many parts with resulting degradation of pastures (World Bank 1994). East of the Indus, in the Cholistan Desert, excessive grazing by nearly 2 million head of cattle, sheep, goats and camels is also reported to be the cause of widespread degradation (Arshad *et al.* 1995).

Agricultural activities

Agricultural activities in ASSOD countries (Map 3.10) embrace a wide range of management techniques from intensive irrigated cropland to traditional shifting cultivation. In the drylands of northern Sri Lanka, for example, subsistence farming is the main cause of soil degradation by soil erosion. Crop yields are reported to have been reduced drastically in recent times and *Chena* slash-and-burn cycles have become shorter as a consequence (Gangogawila 1994).

Agricultural activities are by far the most common cause of chemical and physical soil deterioration and much of this occurs in the form of waterlogging and salinization on poorly managed irrigation schemes. In the Kakrapar irrigation project of northern Gujarat, these problems result from a combination of several factors: water losses from unlined canals; changes in cropping patterns; too frequent irrigation; soils with high clay contents, low permeability and poor natural drainage; and the low topographic gradient of the command area. The construction of a weir at Kakrapar on the Tapi River has allowed just over 400 000 ha to be brought under irrigation since 1957–58. However, while in 1957 no part of the area had a water-table as high as 1.5 m below the surface, by 1980 such shallow water-tables underlay more than 3000 ha (Table 3.18). In 1957, nearly 40% of the area had water-tables more than 9 m deep, but by 1980 the area in this category was virtually zero. With the rise in water-tables, salt is brought to the surface by capillary rise, making salinization a widespread problem in this irrigation project.

Estimates of the costs of salinization and waterlogging in Pakistan indicate that salinization depletes the country's potential production of cotton and rice by about 25%, while the reduction in yields due to waterlogging is the equivalent of about 1.5 million tonnes of wheat a year. In economic terms, these figures equate to US$2.5 billion and US$240 million a year respectively (Ahmad and Kutcher 1992).

Loessic soils are particularly susceptible to accelerated soil erosion if cultivation is not carefully managed. Gullying is widespread on agricultural land on the loess of the Potwar Plateau of Pakistan and attempts to combat the problem have come up against technical, socio-economic, logistic and cultural difficulties (Haigh 1990). Water erosion is similarly prevalent on the eastern part of the Ordos Plateau where the loess is cultivated. In many areas where the loess is just 20–30 cm thick, it has been stripped to the Tertiary bedrock beneath, rendering the land unusable (Hong Jiang *et al.* 1995).

Table 3.18 Rising water-table depths in the Kakrapar Weir irrigation system, Gujarat, in pre-monsoon periods (areas in ha)

Year	*Depth to water-table (m)* 0–1.5	1.5–3	3–6	6–9	>9
1957	0	1037	40 920	204 910	156 712
1970	25	2078	104 077	133 380	166 390
1975	1283	21 557	209 848	88 339	34 992
1980	3213	54 017	183 527	84 940	0

Source: after Ghassemi *et al.* (1995)

Overexploitation of vegetation for domestic use

The overexploitation of vegetation for domestic purposes is largely a cause of soil degradation in the arid and semiarid climate zones. The collection of fuelwood is considered to be the most widespread cause of wind erosion and sand dune reactivation in northern China, affecting nearly a third of all land degraded in this way (Zhu and Wang 1993). Map 3.11 indicates that this problem occurs very largely to the east of Xinjiang, much of this territory in Inner Mongolia. On the Ordos Plateau, an estimated 70% of households were reliant on shrubs for firewood in the late 1970s, but this proportion has since declined substantially as more households have turned to coal. Nevertheless it remains a cause of degradation in some areas, as does the collection of medicinal herbs (Hong Jiang *et al.* 1995).

In India, overuse of natural vegetation causes soil degradation in numerous isolated patches of the south of the country, but it is a widespread cause in the north-east. As much as 80% of the Aravalli Hills, extending from Gujarat through Rajasthan to the southern part of Haryana, have been denuded of their forest cover in recent times. The major portion of the Haryana Aravallis are village common land and in this area overexploitation for fuelwood has increased erosion from the denuded hillsides. The situation has become so critical that the state government has begun a village-based plan to combat the problem (Srivastava and Kaul 1995).

Rising populations are often cited as a driving force behind the unsustainable use of vegetation for domestic purposes, and the scale of vegetation clearance for fuelwood around major Indian dryland settlements in recent decades has been indicated in Section 1 (see page 49). The rising population argument is cited in the Thar Desert by Kumar and Bhandari (1993). The population of both livestock and humans has more than doubled in the Indian Thar over the last four decades. Widespread clearance of natural vegetation for cultivation, and the cutting of above and below ground biomass for fuelwood and other domestic uses, are major causes of the reactivation of sand dunes in the region.

Across the border in Pakistan's Cholistan Desert, where heavy grazing also depletes vegetation cover, shrubs and trees are exploited beyond their regenerative capacity for a range of uses. These include the building of dwellings and fences, as well as for fuelwood. The Khar bush (*Haloxylon recurvum*) is cut and burnt to produce a residue used in the soap industry (Arshad *et al.* 1995). West of the Indus, many villagers throughout Baluchistan are also degrading rangelands by uprooting small shrubs for fuelwood. The demand for firewood and timber is threatening perhaps the world's largest remaining area of juniper woodlands (*Juniperus excelsa*) in the uplands near Ziarat township, despite the area's protected status (World Bank 1994).

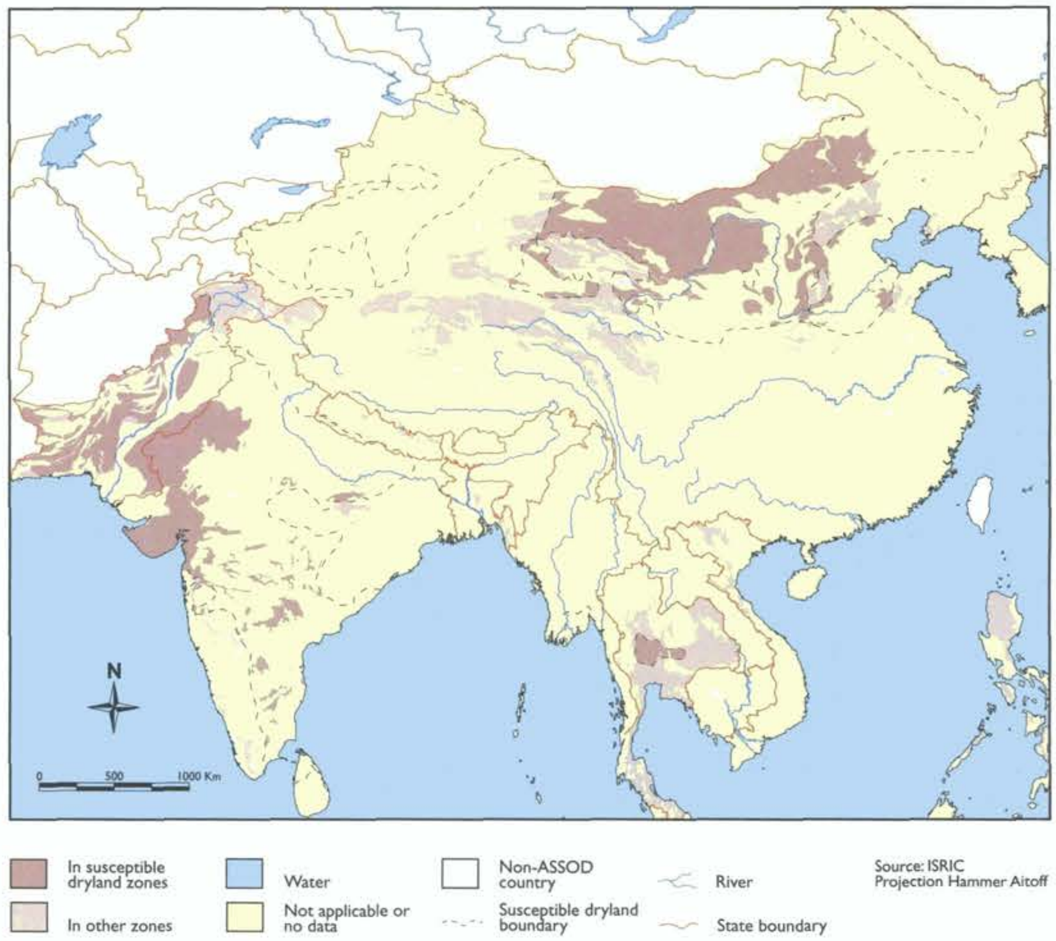
Deforestation and removal of natural vegetation

Deforestation and the removal of natural vegetation is the least extensive cause of soil degradation in the susceptible drylands, although it still affects more than 23 million ha. Degradation due to this cause is most prevalent in the arid zone where loss of the naturally sparse vegetation can quickly result in a decline in the soil resource by wind erosion. Deforestation is hardly recorded as a cause of soil degradation in Pakistan (Map 3.12) largely because forests cover just 2.6% of the national land area (FAO 1995). It is none the less one of the numerous causes affecting degradation on the Potwar Plateau, along with agricultural activities and intensive grazing (World Bank 1992).

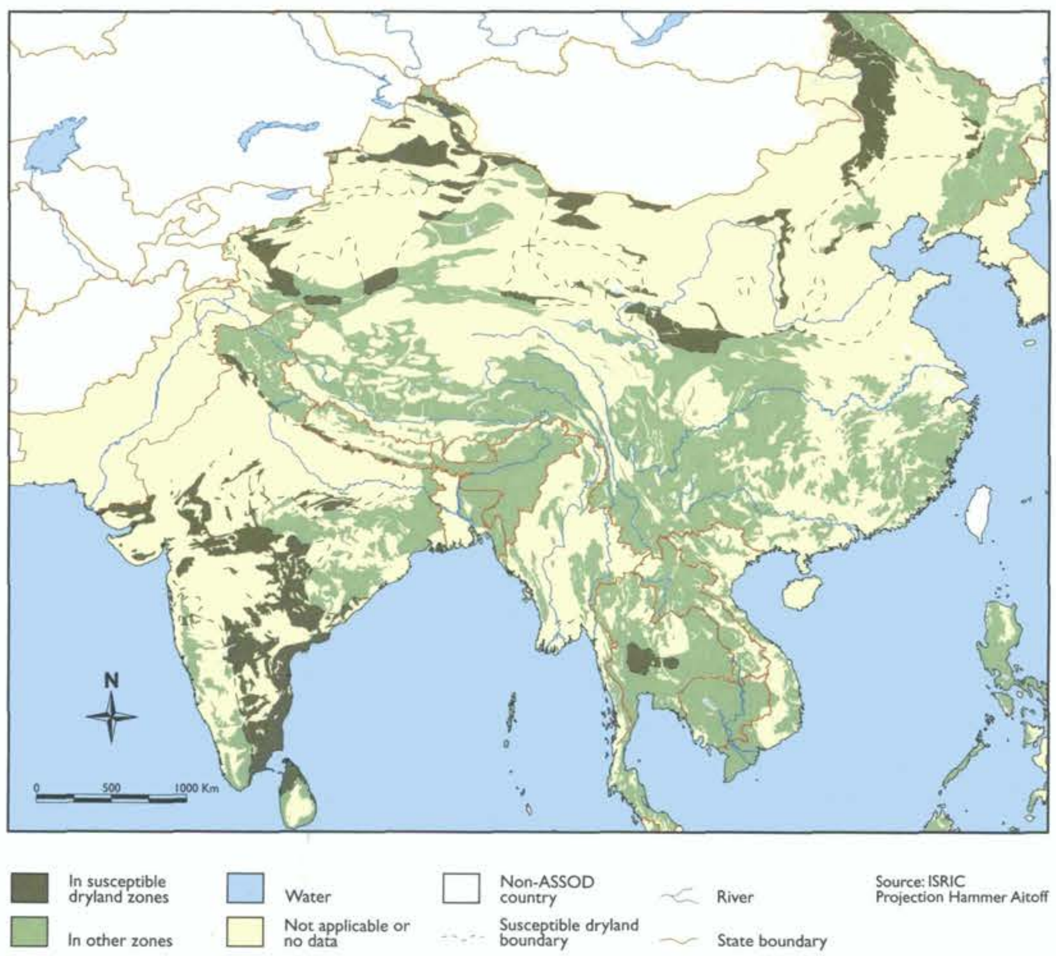
The clearance of natural forest cover is the main cause of secondary salinization across the largest parts of Thailand's Khorat Plateau, although reservoir construction, salt making and irrigation have also played their part (Arunin 1987). The replacement of deep-rooted trees with upland crops such as cassava and kenaf has increased the natural recharge of aquifers, resulting in rising groundwater levels and saline seeps on lower slopes and valley floors. The loss of protective natural vegetation by deforestation also contributes to water erosion in the dryland parts of the Khorat Plateau, while further west deforestation and agricultural practices (the reason for tree-felling) combine to cause the widespread decrease in soil fertility.

Locally serious water erosion has been the main result of land clearance for subsistence agriculture in the drylands of lowland Nepal. A large influx of population from the hills and mountains has felled vast tracts of the cool tropical forest on the *Terai* alluvial plain since the 1960s when malaria was eradicated from the area (Tamang 1995). Elsewhere on the subcontinent, deforestation is confined to areas of India south of the Gangetic Plain.

Map 3.11 Areas affected by overexploitation of vegetation



Map 3.12 Areas affected by deforestation



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Desertification Studies and Issues 4

Section 4 explores three specific desertification issues. First, the uses of *databases and monitoring* at national or regional scales are examined, second, *links with other environmental issues* are considered, and third, *social and economic aspects of desertification* are explored. These three themes are not meant to represent full coverage of the issues concerned, but provide case studies that are indicative of the patterns, links and possible outcomes that make desertification such a difficult but vital issue to tackle effectively. A number of organisations and individuals have conducted the research and surveys that lie behind the pieces in Section 4. Consequently, the delimitation of dryland boundaries is not always coincident with those applied in the GLASOD and ASSOD surveys, though they are broadly agreeable.

Databases and monitoring contains six different examples of approaches that utilise databases to assess different aspects of desertification. The first shows how the methodology used in GLASOD and ASSOD can be developed for use at the regional scale, with the heavily degraded Aral Sea basin the focus of an intensive and complex monitoring programme. People are obviously a core component of desertification, but gaining meaningful data on population distributions in drylands is surprisingly difficult. The second piece explains a new UNDP/UNSO database that allows the mapping of population distributions and densities at global and African scales.

The next two pieces both refer to studies in Kenya. First is an example of using existing national data sources to try and achieve a inexpensive but rigorous methodology that is appropriate to developing world situations. In combining existing national statistics on climate, population distributions, land use and other variables, the limitations and problems as well as the benefits of such an approach are highlighted. The second shows how a UNEP-sponsored programme, the World Soils and Terrain Digital Database (SOTER), can create a database for assessing the risk of erosion; in this case, water erosion in Kenya. From 1993–95 a soils and terrain database was compiled using a methodology developed by the International Soil Reference and Information Centre (ISRIC). This has been used as one of the main components in a national land degradation mapping programme.

Another UNEP-financed project, the World Overview of Conservation Approaches and Technologies (WOCAT) is exemplified in the next piece. WOCAT aims to collect and analyse data on the conservation techniques that are available for mitigation of soil erosion. The next piece is an example of the use of digital mapping to try to provide high quality data that can contribute to resolving conflicts, including those concerned with water access, in the Middle East. The final piece in *databases and monitoring* is a summary of the approaches and findings of the European Commision-funded Mediterranean Desertification and Land Use (MEDALUS) project, which is now in its third phase. This international project has been trying to understand the interactions between biotic, soil and climatic aspects of desertification in southern Europe as well as its land use and social dimensions.

Links with environmental issues contains four pieces that show the complex interactions between desertification and other major environmental issues. Biodiversity is considered first, as the loss of species diversity in drylands is a further negative outcome of desertification. The next two pieces outline important outcomes of vegetation loss in drylands. First, drylands contain plants that have important human uses, and the reduction or removal of such plants can have serious implications both for the communities that currently utilise these species and humankind as a whole which is losing potential benefits. Second, dryland biomass represents a significant part of the total global atmospheric carbon sink. By degrading drylands, particularly rangelands and areas of natural dry woodland, opportunities to sequester enhanced atmospheric carbon concentrations could be lost. The final piece considers the significance of salinization in drylands as a contribution to productive land loss.

The first piece in *social and economic aspects of desertification* concerns the North American Dust Bowl, charting the complex relationships that have existed between land use, climate, and economic and social pressures over the last 150 years. This shows both how 'the Dust Bowl' was not just confined to the 1930s, and how other forms of desertification are threatening land use in the region today. External economic pressures are identified as major factors that led, and continue to lead, to desertification.

The next two pieces examine relationships between social behaviour and land degradation. In many parts of the world poverty amongst rural populations is regarded as a major direct and indirect cause of excessive land use pressures and/or unsustainable land use practices. Pressures on the land, and pressures caused by climatic factors, particularly drought, can lead to migration which, depending on local circumstances, can enhance or relieve desertification pressures. The issue of migration is explored in the context of desertification in Mexico.

The three final pieces concern successful attempts to resolve desertifcation problems at different scales and in different social

Desertification Assessment and Mapping in the Aral Sea Region

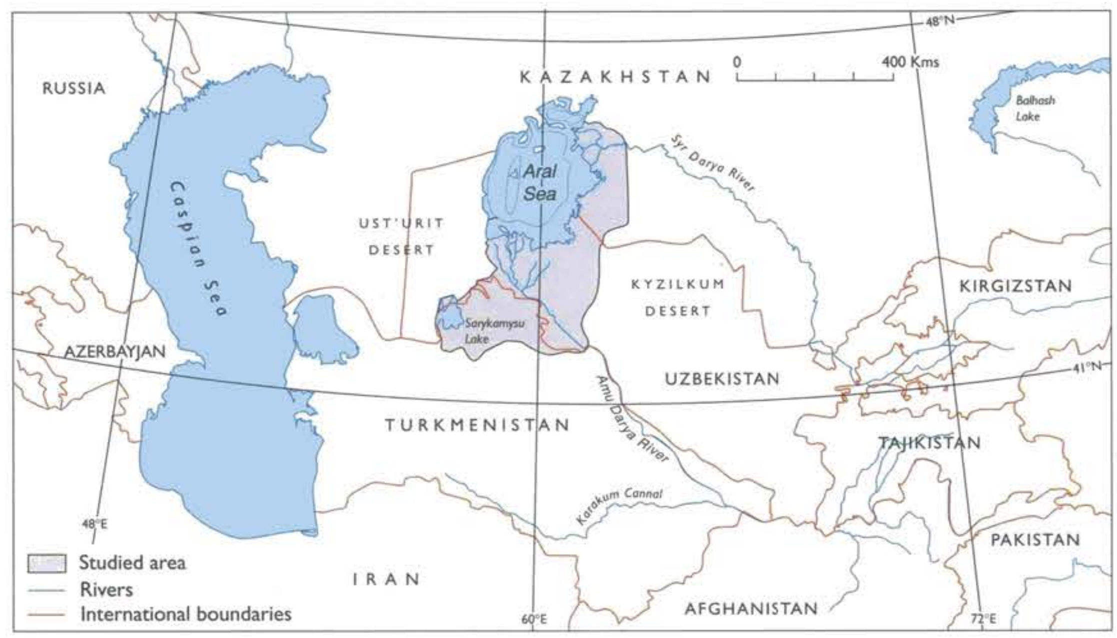
Introduction

The demise of the Aral Sea and its drainage basin is one of the late twentieth century's foremost examples of human-induced environmental degradation (Micklin 1988, UNEP 1992, Glazovsky 1995, UNDP 1995). Most of the problems in the area can be traced to the decision of the government of the former USSR to expand the irrigated area in Central Asia, in order to ensure self-sufficiency in certain crops, particularly cotton (Glantz *et al.* 1993). Intensive development of irrigated agriculture since the 1950s in the then Central Asian republics of the USSR resulted in a dramatic decline in the volume of water entering the sea from its two major tributaries: the Amu Darya and Syr Darya rivers. In 1960, the Aral Sea was the fourth largest lake in the world, but since that time it has lost two-thirds of its volume, its surface area has been halved, its water level has dropped by more than 16 m and its salinity has increased to reach that of sea water.

These dramatic changes have had far-reaching effects, both on-site and off-site. The Aral Sea's fishing industry has completely ceased to function as most of its native organisms have died out (Williams and Aladin 1991), and the delta areas of the Amu Darya and Syr Darya rivers have been transformed due to the lack of water, affecting flora, fauna and soils (Khakimov 1989, Novikova and Zaletayev 1985). The diversion of river water has also resulted in the widespread lowering of groundwater levels (Khakimov 1989). The receding sea has had local effects on climate (Molosnova *et al.* 1987), and the exposed sea bed has become a major source of aerosols contaminating surrounding agricultural land and adversely affecting human health. The irrigated cropland itself has been subject to problems of salinization and waterlogging due to poor management with consequent negative effects on crop yields (Smith 1992). Drainage water from these schemes is characterised by high salinity and is contaminated by high concentrations of fertilizer and pesticide residues which have been linked to poor human health in the region (Glazovsky 1995). The development of irrigation has not been the only cause of desertification in the Aral Sea basin, however. Widespread grazing pressures, technological developments such as construction and drilling activities, and excessive exploitation of woody shrubs for fuelwood have also contributed to the degradation of the region (UNEPCOM 1994).

As part of the international effort to develop an action plan for the conservation of the Aral Sea and its basin, a project was set up to assess the desertification problems of the region. An important first step in this process

Map 4.1 Location of the Aral Sea study area



Map 4.2 Types of territories

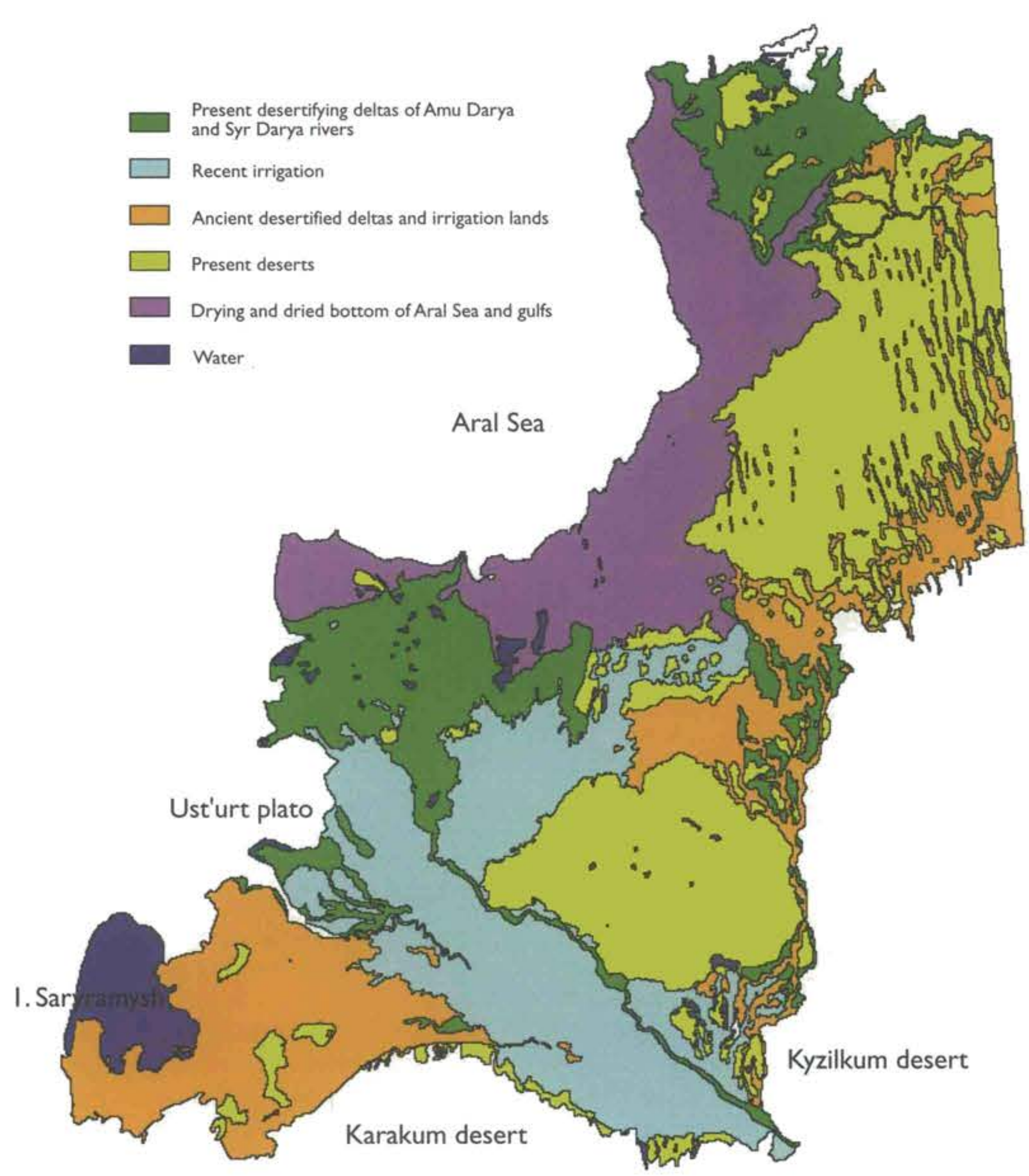


Table 4.1 The 16 main desertification causal chains identified in the Aral Sea study area

Causal chain (cc)	*Code*	*Occurrence of cc in study area*	*Dominance of cc in study area*
Irrigation development → Overregulation of river flow → Water-seizure affects downstream areas	Ir-OR-WS	23.8%	20.7%
Irrigation development → Overregulation of river flow → Drainage water escapes to pollute rivers	Ir-OR-DWE	1.2%	0.2%
Irrigation development → Overregulation of river flow → Secondary changes in natural conditions (e.g. deflation from dried lake bed)	Ir-OR-Sec	18.9%	4.7%
Irrigation development → Watering of irrigated lands → Drainage water escape to depressions	Ir-Wa-DWE	16.8%	3.6%
Irrigation development → Watering of irrigated lands → Water infiltration and increase of groundwater levels	Ir-Wa-Filt	20.8%	18.0%
Irrigation development → Watering of irrigated lands and building of irrigation facilities → Fast drying of territories as a result of large-scale deep drainage systems	Ir-Wa-Dr	9.4%	1.0%
Irrigation development → Watering of irrigated lands → Secondary changes in natural conditions (e.g. enhanced erosion from cropland affected by salinization)	Ir-Wa -Sec	2.7%	0.7%
Irrigation development → Flooding → Inundation (i.e. waterlogging)	Ir-Fl-In	3.3%	0.7%
Irrigation development → Flooding → Secondary changes in natural conditions (e.g. rising water-table in adjacent areas)	Ir-Fl-Sec	0.4%	Does not dominate in any polygon
Pastoralism → Overgrazing → Soil and vegetation degradation	Pas-OG-SV	56.3%	45.4%
Pastoralism → Insufficient grazing → Degradation of vegetation	Pas-IG-V	0.4%	Does not dominate in any polygon
Pastoralism → Secondary changes in natural conditions (e.g. enhanced deflation)	Pas-Sec	32.3%	Does not dominate in any polygon
Technological development → Drilling activities → Soil and vegetation degradation	Tech-DA-SV	3.8%	Does not dominate in any polygon
Technological development → Building of linear structures (e.g. roads, canals) → Soil and vegetation degradation	Tech-BLS-SV	41.5%	0.02%
Technological development → Building of linear structures (roads, canals etc.) → Secondary changes in natural conditions	Tech-BLS-Sec	15.6%	Does not dominate in any polygon
Tree and shrub cutting (e.g. domestic fuelwood consumption)	TShC	39.7%	0.2%

was a GIS-based mapping project focusing on the southern and eastern Aral Sea region and conducted over the period 1991–95. The project was led by groups from Moscow State University and the Russian Academy of Sciences.

The project builds on the methodology developed under the GLASOD and ASSOD schemes, showing how the approach can be refined to provide much greater detail when applied to a smaller study area. While GLASOD and ASSOD focused on soil degradation, the Aral Sea study examines degradation of three separate landscape components – soil, vegetation and landforms – and combines this information to assess the overall state of desertification. The five causes of desertification used in GLASOD and ASSOD have been developed to produce a series of causal chains, and an attempt has been made to identify trends in desertification.

Methodology

The study area of 126 580 km² (Map 4.1) was divided into nearly 1500 mapping polygons based on the interpretation of 1975–89 remote sensing images in the visible and near-infrared wavebands. Cosmos imagery at 1:500 000 and 1:1 000 000, and images at 1:2 400 000 and 1:1 200 000 from the Meteor satellite were supplemented with photography from the Salut and Mir space stations. Analyses of these images were supported by field studies in key plots for ground-truthing. Verification of polygon boundaries was also made by comparison with existing maps of relief, surface lithology, groundwater level and mineralisation, soils, and vegetation. This base map, compiled at a scale of 1:500 000, was then digitised so that thematic maps could be incorporated into a GIS.

Types of territory

The first level of mapping comprised basic maps of relief, surface lithology, soils, ground waters and vegetation, characteristics which combined to give five main types of territory in the study area (see Map 4.2):

1. the present deltas of the Amu Darya and Syr Darya rivers which occupy 15.2% of the study area;
2. lands currently under irrigation (18.0% of the study area);
3. ancient deltas formed when the present rivers flowed along different courses (18.5%);
4. present deserts (29.7%);
5. recently exposed Aral Sea bed (15.1%).

In addition to these five basic terrain types, land presently covered by water (rivers and lakes, but excluding the Aral Sea itself) occupies 3.5% of the study area.

Causes of desertification

As a precursor to mapping the causes of desertification in the area, degradation was examined according to links with human activities, the spatial scale of degradation impacts, and the primary and secondary impacts of desertification.

Using these criteria, four human activities were identified as the main initiators of desertification in the study area: the development of irrigation systems; poorly managed pastoralism; technological developments, and the overexploitation of vegetation for domestic use. Using each of these four activities as a starting point, 16 main chains of causes and consequences of desertification were identified. These causal chains are outlined in Table 4.1. The areas where these chains are the dominant influence on desertification are also shown in Table 4.1 (column 4), and these areas are shown in Map 4.3.

The dominant causal chain may not be the only one affecting any particular mapping unit, however. Column 3 in Table 4.1 shows the total proportion of the study area affected by each causal chain, and Maps 4.4 a–d depict these total areas for a selection of four causal chains. Analysis of the data shown in Table 4.1 and Map 4.3 indicates that just 1.3% of the study area remains unaffected by desertification.

Desertification trends

The main desertification causal chains outlined in Table 4.1 drive sets of dynamic processes in the areas affected. For each mapping unit, desertification trends were identified for each of three basic landscape components: soils, vegetation and landforms. This involved both the assessment of current degradation for each landscape component and a prediction of the final desertified state if the processes affecting these components continue to operate.

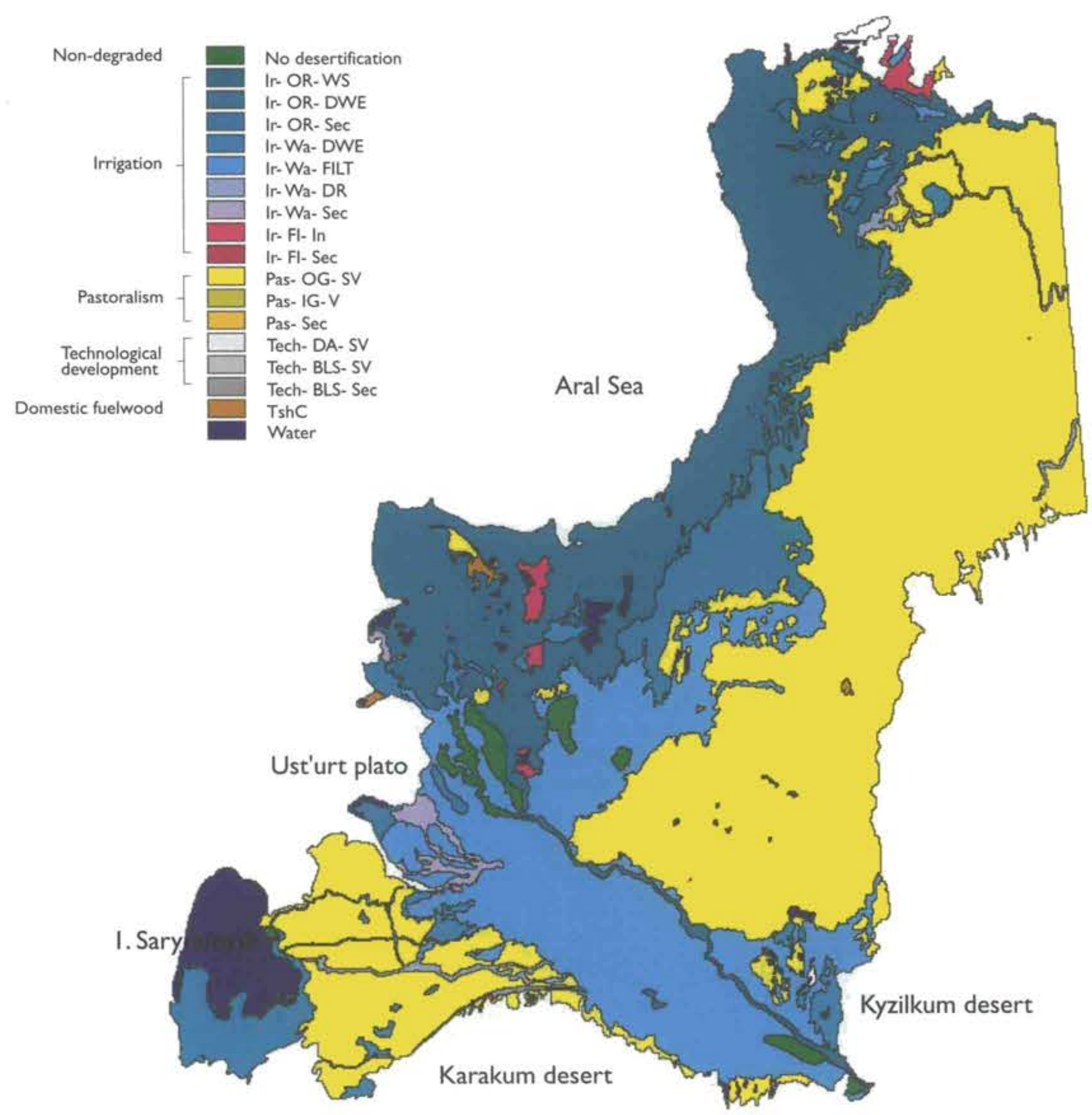
This approach was achieved by adopting a nested hierarchy of desertification classes, types and subtypes. These are shown in Table 4.2 and outlined in more detail below.

Desertification class: two classes of desertification, were identified: 'Abiogenic' landscapes in which vegetation and soil are so severely degraded that they are virtually absent, and "Biogenic' landscapes in which the original soil and vegetation have been transformed towards more desert-like ecosystems.

These desertification classes do not represent the current status of mapping units and are not shown on the maps directly. They are indicative of the direction of change taking place under present processes. Each class, therefore, represents an ultimate quazi-equilibrium desertification state.

Desertification type: the two desertification classes are further subdivided into five types of desertification. These types indicate the form of desertification taking place towards the ultimate desertification class. As with desertification class, the types of desertification do not reflect the present state of mapping units so much as the trends of their changes under present conditions.

Map 4.3 Main causes of desertification (see Table 4.1 for explanation of key)



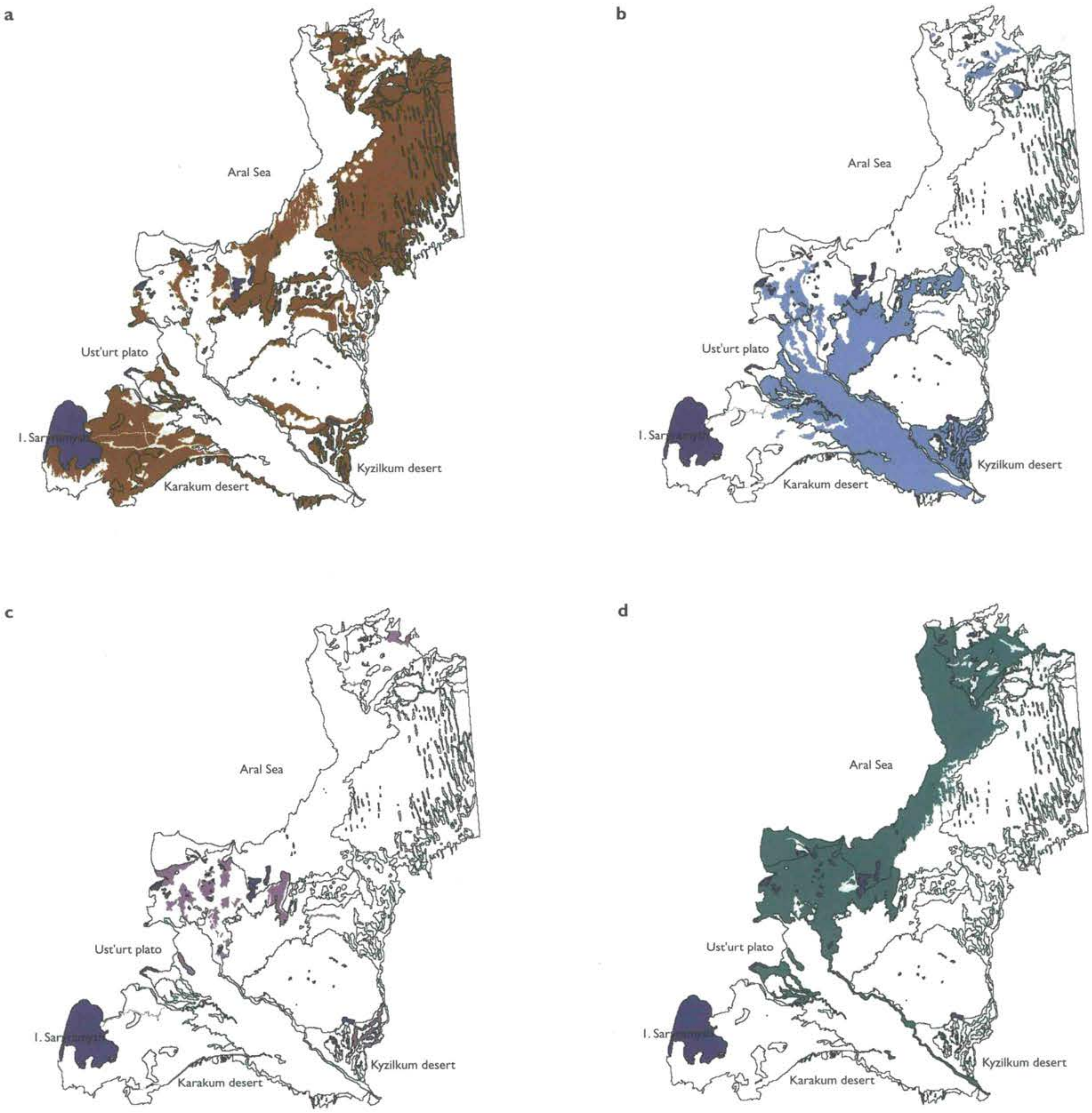
The five types of desertification identified are briefly described below.

- *Biogenic takyrization (Btk)* – the development of landscapes towards the formation of desert takyr plains with xerophytic vegetation on well-developed takyrs and takyr-like soils.
- *Biogenic sandization (Bsd)* – the development of landscapes towards the formation of sand desert with fixed sands and psammophytic vegetation on well-developed sand desert soils.
- *Abiogenic salinization (As)* – the development of landscapes towards the formation of solonchaks without high plants.
- *Abiogenic sandization (Asd)* – the development of landscapes towards the formation of sand desert with shifting sands.
- *Abiogenic degression ('badlandization') (Ab)* – the formation of abiogenic landscapes of clay and detritus deserts as a result of local and mainly anthropogenic impacts on soils (e.g. compaction around drilling rigs, road-building) and/or vegetation (e.g. fires, felling, water erosion, shovelling of topsoil).

Desertification subtype: the types of desertification are in turn subdivided into 13 subtypes to indicate more specifically the processes actually occurring and resulting in degradation of soils, vegetation and landforms in mapping units. The 13 subtypes of desertification identified are briefly described below.

- *Posthalomorphic biogenic takyrization (Btk-ps)* – desiccation and takyr formation on hydromorphic solonchacks and highly salinized soils on interfluve depressions, lake depressions and newly-exposed dried sea bed. This subtype occurs on solonchaks.

Map 4.4 Causes of desertification: (a) clearance of trees and shrubs (TShC); (b) rising groundwater levels (Ir-Wa-Filt); (c) waterlogging (Ir-Fl-In); (d) downstream effects of irrigation development (Ir-OR-WS)



- *Posthydromorphic biogenic takyrization (Btk-ph)* – desiccation and takyr formation on irrigated soils with little or no salt content. This subtype occurs on meadows or bogs without solonchaks or highly salinized soils with halophytic vegetation.
- *Posthalomorphic biogenic sandization (Bsd-ps)* – desiccation and desalinization (e.g. by deflation) of sand and loamy sand solonchaks and salinized soils of river bars and newly exposed dried sea bed. This subtype occurs on solonchaks.
- *Posthydromorphic biogenic sandization (Bsd-ph)* – desiccation of sands and loamy sands, with little or no salt content, on river bars. This subtype occurs on meadows or bogs without solonchaks or highly salinized soils with halophytic vegetation.
- *Posttakyric biogenic sandization (Bsd-pt)* – formation of sand sheets and dunes on takyr and takyr-like surfaces. This subtype occurs on takyrs.
- *Posthydromorphic abiogenic salinization (As-ph)* – salinization of abandoned

irrigated areas, interfluve depressions, lake depressions and newly exposed dried sea bed as a result of desiccation and the increase in salt content of surface waters and high groundwater levels. This subtype occurs on meadows or bogs.

- *Anthropogenic abiogenic salinization (As-an)* – this subtype of desertification usually takes place in currently irrigated areas, along their borders or drainage canals. This subtype is a direct function of poor land use management and can develop on any type of landscape.
- *Posthydromorphic abiogenic sandization (Asd-ph)* – formation of mobile sands by the desiccation of river bars, exacerbated by intensive grazing, exploitation of vegetation for domestic uses and fire. This subtype occurs on meadows and tugai forests.
- *Posttakyric abiogenic sandization (Asd-pt)* – formation of mobile sands on takyrs or takyr-like surfaces, exacerbated by intensive grazing, exploitation of vegetation for domestic uses, fire, drilling and off-road vehicles. This subtype occurs on posthalomorphic or posthydromorphic takyrs.
- *Posthalomorphic abiogenic sandization (Asd-ps)* – formation of mobile sands on solonchaks and/or following the loss saline binding agents in a soil, exacerbated by intensive grazing, exploitation of vegetation for domestic uses, fire, drilling and off-road vehicles. This subtype occurs on solonchaks.
- *Postautomorphic abiogenic sandization (Asd-pa)* – remobilisation of naturally stabilised sand dunes and sheets as a result of intensive grazing, exploitation of vegetation for domestic uses, fire, drilling and off-road vehicles.
- *Abiogenic degression ['badlandization'] of clay deserts (Ab-cd)* – this subtype of desertification usually takes place on relatively fine sediments such as alluvial fans and other slope-foot sediment accumulations such as colluvium and, more rarely, on takyr or takyr-like surfaces. This subtype usually develops in areas of scant vegetation cover and can be accelerated by poor land-use practices.
- *Abiogenic degression ['badlandization'] of detritus deserts (Ab-gd)* – this subtype of desertification usually occurs in coarse sediments such as gravels, grus and coarse-grained sands. This subtype usually develops in areas of scant vegetation cover and can be accelerated by poor land-use practices.

The percentages of the study area affected by each desertification type and subtype are indicated in Table 4.2 and Map 4.5 shows the distribution of these areas.

Table 4.2 Dominating trends of desertification in the Aral Sea study area

Class of desertification	*Type of desertification*	*Subtype of desertification*	*Occurrence (% study area affected)*
Biogenic			27.2
	takyrization		20.7
		posthalomorphic	12.0
		posthydromorphic	8.7
	sandization		6.5
		posthalomorphic	0.6
		posthydromorphic	4.5
		posttakyric	1.4
Abiogenic			67.8
	salinization		36.7
		posthydromorphic	16.9
		anthropogenic	19.8
	sandization		28.1
		posthydromorphic	0.7
		posttakyric	11.2
		posthalomorphic	2.3
		postautomorphic	13.9
	'badlandization'		3.0
		of clay deserts	0.1
		of detritus deserts	2.9
No desertification			1.5
Water surface			3.5

Note: some of the terms used in this table, and in the text, are translations from the Russian and have been retained since they have no direct equivalents in western scientific literature. The term 'sandization', the formation of shifting dunes and sand sheets, is widely used in the Russian and Chinese literature.

Map 4.5 Main types of desertification

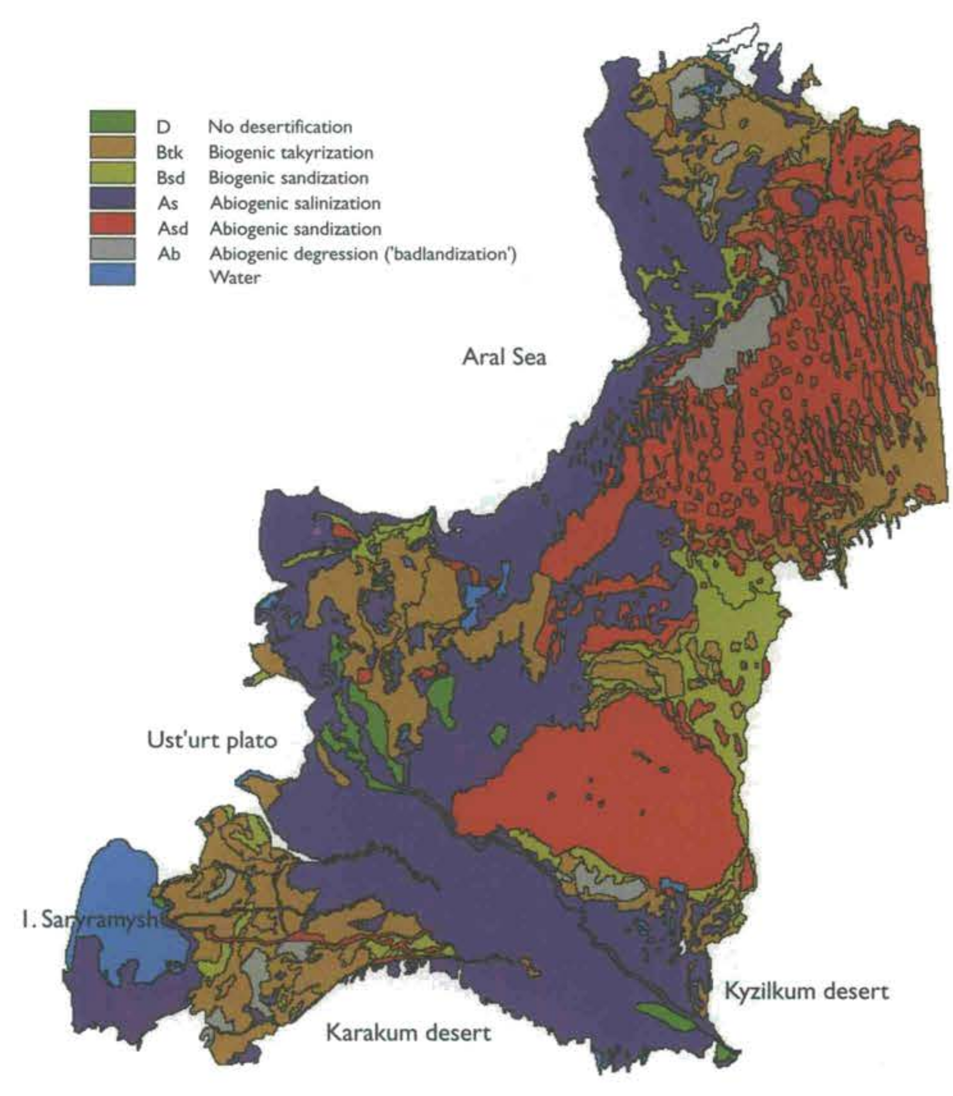
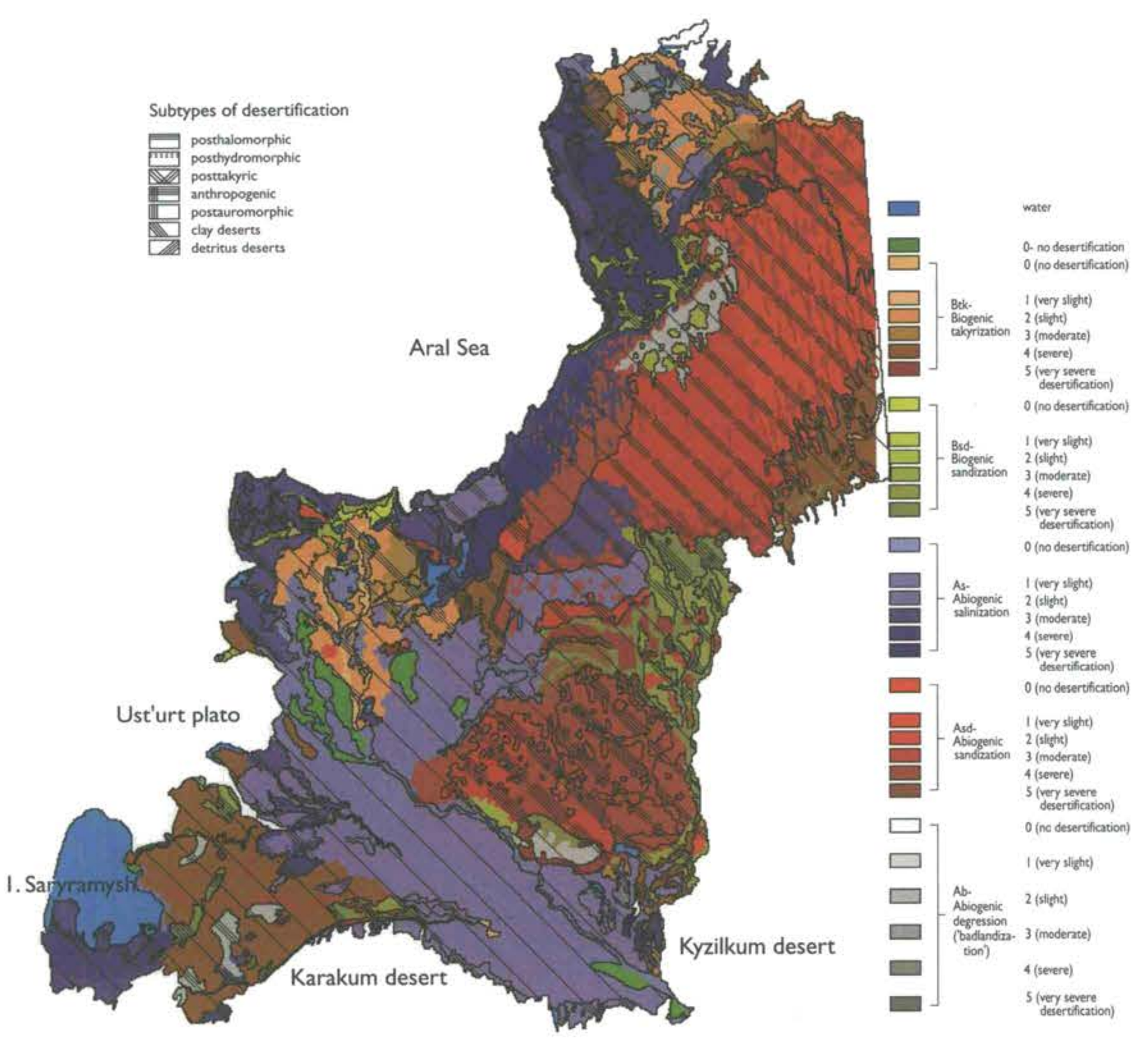


Table 4.3 Parameters indicating the degree of desertification for soils and vegetation for the posthydromorphic biogenic takyrization desertification subtype

	Degree of desertification					
	0 (no desertification)	*1 (very slight)*	*2 (slight)*	*3 (moderate)*	*4 (severe)*	*5 (very severe)*
Soils	Bog and meadow soils	Bog and meadow soils undergoing takyrization	Takyrized bog and meadow soils	Takyr-like bog soils Takyr-like meadow soils	Takyr-like soils	Takyr-like soils Takyrs
Vegetation	Communities of glicophilic hydrophyta *Phragmites australis, Calamagrostis dubia, Salix* sp., *Typha* sp.	Communities of woody, shrub and grass mezoxerophyta *Populus* sp., *Elaeagnus turcomanica, Elaeagnus angustifolia, Halimodendron halodendron, Tamarix* sp., *Alhagi pseudalhagi*	Communities of mezoxerophilic shrubs and grasses, *Tamarix* sp., *Alhagi pseudalhagi, Salsola foliosa, Capparis spinosa*	*on fine-textured soils* Poor communities of haloxerophylic semishrubs and mezohaloxerophylic shrubs, *Anabasis aphylla, Tamarix hispida*	Communities of woody and semishrub haloxerophyta, *Anabasis aphylla, Haloxylon aphyllum*	Communities of semishrub xerophyta, *Artemisia terrae-albae, Salsola orientalis*
				on light-textured soils Communities of woody haloxerophyta and shrub mezohaloxerophyta, *Haloxylon aphyllum, Tamarix* sp.	Communities of woody haloxerophyta and semishrub xerophyta, *Haloxylon aphyllum, Salsola orientalis*	as above

Map 4.6 Degree of desertification of soils by type



Degree of desertification

For each set of desertification processes (the desertification subtypes) a set of field parameters was drawn up to assess the degree of desertification in any particular mapping unit. In each case, separate parameters were derived for soils, vegetation and landforms using a scale of degree that ranges from 0 (no desertification) to 5 (very severe desertification). An example of the parameters indicating the degree of desertification for soils and vegetation for the posthydromorphic biogenic takyrization subtype is shown in Table 4.3.

Map 4.6 shows the degree of soil degradation according to the five main desertification types. Analysis of this map, and the equivalent map for vegetation, yields the proportions of the study area affected shown in Table 4.4.

Analysis of the equivalent map for landforms indicates that 26.6% of the study area is not prone to the processes of relief degradation, 7.2% is characterised by very slight degradation of relief, 9.6% experiences slight degradation, 15.3% moderate degradation, 36.2% severe degradation, and 1.7% very severe degradation of relief.

Diversity and state of desertification

The diversity and state of desertification are based on the degree matrices for subtypes like

Table 4.4 Degrees of soil and vegetation degradation in the Aral Sea study area (by dominating types of desertification)

Desertification type	*Degree of soil degradation*	*Occurrence (% study area affected)*	*Degree of vegetation degradation*	*Occurrence (% study area affected)*
Biogenic takyrization	very slight	0.4	very slight	1.2
	slight	5.0	slight	6.0
	moderate	2.0	moderate	1.8
	severe	10.5	severe	2.9
	very severe	2.8	very severe	8.4
Biogenic sandization	very slight	0.2	very slight	0.2
	slight	0.0	slight	0.3
	moderate	1.4	moderate	1.0
	severe	2.0	severe	0.3
	very severe	3.0	very severe	4.7
Abiogenic salinization	very slight	5.3	very slight	0.7
	slight	15.6	slight	7.7
	moderate	7.9	moderate	3.2
	severe	3.8	severe	4.3
	very severe	4.0	very severe	2.7
Abiogenic sandization	very slight	negl.	very slight	3.1
	slight	7.7	slight	12.9
	moderate	8.4	moderate	8.0
	severe	11.8	severe	3.3
	very severe	0.2	very severe	0.8
Abiogenic 'badlandization'	very slight	negl.	very slight	negl.
	slight	2.0	slight	1.6
	moderate	0.7	moderate	1.1
	severe	0.3	severe	0.3
	very severe	negl.	very severe	negl.
No desertification		1.5		19.6
Water surface*		3.5		3.5

* includes cultivated land

Table 4.5 Diversities of soil and vegetation degradation in the Aral Sea study area

Diversity of soil degradation	*Occurrence (% study area affected)*	*Diversity of vegetation degradation*	*Occurrence (% study area affected)*
No diversity or extremely low	8.4	No diversity or extremely low	35.8 *
Very low	44.6	Very low	41.3
Low	35.1	Low	18.6
Moderate	10.3	Moderate	3.0
High	1.5	High	1.0
Very high	0.1	Very high	0.3
Water surface	3.5	Water surface	3.5

* includes cultivated land

the one shown in Table 4.3 for soils and vegetation affected by posthydromorphic biogenic takyrization.

The diversity of desertification is an indication of the spatial variability of desertification in the landscape. It is based on evidence of the heterogeneity of degrees found within a mapping polygon: if the unit contains areas experiencing desertification to a very slight, moderate and very severe degree, the diversity is higher than in a unit where all land is degraded to the same degree. In other words, a high measure of heterogeneity indicates a high diversity, and a low measure of heterogeneity indicates a low diversity. Hence, in a mapping unit affected by posthydromorphic biogenic takyrization (see Table 4.3), the diversity of soil degradation is categorised as very high if the unit contains soils degraded to all the different degrees of desertification, from bog and meadow soils to takyrs. Conversely, if the mapping unit has less heterogeneity in terms of degree of desertification (e.g. only takyr-like soils and takyrs are present, or only meadow soils and meadow takyrizing soils) then the diversity of soil degradation in this unit is low. The diversities hence are determined as follows:

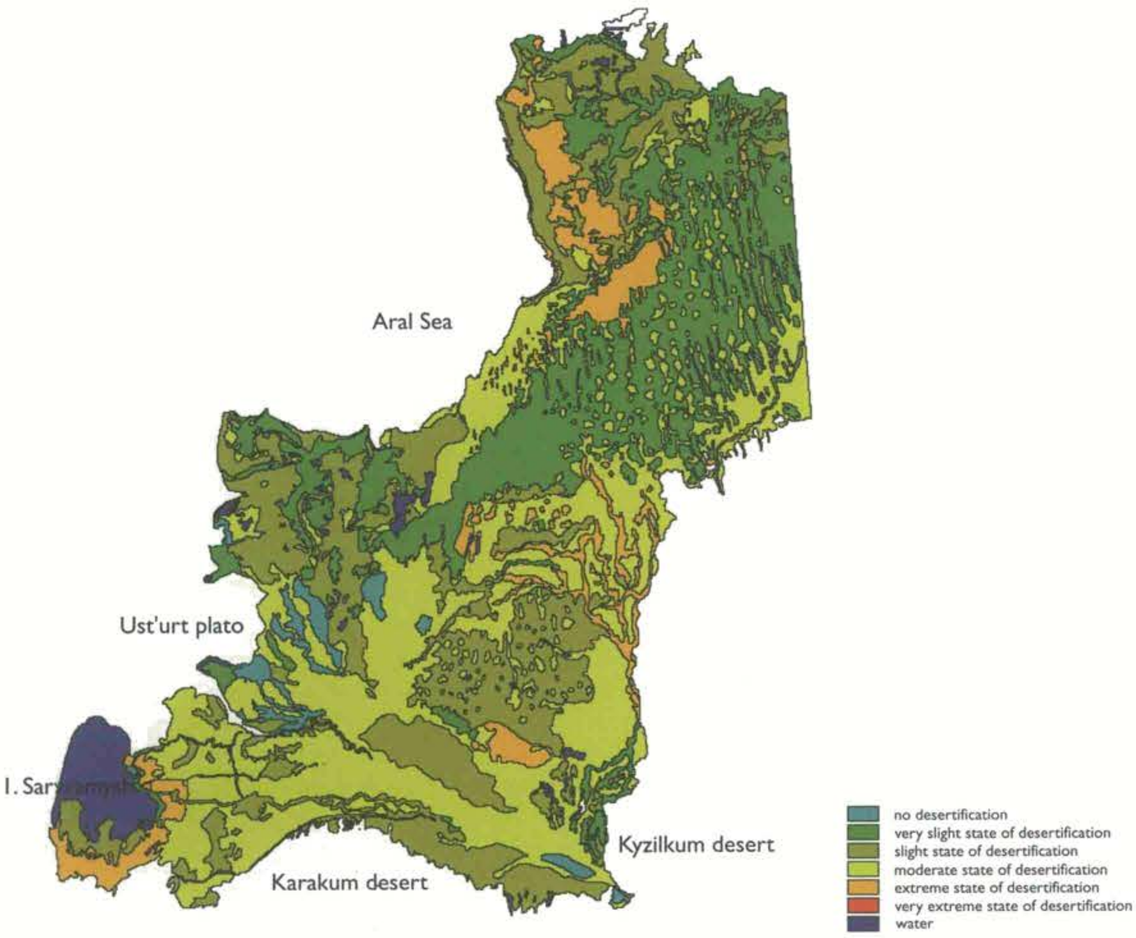
- very high degradation diversity – evidence of six degrees of degradation present;
- high degradation diversity – evidence of five degrees of degradation present;
- moderate degradation diversity – evidence of four degrees of degradation present;
- low degradation diversity – evidence of three degrees of degradation present;
- very low degradation diversity – evidence of two degrees of degradation present;
- no degradation diversity, or extremely low degradation diversity – only one degree of degradation present.

Table 4.5 summarises information on desertification diversities for soil and vegetation in the study area. The measure of diversity within a mapping unit is often closely related to the rate at which desertification is occurring. If, for example, the desertification diversity of vegetation in a unit is low, indicating that all vegetation is degraded to the same degree, then it is probably fair to assume that the rate of vegetation degradation is low. If, by contrast, vegetation in a mapping unit is degraded to a wide range of degrees (a high diversity) then this probably reflects the fact that desertification is occurring rapidly (i.e. vegetation in some parts of the polygon has been degraded to a severe degree, but the same processes have only recently begun to degrade vegetation elsewhere in the polygon).

It is worth reiterating the difference between the measures of degree and diversity. A mapping unit with an extremely low diversity of degradation may have any degree of desertification: at one extreme, it could be an area that has been very severely desertified, but it might be an area that has suffered no desertification. Hence the diversity of desertification should be considered in conjunction with information on the degree.

While the degree and diversity of desertification are measures applied to the separate landscape components of soil, vegetation and landforms, state is a measure that combines information for the three landscape elements to give an overall measure of the desertification status of a mapping unit. This is achieved by comparing the degrees of desertification for each of the three landscape components.

Map 4.7 State of desertification



Although any mapping unit may contain areas degraded to different degrees (the basis of the diversity), an average degree of degradation for each landscape component within each unit can be calculated. Calculating the divergence of these average degrees gives a measure of state. Hence, for example, if the average degrees of degradation for soils, vegetation and landforms are all very severe, the area can be said to be in a very extreme state of desertification. Conversely, if the average degrees of degradation for soils, vegetation and landforms diverge widely (e.g. vegetation is very severely degraded, but soils and landforms are only very slightly degraded), the state is low. In simple terms, the more extreme the state of desertification in an area, the harder the task of rehabilitation.

The logic behind this approach, a particularly strong point of the assessment scheme, reflects the fact that soils, vegetation and landforms are transformed at different rates in response to desertification processes. As an example, vegetation responds quickly to excessive grazing of an area (its coverage is depleted), but any erosion that subsequently degrades soils and alters the area's geomorphology will take place some time after the animals have moved on.

The following scale is used to calculate the overall state of a mapping unit:

- very extreme state of desertification – the difference between degrees of desertification of vegetation, soils and landforms is 0;
- extreme state of desertification – the difference is 1;
- moderate state of desertification – the difference is 2;
- slight state of desertification – the difference is 3;
- very slight state of desertification – the difference is not less than 4.

As a general rule, areas with high diversities of desertification exhibit slight states, indicating that one or two landscape elements are much less degraded than another. The opportunities for rehabilitation of such areas is relatively good, since some landscape components are still in the early stages of degradation. Areas at the extreme end of the state scale tend to be those most desertified, where all components of the landscape have been degraded to a severe degree (and hence display relatively low diversities). These are areas where desertification processes are likely to have been operating for longer, since soil and landform changes tend to be slower than the degradation of vegetation.

The one difficulty with this scheme comes in areas with very little or no desertification. Using the scale above, an area with very slight degrees of degradation for all three landscape units, and therefore a low diversity, would also be categorised as being in a very extreme state. Hence, for areas where desertification has not reached severe or very severe degrees, another scale has been devised. This complementary scale is still based on the principle of correspondence for degrees of desertification for the three landscape components, but it uses an additional factor: the principle of homogeneity in terms of the type of desertification that affects the area. Hence, for mapping units where no degree of degradation is severe or very severe, state is calculated according to the following scale:

- very extreme state of desertification – only one type of desertification affects the area and the difference between degrees of desertification of vegetation, soils and relief is 0;
- extreme state of desertification – only one type of desertification affects the area and the difference between degrees is 1;
- moderate state of desertification – more than one type of desertification affects the area (usually not more than two related types) and for each type the difference between degrees of desertification of vegetation, soils and landforms does not exceed 1;
- slight state of desertification – more than one type of desertification affects the area but two categories are recognised: a) where not more than two characteristically combined types of desertification (e.g. Btk-As) are identifed, and the difference between degrees of desertification of vegetation, soils and landforms for either of them exceeds 1; or b) where more than two types of desertification are identified, and the difference between degrees of desertification of vegetation, soils and landforms for any of them does not exceed 1;
- very slight state of desertification – three or more types of desertification affect the area and the difference between degrees of desertification of vegetation, soils and landforms exceeds 1 for any of them.

As Map 4.7 indicates, there are no parts of the Aral Sea study area at this scale of analysis where desertification has reached a very extreme state. Small parts of the area (8.2% in total) are in an extreme state, but more than one-third of the territory (36.7%) is in a moderate state of desertification. About half of the whole area is in a slight or very slight state of desertification (26.4% and 23.7% respectively), while 1.5% of the study area is not prone to desertification.

Adapted from original text by G. Kust.

Population and Desertification

Introduction

Desertification is a consequence of people's efforts to use natural resources in environments that are highly susceptible to natural variability (Thomas and Middleton 1994). A full understanding of desertification, therefore, must incorporate an examination of issues that relate to the human populations of susceptible drylands. If solutions are to be found for desertification problems, attention must focus on human actions and human–environment relationships. To this end, the Convention to Combat Desertification commits its parties to the development and implementation of programmes for dryland management by focusing on the needs of affected populations. At the global level an important first step towards achieving this goal is to gain a reliable picture of the distribution of populations in areas experiencing desertification. When combined with detailed local studies of social issues that contribute to desertification and the positive actions taken by NGOs, local communities and other parties, this will provide a valuable hierarchical input to addressing the desertification problem at scales ranging from global to individual communities.

To this end UNDP/UNSO has undertaken a detailed global assessment of the distribution and density of human populations in susceptible drylands. The assignment has been undertaken in conjunction with the World Resources Institute, Washington DC, and has included both a global and a detailed African assessment.

Expressing population characteristics

At its simplest level, human population can be expressed in terms of absolute numbers. From an environmental viewpoint, however, it is also valuable to consider population pressure, a complex concept that is related directly or indirectly to the environment through the impact of land-use practices. A simple measure of population pressure is population density. This is by no means a full expression of population pressure, since it takes no account of land use, socio-economic factors or the carrying capacity of the land, which in itself varies through time in response to changes in background environmental conditions. Furthermore, pressure can be exerted on the land in an area by people residing elsewhere, for example by the need to grow food to support urban populations. None the less, population density is a measurable spatial demographic factor, being the ratio of number of people per unit area, and can therefore be evaluated against environmental factors in order to assess human pressures thereon. If the population density is greater than the density supportable by the area's resources, degradation is likely to take place. In this section the UNDP/UNSO (1997) population assessment is explained and presented for global and African drylands, along with a consideration of factors that cause dryland peoples to exert pressure on the environment.

Population in global drylands: data sources and methods

To determine population densities in susceptible drylands it is necessary to combine both data that determine the extent and distribution of dryland climatic zones and data on population distributions. In order to do this at the global level, the climate surface data used to delimit aridity zones in this atlas (see pages 2–7) are used together with the population surface produced by the US National Center for Geographic Information and Analysis (NCGIA). The latter uses census data collected at first and second subnational administrative levels, for approximately 15 000 administrative units world wide (Tobler *et al.* 1995). Population counts were extrapolated to 1994 in order to standardise the year of assessment. Aridity surface, population distribution data and country boundary information were handled and analysed in raster form using an ARC/INFO GIS system. The assessment of population densities in Africa used by UNEP (1992) included some higher resolution population data sets that relate to third order administrative units. These were not incorporated in this assessment because of their restricted spatial coverage. The current approach therefore maximises the spatial consistency of the population data.

Population in global susceptible drylands

The data in Table 4.6 show the total human population in each aridity zone for each continent. Data for hyperarid areas are included for although they fall outside the susceptible drylands, they do support significant human populations in some parts of the world, albeit that they are usually heavily reliant upon resources imported from outside the hyperarid zone. This is especially the case in Africa, where almost 10% of the population live in the driest areas, in South America, where several urban centres are located in the Atacama Desert, and in parts of the Arabian Peninsula and central Asia. If the African data are further broken down they reveal that in North Africa, 38% of the population lives in hyperarid areas. This figure includes the Nile Valley, where a special situation is created whereby large numbers of people are

Table 4.6 Population of the world's susceptible drylands, % figures refer to % of total population of the respective continent

	Hyperarid		*Arid*		*Semiarid*		*Dry subhumid*	
Africa	58 175 624	(9%)	41 366 493	(6%)	117 573 208	(18%)	109 038 742	(16%)
Asia	29 506 286	(1%)	161 556 598	(5%)	500 695 158	(15%)	657 899 360	(19%)
Australasia	0	(0%)	275 039	(1%)	1 352 905	(5%)	5 318 077	(19%)
Europe	0	(0%)	628 630	(<1%)	28 811 499	(5%)	115 146 764	(21%)
S. America	3 877 706	(1%)	6 330 581	(2%)	46 851 867	(16%)	33 777 496	(12%)
N. America	508 971	(<1%)	12 750 631	(3%)	53 900 339	(13%)	24 342 220	(6%)

Source: UNDP/UNSO 1997

Table 4.7 Population density (per km²) in drylands

	Hyperarid	*Arid*	*Semiarid*	*Dry subhumid*
Africa	8.6	8.1	22.9	40.6
Asia	10.6	25.9	72.2	186.5
Australasia	0	0.1	0.4	2.4
Europe	0	5.7	27.4	62.8
N. America	16.4	15.6	12.9	2.9
S. America	15.1	14.2	17.7	16.3

Source: UNDP/UNSO 1997

Table 4.8 Population totals and densities in African susceptible drylands, (data must be read in conjunction with the notes where indicated)

Country	*Area[1] of susceptible drylands (km²)*	*Area of susceptible drylands expressed as a % of all land available for agriculture and pastoralism (exc. hyperarid areas)*	*Population in susceptible drylands*	*% total popn in susceptible drylands*	*Population density (per km²)*
North Africa	**1 093 231**		**67 834 225**		62.0
Algeria	409 967	99	24 087 447	89	58.8
Cape Verde no data available					
Egypt[2]	45 745	100	55 649 910	10	123.5
Libya	175 752	100	3 453 550	68	19.7
Morocco	348 806	100	26 424 421	98	75.8
Tunisia	112 961	100	8 218 897	98	72.8
Sahel	**6 368 567**		**145 850 242**		22.9
Benin	63 522	55	1 322 524	39	20.8
Burkina Faso	259 877	95	9 892 060	97	38.1
Cameroon	77 542	17	3 116 641	23	40.2
Central African Republic	71 904	12	271 285	9	3.8
Chad	682 233	93	5 173 582	84	7.6
Ethiopia	925 372	74	23 556 288	42	25.5
Gambia	10 756	100	849 187	100	79.0
Ghana	64 934	27	3 074 410	25	47.3
Guinea	6961	3	89 757	1	12.9
Kenya	505 043	87	10 001 987	39	19.8
Mauritania	317 287	100	1 586 557	73	5.0
Niger	559 233	100	8 578 145	98	15.3
Nigeria	467 708	51	36 138 781	38	77.3
Senegal	174 622	88	6 967 980	91	39.9
Somalia[3]	544 019	100	8 760 129	92	16.1
Sudan	1 568 211	92	22 745 446	82	14.5
Togo	8604	15	943 818	24	109.7
Uganda	60 739	25	2 781 665	15	45.8
Southern Africa	**3 181 615**		**59 567 151**		18.7
Angola	462 159	37	3 620 021	31	7.8
Botswana	583 658	100	1 503 114	100	25.8
Lesotho[4]	16 473	55	1 158 728	60	70.3
Mozambique[3]	411 368	52	9 140 986	54	22.2
Namibia	903 294	100	1 487 081	98	1.6
South Africa[3]	1 128 699	93	31 711 110	79	28.1
Swaziland[3]	13 499	78	632 428	74	46.8
Zambia	326 804	48	4 641 177	53	14.2
Zimbabwe[3]	381 478	99	10 795 641	97	28.3
Other	**710 660**		**24 948 538**		35.1
Burundi	1370	5	235 690	4	172.0
Congo DR	65 305	3	743 991	2	11.4
Madagascar no data available					
Malawi	62 726	52	5 920 910	57	94.4
Rwanda	4800	19	808 201	10	168.4
Tanzania	576 459	61	17 239 746	61	29.9

Data from Corbett *et al.* (1996), UNDP/UNSO (1997)

Notes:
1 The climate surface used for this Africa population survey differs from that used elsewhere in the atlas and results in different area estimates of susceptible drylands.
2 Eygpt is an unusual case, since 90% of the population (nearly 49 million people) live in the hyperarid Nile Valley. Thus while only 10% of the population live in susceptible dryland areas, 90% live in a situation where they are dependent on the waters of the River Nile and not on precipitation falling directly on the land area in which they live, grow crops and keep animals. Similarly, a (smaller) proportion of the population of the Sudan are also dependent directly on Nile waters in a hyperarid area.
3 The area of susceptible drylands in this survey is overestimated relative to that calculated according to the climatic surface used elsewhere in this atlas.
4 Lesotho has no susceptible drylands according to the climatic surface used elsewhere in this atlas.

supported in this otherwise hyperarid area by the perennial River Nile.

The importance of the susceptible drylands in supporting a significant component of the world's population is clear from Table 4.6. Indeed, in Africa, 40% of the total population, or nearly 268 million people, live in these areas prone to drought and susceptible to desertification. Equivalent figures for Asia are 1320 million people, (39%) and for South America 30%. These figures clearly indicate why desertification is regarded as a problem of great significance.

Table 4.7 shows the population data expressed as densities (population per km^2). The range of average population densities is considerable both between different aridity zones and within the same zone in different continents. Asia has the highest population densities in all three susceptible dryland zones while Australia has relatively low overall population densities in all its susceptible dryland zones, when compared to the other continents. Despite the limited number of people living in Australia's arid areas, the GLASOD survey demonstrated that significant soil degradation problems exist. This point shows that population numbers alone cannot always be used to explain the occurrence of land degradation, or to predict where future degradation problems will occur: in the interior of Australia, for example, it is relatively extensive pastoral activities that are often associated with soil erosion problems (Pickup and Stafford Smith 1993).

The greatest population densities occur in semiarid and dry subhumid areas. This is to be expected since in terms of the susceptible drylands as a whole they offer the greatest potential for human activities, particularly agriculture. As populations and land use pressures grow in these areas, both people and the environment become more prone to the impacts of climatic variability (Glantz 1994). The high population densities in the dry subhumid and semiarid zones of many continents mean that when environmental pressures increase, for example during times of drought, there exists less opportunity for flexibility in human actions. Care, however, needs to be taken when making generalisations for population data, for while population totals and densities may serve as gross indicators of desertification risk, misleading pictures may emerge if taken alone (UNDP/UNSO 1997). There are, for example, no clear relationships between population density and erosion (Blaikie 1985, Warren *et al.* 1996). On the one hand, more people consume more resources and therefore may create more degrading processes, on the other, more people can make a greater contribution to conservation measures. There is a growing number of examples from around the world that detail situations where rising population numbers and increasing population densities can contribute to declining or low rates of degradation (e.g. Mortimore 1989, Mainguet 1990, Tiffen *et al.* 1994) and rural population decline can result in enhanced soil erosion (e.g. Millington 1989, Thomas and Middleton 1994). In such situations it is necessary to exercise care in seeking the reasons behind them, in order that the full range of socio-economic factors, such as changes in land tenure and local governance, as well as the demographic issues, which can be incorporated in analyses that seek explanations (Tiffen *et al.* 1994).

A number of reasons explain why the relationships between population and degradation are so complex. One factor that is certainly important is the range of socio-economic triggers, or 'root causes' that can lead to land degradation (Table 4.8). As UNDP/UNSO (1997) note, political and socio-economic factors are often the main drivers of land degradation. One issue noted as particularly important in recent decades is increased rates of migration caused by war, drought and famine (Westing 1994). Migrations can lead to rapid changes in population densities at local and regional scales, and where this occurs significant environmental pressures can ensue.

Another issue is that population growth rates are important in determining the rate at which pressures are exerted on the land. Some dryland countries have experienced dramatic population increases in the last 30 years (Figure 4.1), leading to rapidly growing demands for food that result in agricultural expansion and intensification. In the semiarid areas of Inner Mongolia for example, rapid population increases since the 1950s are believed to have made a marked contribution to enhanced land degradation (Takeuchi *et al.* 1995). An important consequence of increased pressures to produce more food is that a number of studies show how traditional systems of agriculture that incorporate fallow periods are declining as more land comes under permanent cultivation to feed rising populations (Bremen *et al.* 1990).

Drylands in both the developed and less developed countries now support many large urban centres (Cooke *et al.* 1982, Beaumont 1989). Urban centres not only have high population densities, but exert a range of direct and indirect impacts on the environment that contribute to desertification. Direct impacts include enhanced demands on water resources leading to groundwater depletion, demands for fuel which, in the developing world contribute significantly to fuelwood exploitation (see pages 48–49), the creation of waste products, and demands for food. Perhaps the most significant indirect factor is the attraction urban centres offer to rural populations in terms of employment opportunities (both real and imagined). Mortimore (1993) outlines how the displacement of poor rural peoples from the land for a variety of reasons makes them more dependent on off-farm income sources, and these are frequently sought in urban areas. In some countries this can contribute to a marked decline in the

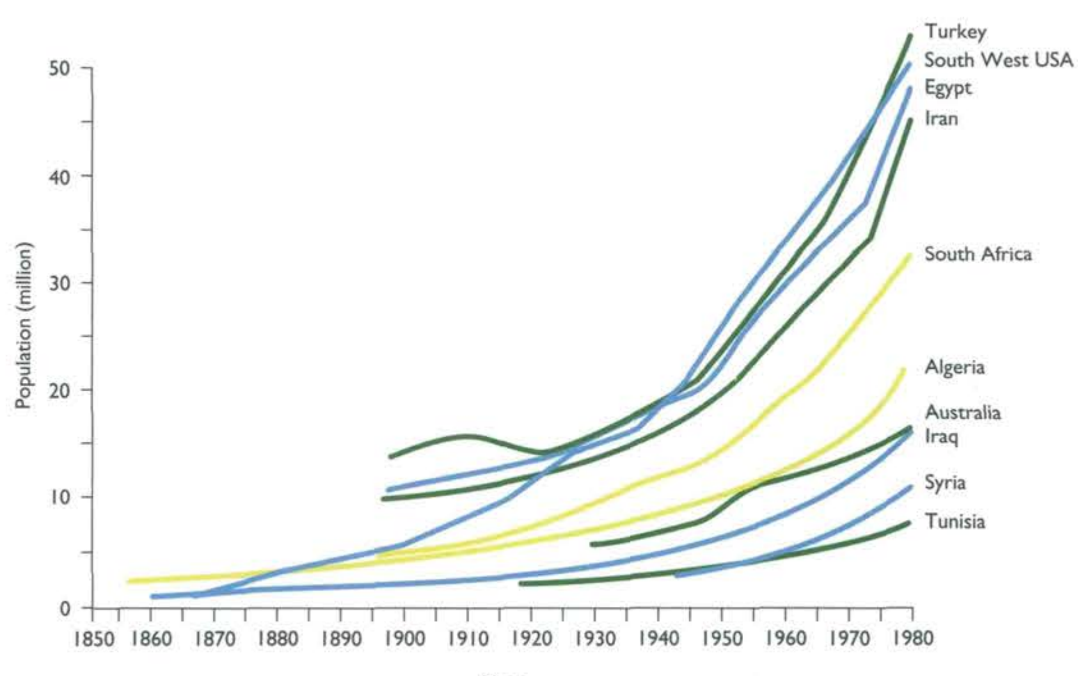


Figure 4.1 Population growth in selected countries

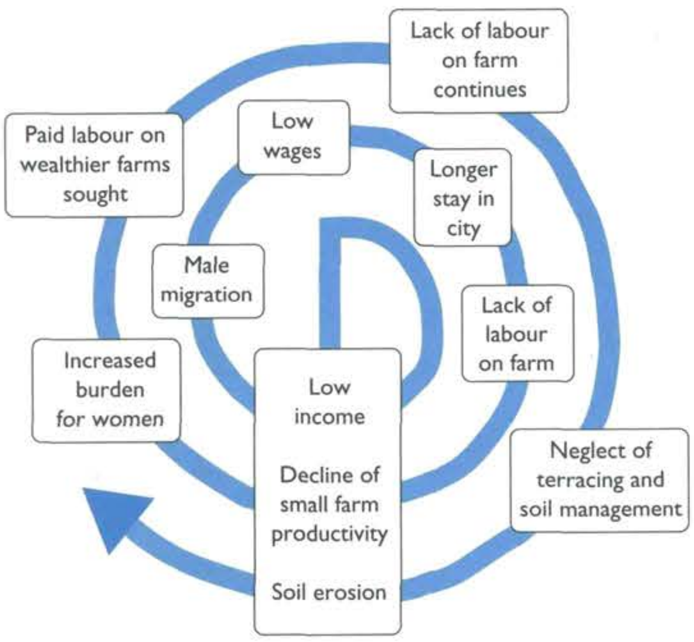


Figure 4.2 The implications of rural–urban migration for subsistence farming (after Millington *et al.* 1989)

agricultural labour force (Millington *et al.* 1989), which in turn can have marked and complex impacts on degradation and rural populations (Figure 4.2). One study notes how in parts of the Sudan many families already have more land than labour available to cultivate it (Myers *et al.* 1995).

Population in African drylands: data sources and methods

The assessment of population densities in Africa's susceptible drylands by UNDP/UNSO (1997) utilises a slightly different approach both to that used in the global assessment above, and the African assessment in UNEP (1992). UNDP/UNSO's (1997) assessment aims to provide information that is usable at the country level in Africa. Given the manner in which social and economic data are collected, the population data set (Tobler *et al.* 1995) is already available in an appropriate format. The climate surface data used in GLASOD, however, are not. As outlined in pages 2–7 the climate data were confined to the 1951–80 timeband for the purposes of standardising the determination of aridity zones, and also to permit inter-timeband comparisons of the extent of aridity to be made (Hulme and Marsh 1990). Such an approach has been deemed important for assessing the context in which land degradation occurs, and for building in the highly significant components of climatic variability and climatic change in any future assessments (e.g. Hulme 1996).

For practical reasons the same timeband approach is less suitable for country-by-country assessments however. This is because the density of climate stations contributing data for any particular timeband may be low for certain countries, especially those that are small (Corbett *et al.* 1996). Consequently the approach adopted by UNDP/UNSO (1997) in the African population density survey places emphasis on an enhanced spatial resolution of data for the determination of aridity zones at the country level, using the climate database of the International Centre for Research in Agroforestry (ICRAF) in Nairobi. A result is that the aridity zones used to express population densities are not exactly compatible with those used to determine soil degradation in the GLASOD survey. In some locations, particularly northern and southern Africa, some marked differences occur between the results of the two assessments in the areas ascribed to individual climate zones. Especially in some countries, the percentage land area ascribed as susceptible dryland is far greater than in the climate surface used in the previous sections of this atlas. For example, enhanced susceptible dryland areas appear particularly for Mozambique, Somalia, South Africa and Zimbabwe. Lesotho has susceptible drylands in the ICRAF climate surface but none in the main atlas climate surface. These differences are not surprising, since the different temporal dimensions of the surveys increases the likelihood of the extent of aridity zones being affected by the occurrence of climatic variability in drylands. The incorporation of very short time series of data for some of the additional climate stations in the ICRAF data means that longer-term trends, which average out the effects of drought (and rainfall-enhanced) periods, are missed out. Given the different bases and purposes of the surveys, however, it is important that neither is regarded as an assessment of the accuracy of the other. Both datasets possess accuracy in the context of their own criteria and uses. Overall the area of Africa delimited as susceptible drylands is very similar in the two analyses: 43% in the GLASOD survey and 45% in the UNDP/UNSO (1997) analysis.

Population densities and land degradation in African susceptible drylands

Although over 40% of Africa's population lives in susceptible drylands according to the UNEP (1992) assessment (see Table 4.6), Map 4.8 clearly shows that African population densities are generally greatest outside the susceptible drylands, with one major and notable exception. Some of the highest densities in Africa as a whole, in excess of 500 people/km^2, are found in parts the Nile Valley of Egypt because of its special life-supporting characteristics. More locally, dryland densities only exceed 125 people/km^2 in the vicinity of urban centres, for example around cities along the Mediterranean coast of North Africa, and in the Sahel at Bamako in Mali, Accra in Ghana, Dakar in Senegal, Porto Novo in Benin, Kano and Kaduna in Nigeria, Khartoum and Omdurman in the Sudan, Asmara in Eritrea and Dire Dawa in Ethiopia and Mogadishu in Somalia. Spaeth (1995) has reported explosive population growth around Niamey in Niger, at a rate of 10% per annum. The southern African susceptible drylands only support this density around Maputo in Mozambique.

On the whole susceptible drylands support only low population densities, and in many areas such as most of the western part of the southern African region this falls below 2.2 people/km^2. In looking for reasons for the general spatial trends in susceptible dryland population density, the most likely is water availability as controlled by climate and hydrology, for the broad patterning of density classes closely follows that of climatic zones.

Country analysis for African susceptible drylands

Table 4.8 shows the size of populations living in susceptible drylands in African countries according to the UNDP/UNSO (1997) assessment, together with population densities and the amount of productive land in these countries that is susceptible to desertification. For comparative purposes the division into North Africa, the Sahel and southern Africa, employed in the African section of this atlas, is retained, and Egypt, although strictly located in the hyperarid zone, is included within the susceptible drylands for the reasons noted above. These data are useful as they indicate the relative reliance of different countries on dryland areas to support people and to provide food. This is also effectively an indicator of the vulnerability of different countries to the hazard of desertification and the risk of drought.

It can be seen that 10 countries in Africa have their productive lands wholly placed in susceptible drylands, with a further five having over 90% of productive lands and a very high percentage of the population in these climatic zones. All the countries in North Africa fall into this category, which can be regarded as highly vulnerable. Six Sahelian states, Burkina Faso, Chad, Gambia, Mauritania, Niger and the Sudan have all or most of their populations and usable lands in dryland areas susceptible to degradation. In southern Africa, Botswana and Namibia have their peoples and lands dominated by dry conditions. These 13 countries have marked variations in population densities. The highest densities occur within the North African countries ranging from 123.5 people/km^2 in Egypt, to 19.7 in Libya. Algeria, Morocco and Tunisia have high densities and a number of degradation problems occurring in these countries have been previously highlighted. Namibia in southern Africa has the lowest population density at 1.6 people/km^2. It can also be seen from Table 4.8 that Togo, Rwanda and Burundi have small dryland areas which have high population densities. In fact the last two countries do not have any susceptible drylands in the time-bounded climate zones of the GLASOD survey. It might be expected that such areas, even if small, would be particularly vulnerable to degradation with such high rural population densities.

Population density and severity of degradation

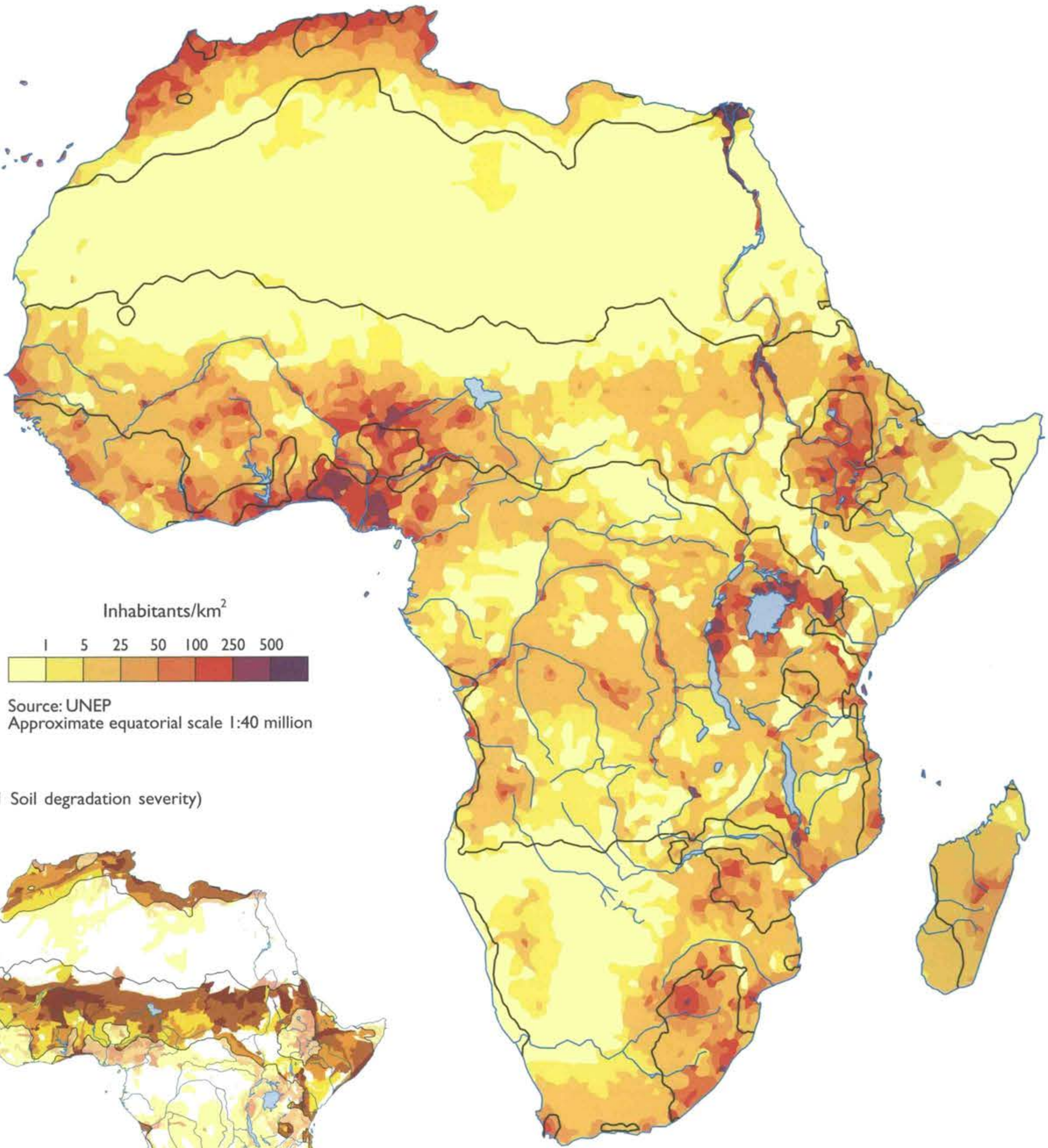
It has been indicated earlier in the discusion of global dryland populations that several authorities have noted there to be little relationship between the degree or severity of human-induced dryland degradation and population density. This view is borne out in the African context by analysis of the overall degradation severity and population density Maps 2.1 and 4.8, the former taken from Section 2 of the atlas. While these maps utilise different climatic surfaces, a comparison of overall patterns is feasible since dryland areas largely coincide. Locations where high degradation severity and high population densities coincide, such as in the Nile Valley and at some locations along the North African coast, can be identified. There are, however, situations where densities are high but degradation severity is not, for example around Kano in Nigeria (Mortimore 1989), and others where high or very high severity occurs under conditions of low densities, as in parts of South Africa and Somalia. The likely explanation for this is that population density is but one socio-economic factor that affects the propensity of a society to degrade the environment, with for example, the levels of technology available being another. A further complicating factor, preventing simple population–degradation relationships being deduced, is environmental variability. For example, similar population densities and land-use histories can lead to very different problems and severities of degradation if, for example, soil types are dissimilar, due to differences in vulnerability and resilience.

The information in Map 2.1 and data in Table 4.8 are useful for identifying overall spatial patterns of population in areas susceptible to degradation. As already noted, this type of information does not provide a full explanation of the human dimension of the desertification problem, nor a complete picture of human-environmental links. Two related points can illustrate this in the African context. Since world awareness was raised to the desertification issue in the 1970s, the most widely perceived human problems have occurred in countries within the Sahel region. There has been a complex interplay between natural environmental factors, particularly drought, and social issues, such that at the regional and sub-national level population densities and density differences bear little relation to the distribution of the most severe human tragedies and difficulties, even though areas of high population concentrations might be expected to have experienced the greatest problems. A complex interweaving of factors, such as land tenure systems, which vary markedly even within individual countries (Thébaud 1995), political and economic issues, including those that may influence the distribution of available food at times of stress (Olsson 1990), and differences in the spatial scales of decision making and environmental response to desertification (Lambin 1993), have all contributed to the array of social outcomes to desertification and drought in the Sahel. Second, Table 4.8 shows that the countries of North Africa have some of the highest population densities in dryland Africa, and while degradation problems do occur and are locally significant, they appear to be less severe in their impact on populations than in other regions. Again, many explanations may contribute to this, but one that cannot be overlooked is that high population densities may in part be due to specific, favourable, environmental circumstances. For example, in North Africa both sedentary and nomadic populations have been supported for centuries by oases that utilise groundwater aquifers (Allen 1984). Beaumont (1989) notes that these can develop a remarkable range of activities than can be both self-sustaining and supportive of population growth. In conclusion, these points all indicate the need for detailed considerations of the human dimension of degradation, beyond the scope of this atlas, to be carried out at a larger scale, more appropriate for investigation of their complex interactions and impacts on the environment.

Population density and degradation cause

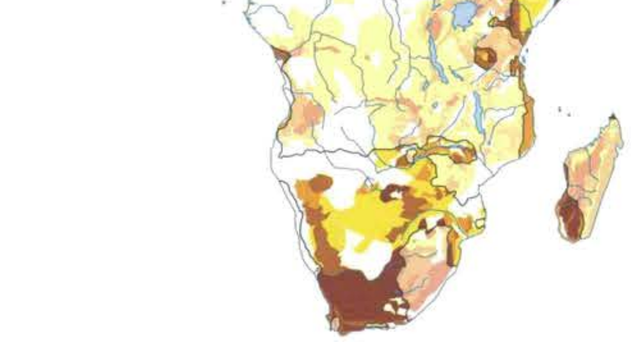
A closer relationship might be expected between population density and causal factors, especially in the case of domestic overexploitation caused by fuelwood collection, a process that is likely to be greatest where demand is highest, near locations of high population density. Again, however, comparison of Maps 2.1 and 4.8 shows no clear relationship, with the fuelwood problem being greatest in central and northern Sahel areas (Thomas and Middleton 1994), where population densities are low. Other factors must again be brought into consideration; in this case the fact that trees attain a lower density in such areas makes the environment more susceptible to soil degradation because tree removal can more readily reach critical proportions even when human population densities are relatively low.

Map 4.8 Estimated population densities



Source: UNEP
Approximate equatorial scale 1:40 million

(**Map 2.1** Soil degradation severity)



Developing the Capacity for National Desertification Assessment: A Kenyan Study

Introduction

Following successes in the application of a variety of indicators for assessment and mapping of land degradation at location and district levels in Kenya, a study was undertaken on the possibilities of applying these methodologies to develop a national database for land degradation assessment. A flexible national database has the potential to act as both a data source that can be used at a range of spatial scales by groups involved in degradation mitigation, and as a means of monitoring the occurrence of degradation. In developing countries, a key issue is the cost of developing such a database. The study, which was undertaken entirely by national experts over a period of 18 months using existing facilities in government departments, confirmed that similar assessments are feasible.

Land degradation in Kenya

Kenya's economy is primarily dependent on agriculture, though only about 20% of the land has adequate rainfall and soils suitable for stable agricultural production. The remaining 80% consists of susceptible drylands where the dominant traditional land use is nomadic pastoralism. Sedentary agriculture has increased significantly in recent decades, even in some of the driest areas of the country. The population of Kenya in 1989 was estimated at 26 million (Government of Kenya 1994) with a growth rate of about 3.5%. Although the rate of population growth is slowing, the country faces significant issues relating to the production of food, which are increasing pressures to further utilise and develop dryland areas. While there are some notable success stories in the simultaneous intensification of agricultural production and the reduction of soil degradation in dryland areas (Tiffen *et al.* 1994), problems of desertification or potential desertification are significant. The problem of desertification, including its root causes, social and policy implications, has not been accorded high priority, especially in many developing countries, in the face of other competing demands on the national resources. Creation of awareness and establishment of national programmes of action to combat desertification are therefore major objectives of the Convention to Combat Desertification (CCD).

GLASOD uses a set of indicators to assess actual desertification at the global scale (see pages 14–19). Other studies, at national and regional scales, have used various criteria for classifying land in terms of the severity of degradation *hazard*. Results of some of these studies, including a detailed pilot study of the Baringo District in Kenya (Grunblatt 1990), were included in the first edition of this atlas (Grunblatt, *et al.* 1992). One outcome of this Kenyan study has been the suggestion that the process of land degradation assessment and mapping could be simplified and hence more rapidly applied to cover the whole country by limiting the number of indicators and using remote sensing and other information already acquired by various national institutions. The approaches, methodologies and results of a follow-up study to assess the potential for the establishment of a national land degradation hazard assessment database in Kenya are presented below.

Data for land degradation assessment

Adriaanse (1993) has proposed a three-component framework for assessing the dynamic characteristics of land quality: pressure, state and response.

Pressures are being exerted on land resources due to natural (climatic) characteristics and/or human activities that may not be compatible with the nature of the resource base, which constitute the driving force for land degradation.

The *state* of the natural resource base has two components: the situation at a given time (the baseline), and the nature and rate of changes that may be taking place. Changes are driven by pressures and lead to the risks prevalent at a particular location.

Responses to the state or risk of environmental degradation take place at the farm, community and national levels. Responses are activities that may be taking place either to alleviate pressures or to adapt the state of the environment to the pressures exerted upon it. Responses may include abandonment of land if it is degraded beyond certain levels.

To utilise effectively this framework at national or regional levels, data are needed for key parameters, together with efficient systems of information storage and retrieval, and a clear understanding of cause/effect relationships amongst the parameters used in the assessment. In reality, in many developing countries the data that are necessary for the full implementation of this approach do not yet exist. The Pressure–State–Response framework is none the less useful for defining indicators and focusing the selection of methodologies and sources of data for a study such as the one conducted in Kenya. Since 'response' is mainly location or community specific, even if it is facilitated by national directives and policies, this study has focused on issues of pressure and state.

From the outset of the study it was recognised that the causes and processes of land degradation were so diverse and interrelated that no meaningful assessment could be achieved without the inputs of a wide range of disciplines. Furthermore, in a country such as Kenya whose economy is closely tied to land resources, there are many public institutions, both governmental and non-governmental, with mandates and responsibilities that cover various aspects of planning, research, training and management of natural resources. There are, therefore, sensitivities regarding access to national data sets, and the need to build capacity within Kenyan institutions for future updating of the data sets. A number of key institutions were therefore selected on the basis of the information they collect and their potential as users of land degradation indicators at various levels. The heads of these institutions were then fully involved in the design and implementation of the study, including selection of senior technical officers from their staff for participation in the joint, multidisciplinary study team.

In the absence of time series data that could be used to assess trends in degradation, the project focused mainly on development of **baseline** data sets on those aspects that could be adequately documented. Considering that land degradation is frequently a slow and insidious process, and the lack of continuity in national data sets, 'baseline' was defined as the average conditions indicated by data collected over a period of about 5 years up to the time of the study in 1993. In the case of climatological parameters, a period of 37 years, 1957–93, is used to define averages (Government of Kenya 1993).

For each of the parameters selected, available data were assembled, quality controlled, mapped, coded and digitised. Thematic data sets were established through the systematic evaluation and merging of existing sources of information and the production of a nationally integrated GIS database of land quality characteristics at a scale of 1:1 million. Usability was a key purpose of the study. The data sets were therefore generated so that they can be updated and upgraded to larger scales (district, location, catchment) as more information becomes available, used to store historical data and thus facilitate future evaluation of changes and their rates, and so that they can be accessed through computer networks.

Thematic data sets were combined with geographical information to form an integrated GIS database. Maps of land degradation indicators were produced, checked for consistency and adjusted as necessary. Levels of land degradation hazard were assigned to various land units by overlaying thematic maps. Only limited field visits were possible within the study period and these were used mainly to verify the validity of the systems used to classify vegetation types and their application for the assessment of fuelwood availability.

Components of the database

Climate

Climatological influences on land degradation may be direct (as in the case of extended droughts which may result in destruction of ground cover and exposure of the soil to severe wind erosion) or indirect. Moisture availability, through rainfall and the combined impact of precipitation and potential evapotranspiration, is the key climatological component related to degradation in this predominantly dry country. Moisture indicators fall into two categories: those related to frequency and probability of drought, and those related to rainfall erosivity. From the climatological data sets, maps of annual, monthly and seasonal rainfall variability and evapotranspiration were generated and used to indicate probabilities of prolonged droughts and other extreme rainfall events. Map 4.9 shows the aridity pattern in Kenya as indicated by the ratio of precipitation (P) to potential evapotranspiration (PET). For simplicity, but noting limitations in such an approach, the arid ($0.2 < P/PET < 0.5$), the semiarid ($0.5 < P/PET < 0.65$) and the humid/subhumid ($P/PET > 0.65$) regions were classified respectively as regions of severe, moderate and slight hazard of land degradation. The aridity index isolines shown in Map 4.9 can be used to demarcate agro-climatic zones reflecting differences in water availability.

Soil erosion indicators

An update of the Kenya Soil Survey 1:1 million scale digitised assessment of soil erosion hazard based on the Universal Soil Loss Equation was used to assess water erosion (Map 4.10) because of problems with the application of the Soil Water Erosion Assessment Programme (SWEAP) model developed at the International Soil Reference and Information Centre (ISRIC). Five per cent of the land area is classified as subject to very severe water erosion hazard, 26% as severe, 12% as moderate and 57% as slight. This assessment is subject to the assumptions and generalisations which have to be made regarding some of the parameters in the Universal Soil Loss Equation, especially those concerning land cover, slope length and soil management.

Wind erosion

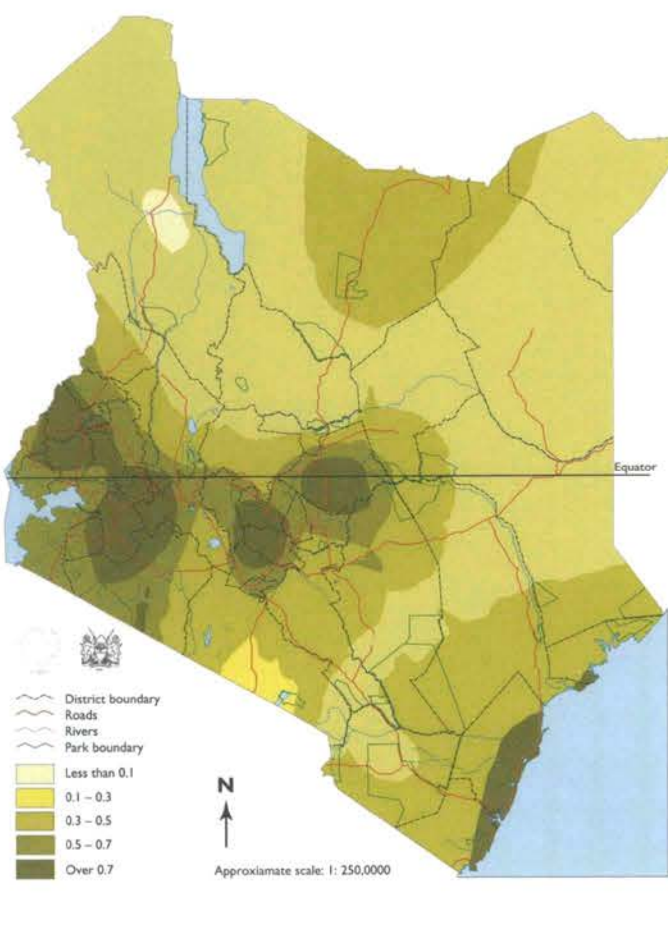
By combining wind erosivity indices derived from the modified Chepil equation of FAO (1979), with estimates of soil erodibility, aridity indices and vegetation cover, an assessment of the wind erosion hazard was made for the areas considered susceptible. Only eight meteorological stations possessed data suitable for the calculation of wind erosivity, so wind erosion hazard ratings could not be mapped. Of the eight stations, one had a very high wind erosion risk, six a high risk and one a moderate risk.

In addition to wind erosivity, the dust load in the atmosphere was also used as an indicator of wind erosion. Analysis of visibility observations from the eight stations showed that suspended dust is common at all of them, but Lodwar and Marsabit (Map 4.9) had the highest frequency of sand storms.

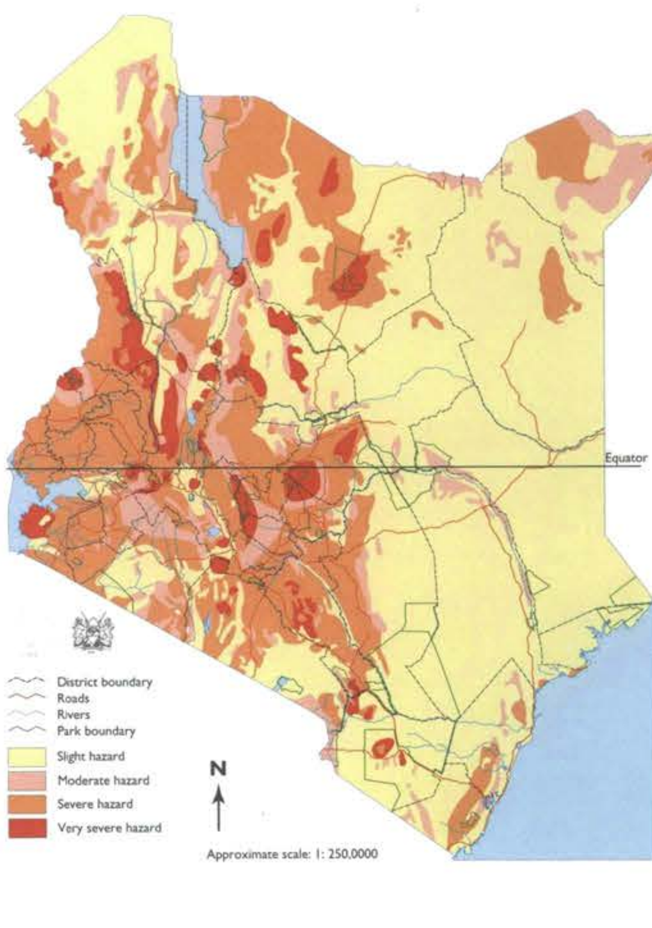
Vegetation indicators

The abundance, productivity, species composition and canopy structure of natural vegetation are valuable indicators of land quality and also of the extent and severity of land degradation. Undesirable chemical changes in the soil (e.g. acidity, salinity or alkalinity) are often indicated by disappearance of unadapted plant species and build up of species that are more tolerant to such conditions. Replacement of shallow-rooted grasses and shrubs by deep-rooted drought tolerant trees and shrubs may indicate loss of topsoil or serious loss of water-holding capacity due to erosion.

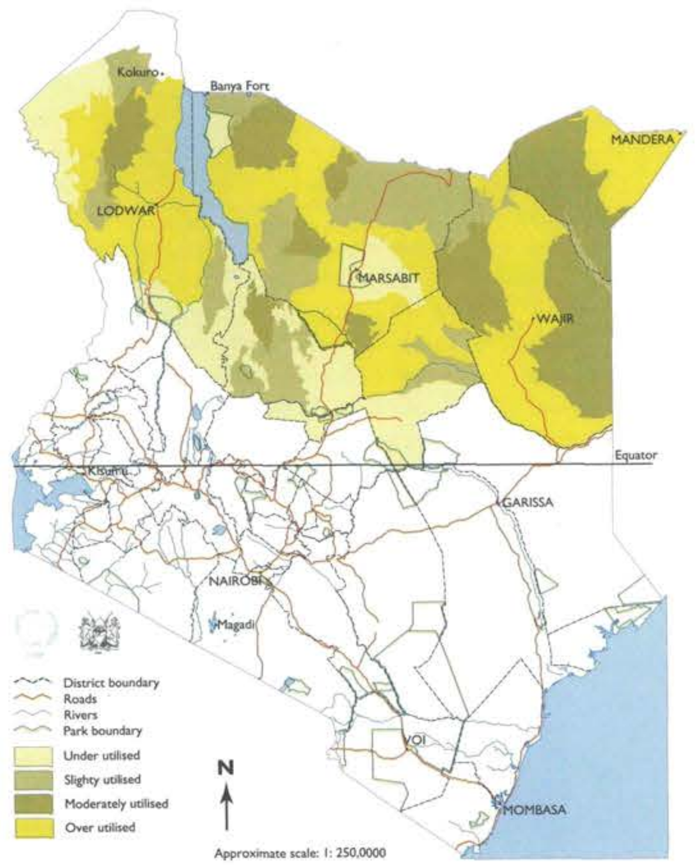
Map 4.9 Aridity index (P/PET) isolines for Kenya



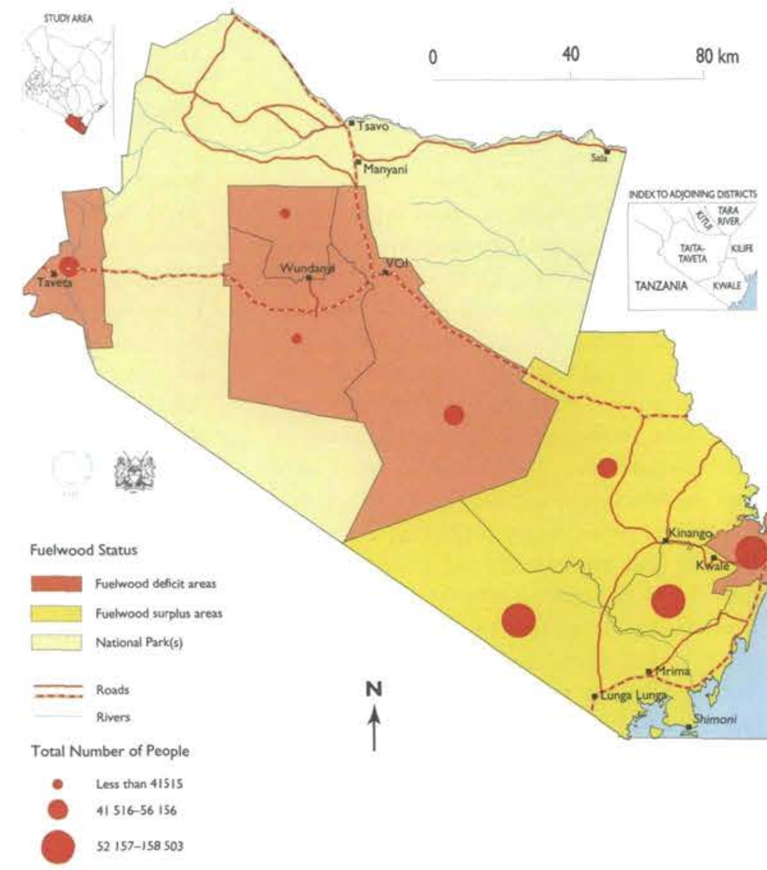
Map 4.10 Water erosion hazards in Kenya based on the Universal Soil Loss Equation



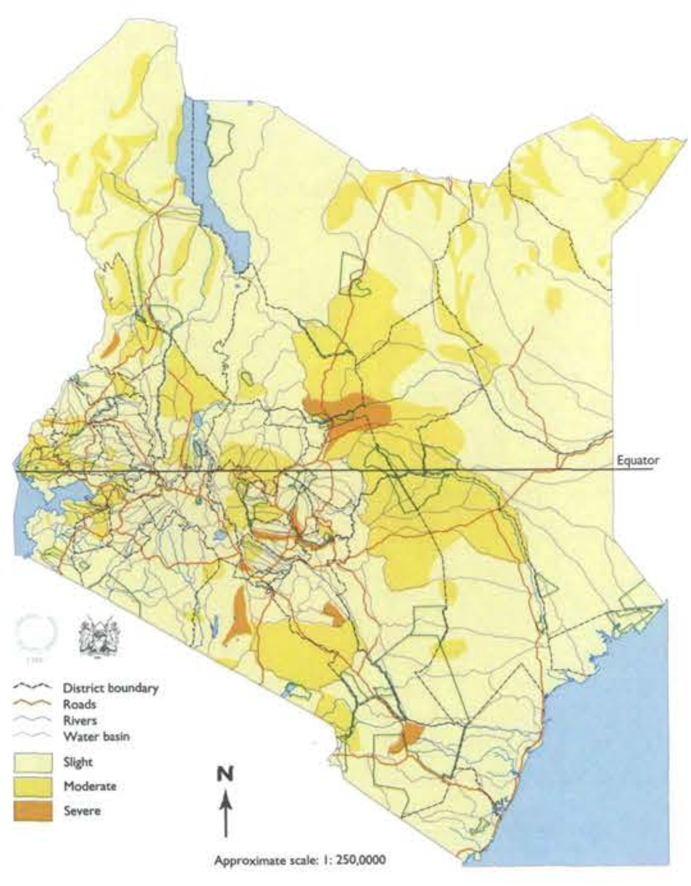
Map 4.11 Land degradation hazard in northern Kenya based on range utilisation



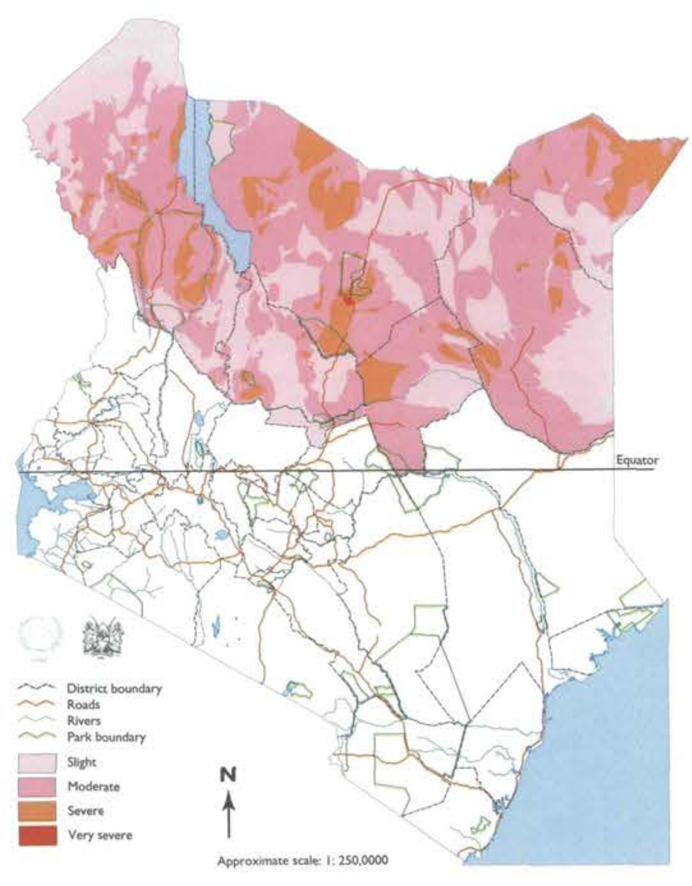
Map 4.12 Land degradation hazard in Kwale and Taita-Taveta Districts based on fuelwood deficit



Map 4.13 Land degradation hazard in Kenya as indicated by conditions of water resources



Map 4.14 Integrated land degradation hazard in northern Kenya using climatological, water erosion, range utilisation and water resources indicators



Grazing pressure and charcoal burning may also lead to the predominance of unpalatable or otherwise undesirable plant species.

These ecosystem characteristics are in practice difficult to map, since they usually affect relatively small patches of land and display seasonal variations. Remote sensing imagery can be useful as sources of general vegetation characteristics, but the outcomes are ideally subject to fieldwork confirmation A simple vegetation classification was derived from satellite image holdings in Kenya, based on four main vegetation communities: forests and woodlands, shrublands, grasslands and bare lands. Field visits were used to verify classification prior to data entry in the GIS.

Range utilisation
The observed state of vegetation cover needs to be linked to land use to assess degradation hazard. A measure of range utilisation, linked to livestock usage was determined; Map 4.11 shows the mapped data for the northern part of Kenya, where this survey suggested 41% of the mapped area is overutilised, 23% moderately utilised, 17% slightly utilised and 19% little utilised.

Fuelwood indicators
Over 70% of the Kenyan population live in rural areas and are entirely dependent on fuelwood as the source of energy for cooking and other domestic purposes (Government of Kenya 1987). Fuelwood, often in the form of charcoal, supplies an estimated 50% of the urban population as well. The fuelwood deficit, the difference between actual demand and sustainable supply, is therefore an important aspect of the land degradation hazard in Kenya. Notwithstanding possible limitations in data that are available on fuelwood use (see pages 48 and 70), assessment of this indicator was made by compiling estimates of demand from previous surveys, projecting growth of that demand in terms of population growth and distribution of human settlements, and transferring, where possible, demand in cities and major urban areas to the known and projected sources of supply. Fuelwood supply was estimated from an assessment of the structure and distribution of vegetation units considered suitable and accessible for fuelwood harvesting. The sensitivity of this indicator and the value of the district level database are demonstrated in Kwale and Taita-Taveta Districts (Map 4.12). The assessment cannot, however, be absolute as the areas showing deficit could expand or contract depending on future availability of cheaper alternative sources of cooking fuels, more widespread use of more efficient cooking stoves, or improvement of family incomes which usually results in transition from wood-based to oil-based fuels and electricity, especially in urban areas.

Water resource indicators
The state of water resources is a valuable indicator of land quality. High sediment contents in rivers, lakes and dams often indicate high rates of soil erosion. Increases in the frequency and height of flood peaks under similar climatic conditions are potentially indicators of enhanced runoff due to vegetation clearance and/or soil compaction. If climatic factors can be excluded, a falling water-table may be attributed to either excessive water abstraction or land degradation resulting in reduced infiltration and hence less groundwater recharge. Poor water and land management in irrigation schemes may also lead to impeded drainage and a rise in the water-table.

The use of water resource indicators was investigated for each of the main Kenyan drainage basins, taking advantage of the data already compiled under the Water Resources Assessment Project (WRAP) in the Water Development Department. Assessment of land degradation based on runoff intensity, flooding, and sediment deposition (Map 4.13) shows that a large number of sub-catchments and virtually all drainage basins in Kenya are already affected by various degrees of land degradation.

Socio-economic indicators
Several socio-economic factors are potentially useful indicators of degradation hazard, including population density and settlement distributions, poverty and nutrition levels, and land use types. Gaining reliable spatial data for such variables is more difficult, and the available data were found to be rarely quantitative, of variable quality, and sometimes inaccessible. None were therefore used in this study.

Integration of indicators and overall assessment of land degradation

To date, an integrated assessment of the combined parameters of aridity indices, soil erosion hazard, water resources and range utilisation has been conducted for the northern half of the country. The resultant degradation hazard map is shown in Map 4.14. In the absence of a proven scientific methodology for hazard assessment, the terms used in the study were qualitative and based on the assumption that factors are additive, i.e. the more negative factors affecting an area the greater the hazard. According to this assessment, the degradation hazard is very severe in 170 km^2 or 1% of the area, severe in 33 598 km^2 (13%), moderate in 142 729 km^2 (53%) and slight in 91 807 km^2 (33%).

Conclusion

Land degradation is a process of change that can only be assessed realistically by comparing the existing conditions with some baseline conditions established at a given period in the past. While some of the parameters that constitute land quality, such as soil characteristics and climatic conditions, may change with a time scale of decades or generations, others such as vegetation, population density and intensity of land use may undergo significant changes even on an annual basis. The database presented here has been established as a planning tool that should be continually improved as new information becomes available. The database developed in this study makes it possible, for the first time in Kenya, for planners and researchers to access simultaneously and conveniently a wide range of information concerning land quality, and to address the question of sustainable development by simulating options and their possible impact on land quality.

It is inevitable that conducting an investigation such as this brings to light a range of difficulties and limitations in data sources. In spite of many deficiencies, the judicious selection and quality control of information, usually available as part of other, routine investigations, can be used to construct an initial national database for land degradation assessment. Major deficiencies at this stage are the omission of mapping surfaces for wind erosion and socio-economic parameters.

A number of general lessons can be learned from this first attempt to compile a Kenya degradation database. A national database of indicators can be established within the relatively short period of one and a half years. However, there must be total commitment to collaboration and sharing of resources among autonomous government institutions which are custodians of national data sets, and limited resources need to be made available so that the integration of data into a GIS can be achieved. This Kenyan study shows what can be achieved even when for different reasons data quality and availability are highly variable. It demonstrates a methodology that can be used for planning at the national level, and which may provide a basis for initial land classification for rehabilitation, investment or development.

Material provided by F. Wangati.

Water Erosion Risk in Kenya: A Survey Using the SOTER Methodology

Introduction

Agriculture employees more than 80% of Kenya's population, which is growing at an annual rate of 3.4% (UN 1993). However, less than 20% of Kenya has an aridity index value (see page 111) in excess of 0.40 (Map 4.15) and is considered ideally suited for agriculture. In these areas the major land use is small-holder rainfed farming. Farmers both supply national and local markets and produce cash crops such as coffee, tea and increasingly horticultural produce. The remaining 80% of the country is either used for livestock production or as national parks and wildlife reserves (Map 4.16, Sombroek 1980). The rich variety in landscapes and the presence of a unique fauna has made Kenya a prime attraction for international tourists. Annually more than 750 000 tourists spend a holiday in the country and visit national parks.

The growing population and the expansion of economic activities have put significant pressure on the environment and are a potential source of conflict between various land use options. Locally, for example in the Kaibon Catchment in West Pokot, degradation has already lead to a permanent loss of biological functions of the land, or irreversible desertification. As a result of existing and potential desertification, evaluation of the availability of natural resources and the potential for degradation are important aspects of attempts to attain sustainable use of the environment.

Natural resources have been surveyed nationally and the relevant information has been captured in a wide range of geographic databases. From 1993–95 a 1:1 million soils and terrain database was compiled by the Kenya Soil Survey using a methodology developed by the International Soil Reference and Information Centre (ISRIC) and financed by UNEP. This database has been used as one of the main components in a national land degradation mapping programme during the years 1995–96. This case study demonstrates a methodology that can be used to assess degradation risk, focusing on water erosion and the lands where it is a potential threat to environmental sustainability.

Approach

Methods of soil erosion modelling and monitoring have primarily been developed mainly for small-erosion plot- or catchment-scales (Stocking 1996). Most models require a large set of parameters that are often not available at a national level. To assess erosion risks at the national scale, therefore, requires a new methodological approach if results are to have an acceptable level of reliability. The model used for the creation of the erosion risk map is a

Map 4.15 Agro-climatic zones

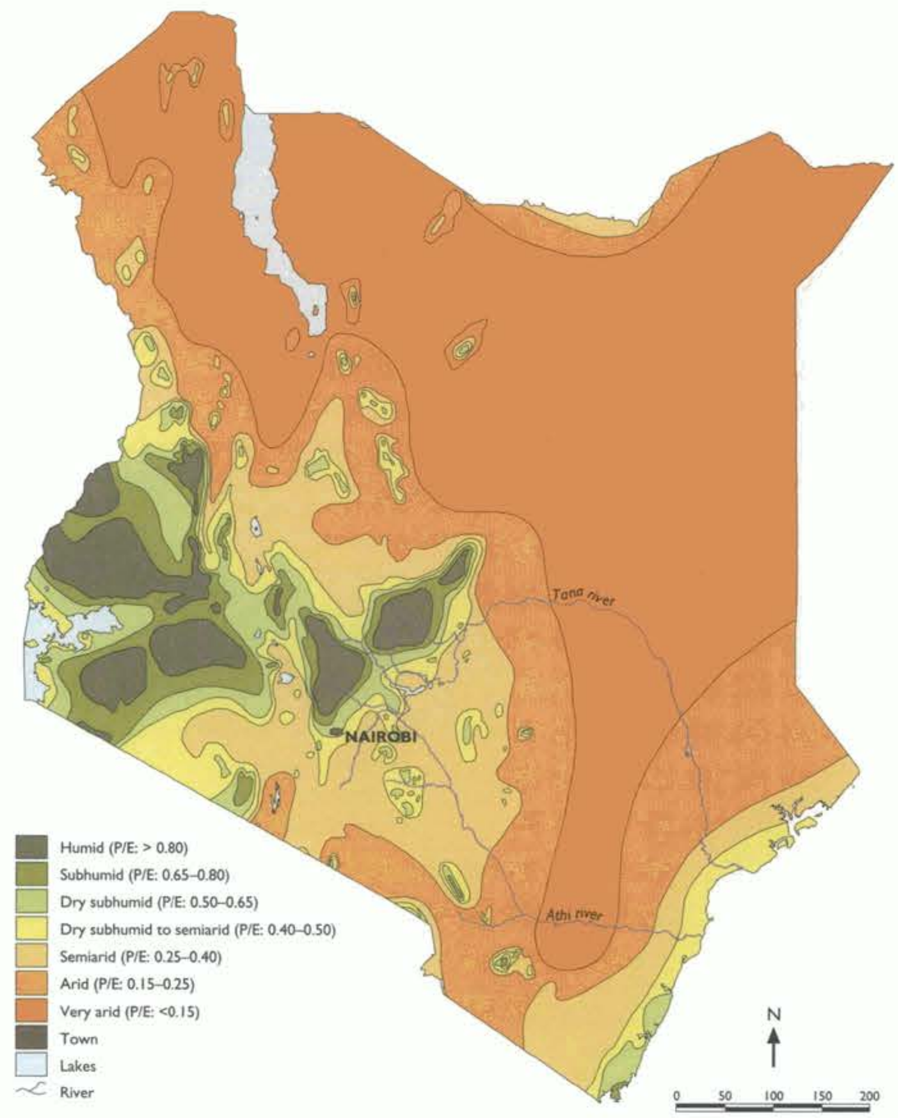
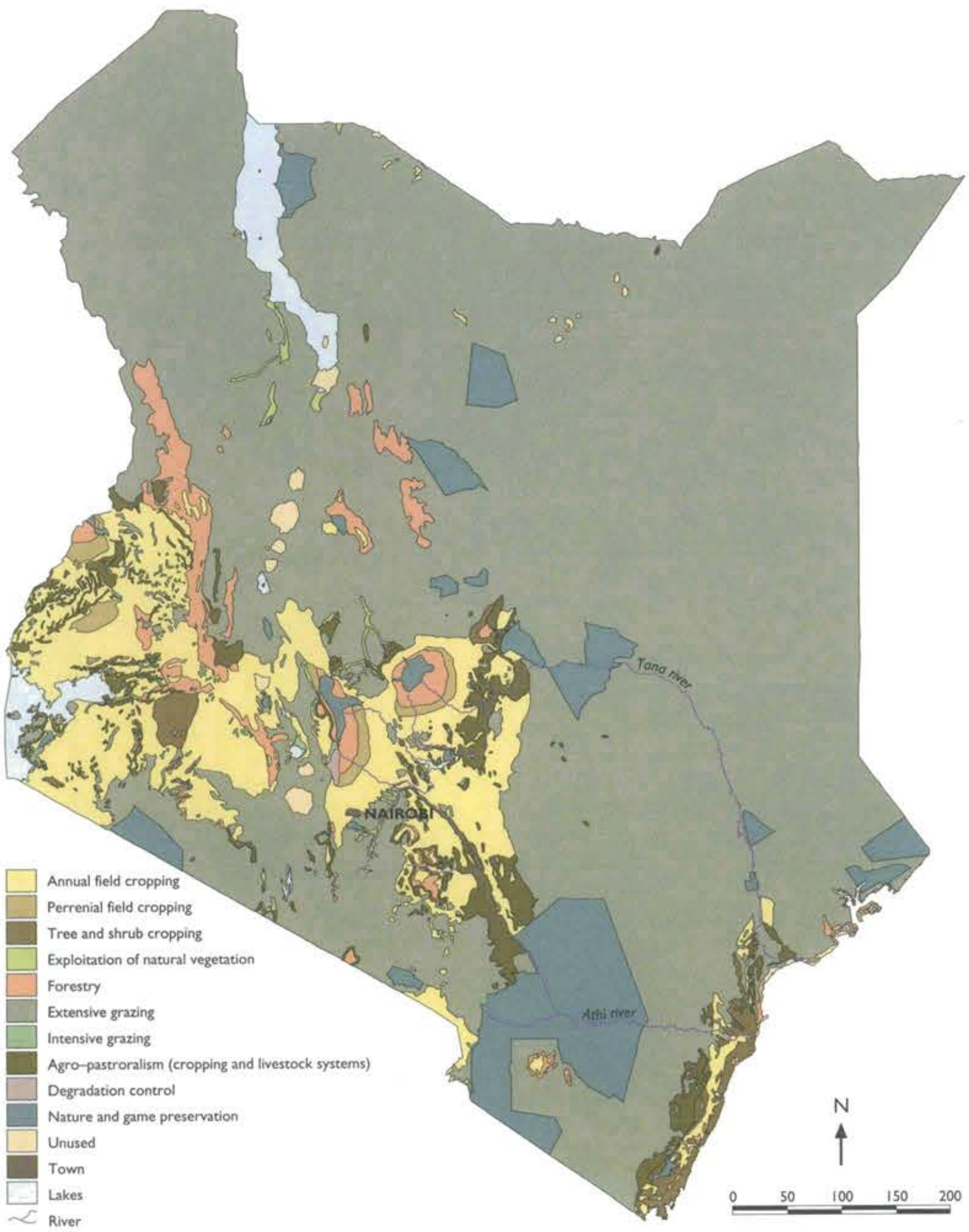


Table 4.9 Data used in modelling the water erosion risk in Kenya

	Required	*Source*
1	Rainfall erosivity	+ 60 rainfall stations
	a) Monthly rainfall	Agro-Climatic Zones
2	Topography	
	a) Slope gradient	Terrain data from SOTER database
	b) Slope length	Terrain data from SOTER database
3	Soil erodability	
	a) Organic C content	Surface layer data from SOTER database
	b) Very fine sand content	Surface layer data from SOTER database
	c) Silt content	Surface layer data from SOTER database
4	Land cover	
	a) Land use	Land use/vegetation from SOTER database
5	Land management	
	a) Land use	Land use/vegetation from SOTER database

Note: the rainfall data have been extracted from the AMDASS database (FAO 1992), completed with data from KMD (various years). Soils and terrain data as well as land use data have been derived from KSS, in particular the Exploratory Soil Map of Kenya (Sombroek *et al.* 1982) and a range of larger-scale studies. Additional land use data have come from KREMU (1983).

Map 4.16 Land use



modified version of the Universal Soil Loss Equation (Wishmeier and Smith 1978). This uses a multiplication of rainfall erosivity, soil erodibility, topography, land cover and land management. The modifications take account of the absence of rainfall intensity data and the lack of topographic detail available in Kenya and many other African countries.

Several conversions of available data into the level required by the model have been applied, with the following factors incorporated because of their impotance in potential erodibility. Table 4.9 shows the data inputs used in the assessment of these factors.

- Impact energy. Rainfall erosivity is determined by the kinetic energy of the raindrops which in turn can be derived from the intensity of rain storms. As data on intensities are not available for most meteorological stations in Kenya, an index of monthly over annual precipitation, the modified Fournier index (Van den Berg and Tempel 1995) has been used. This index has been validated in various parts of the world with acceptable results. Zones with equal rainfall intensities follow the broad agro-climatic zonation of the country (Map 4.15).
- Organic matter and particle size. Soil erodibility depends on organic matter content and the percentage of very fine sand and silt. This information can be derived from the profile information of each soil in the database. Map 4.17 gives an indication of the spatial variability of the dominant soils in the country.
- Topography influences the erosion risk by its effect on overland flow of non-infiltrated rainfall and the subsequent detachment of soil particles. Factors that determine the topography is this respect are slope gradient and length of slope (Map 4.18).
- Ground cover. The cover afforded by vegetation and crops is a protective factor against the impact of raindrops. During the growing cycle of plants the cover of the soil varies. Annual crops in particular have a very low to non-existent cover during the planting and emergence period, a time when rainfall intensities can be very high.
- Management. Human activities in the form of management practices are included in the erosion model too as a final but highly important factor that influences erodibility.

Results

The results generated by the modified USLE model are given as an erosion risk or hazard index in Map 4.19, with hazard interpreted on a qualitative scale The various factors that determine to a large extent the outcome of the analysis are discussed below.

Topography and rainfall

High erosion risks exist in the areas where topography is steep, rainfall intensities are high and human influence in the land use is strong. In most areas with slopes over 30% the water erosion risk is high, even in the drier areas of the country as thin vegetation covers afford little protection when heavy rainstorms occur. Where human influences are absent or limited, the natural vegetation gives better protection and the erosion risk is much lower, for example in the national parks and on the high mountains and hills (Mount Kenya, the Aberdares and Mount Elgon). Other mountainous and hilly areas outside national parks have a high erosion risk even where rainfall is much lower. Figure 4.3 shows the water erosion risk by climatic zone.

Soils

Although rainfall and topographic conditions have an important impact on erosion risk, it is clear from Figure 4.3 that soil conditions are sometimes overruling. A comparison between the areas to the north and east of Nairobi reveals interesting differences. Although higher rainfall intensities and steeper topography occur in the northern area, the erosion risk is higher in the east. Both areas are used for agriculture and the main differences are due to soil conditions: well structured Nitisols with a good infiltration versus sealing Acrisols/Luvisols with a high runoff.

Land use

It is clear that land use, and in particular annual crops, can enhance soil erosion

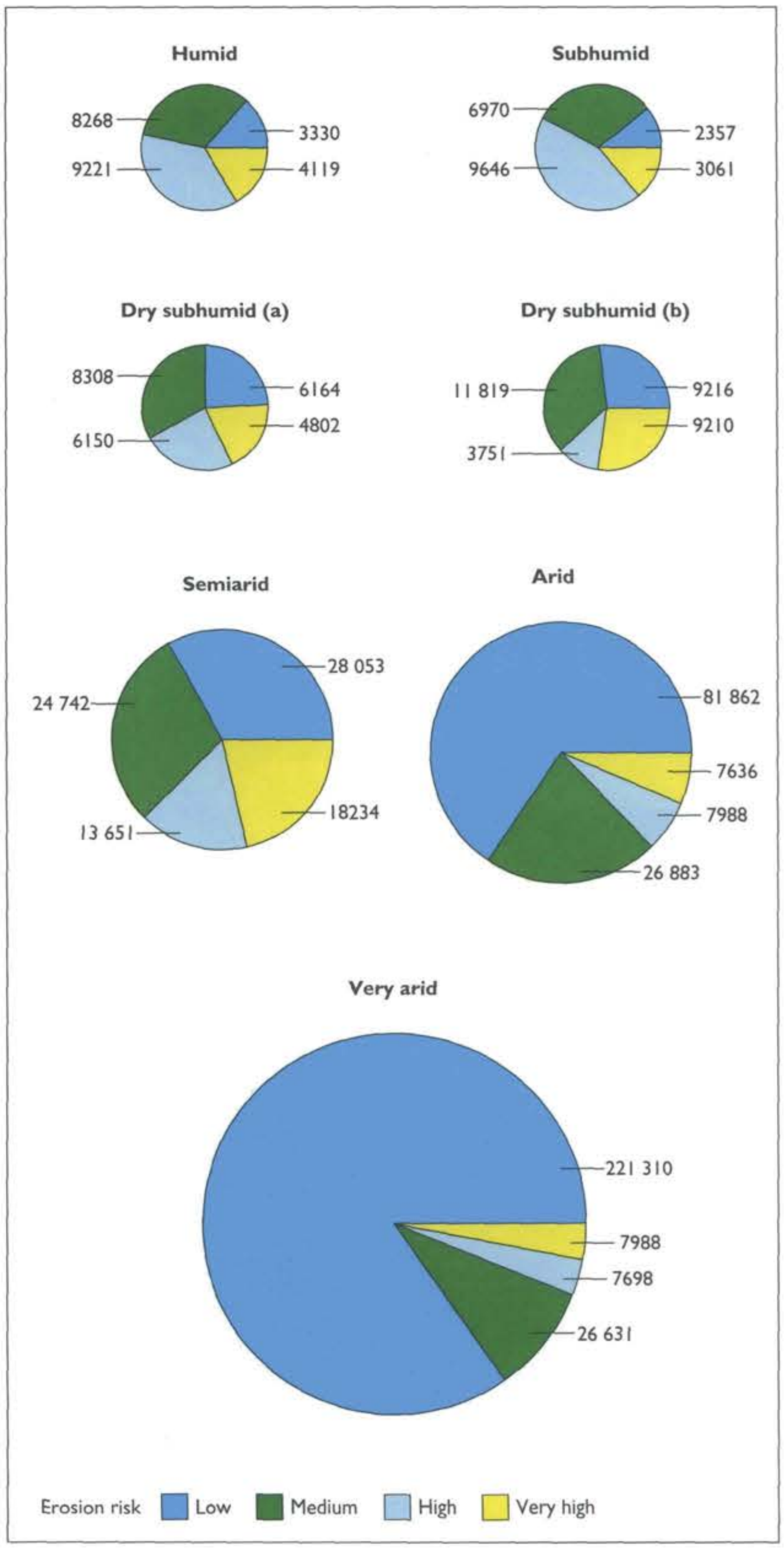


Figure 4.3 Erosion risk classes per agro-climatic zone (in 10^3 km^{-2})

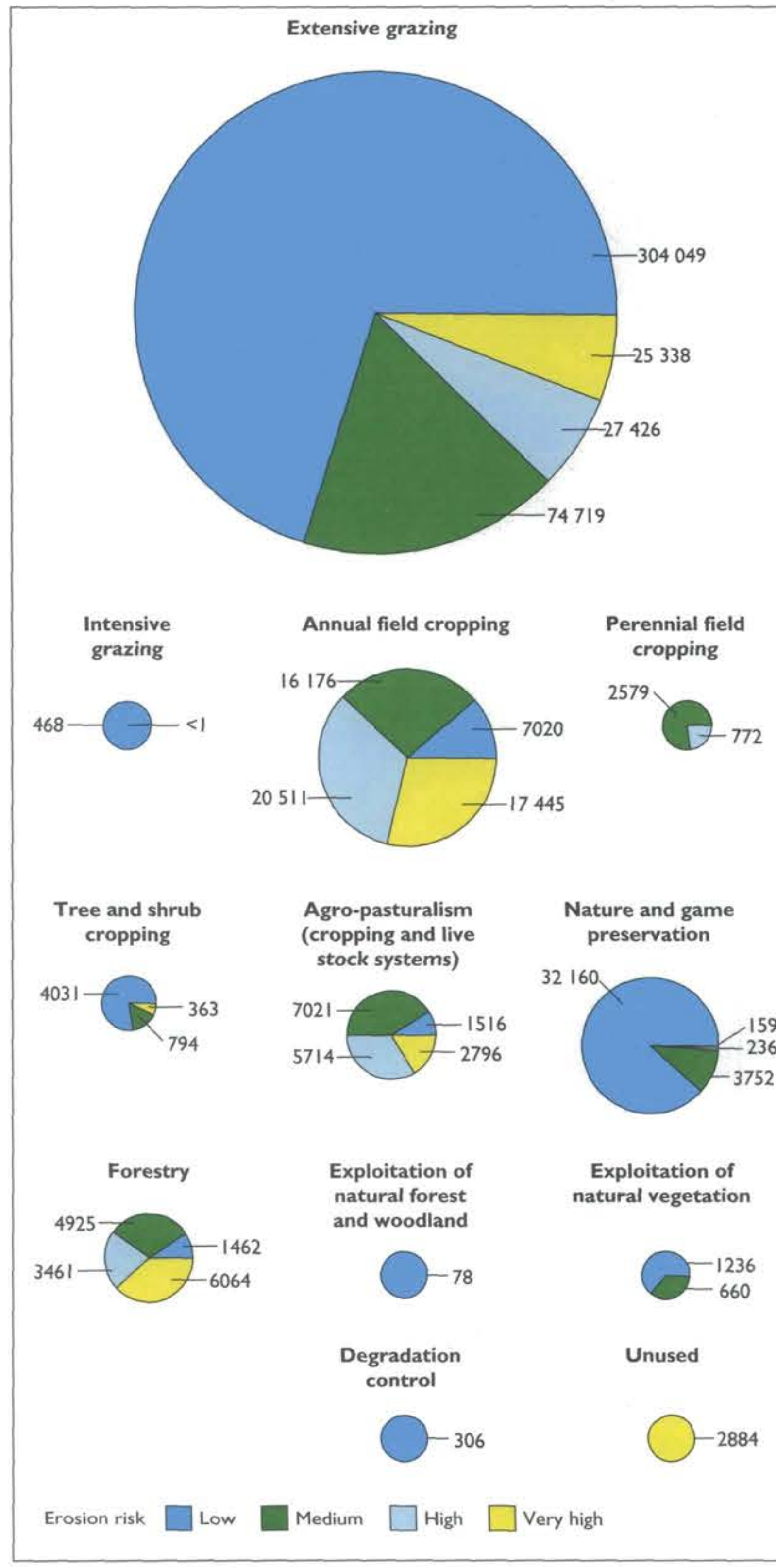


Figure 4.4 Erosion risk classes per major land use type (in 10^3 km^{-2})

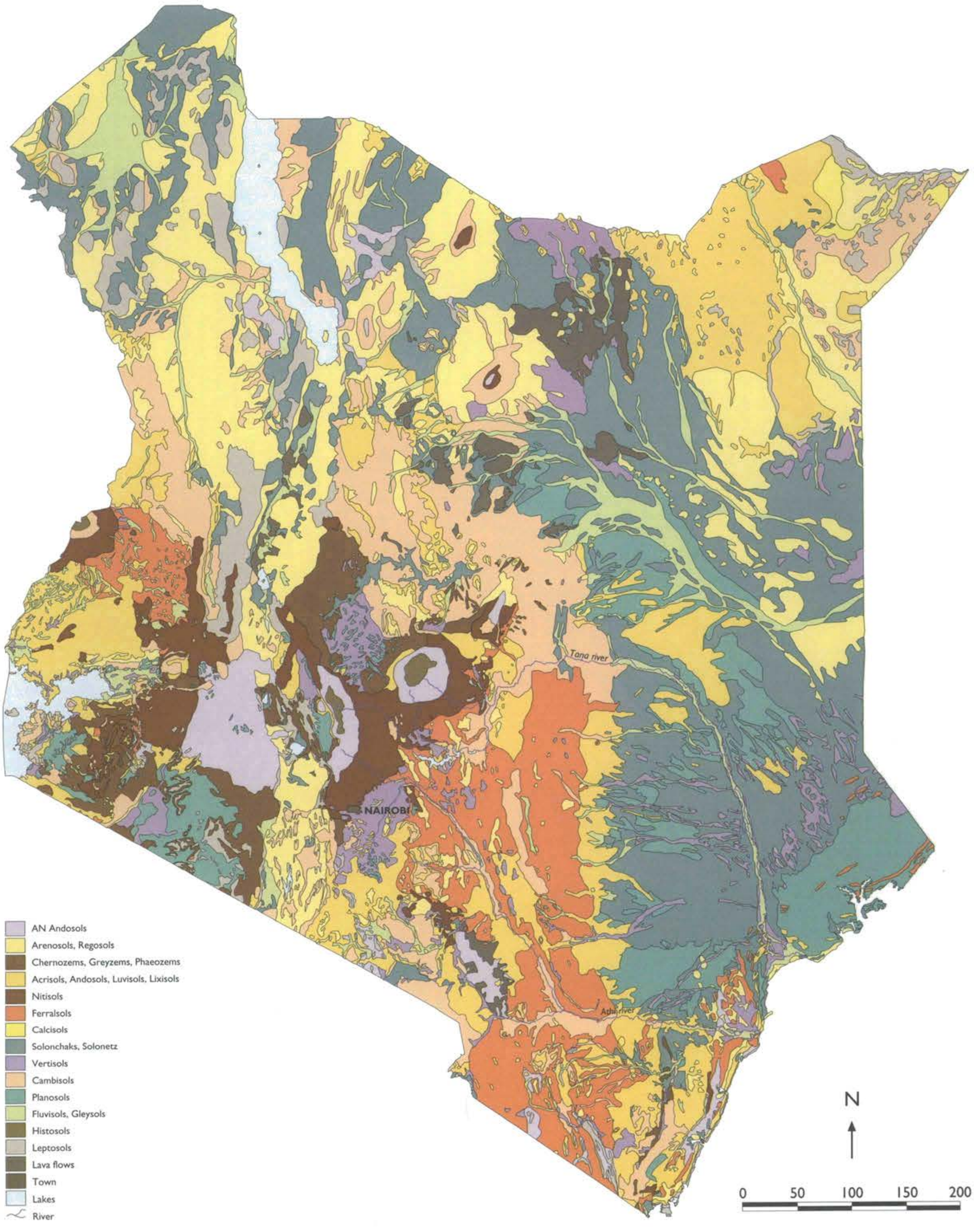
enormously, when no proper soil conservation measures have been taken. A striking difference in erosion risk exists between annual and perennial crops like tea (Figure 4.4). Areas under tea do not seem to have a high risk. Figure 4.4 shows the erosion risk in areas under different land use practices.

Conclusion

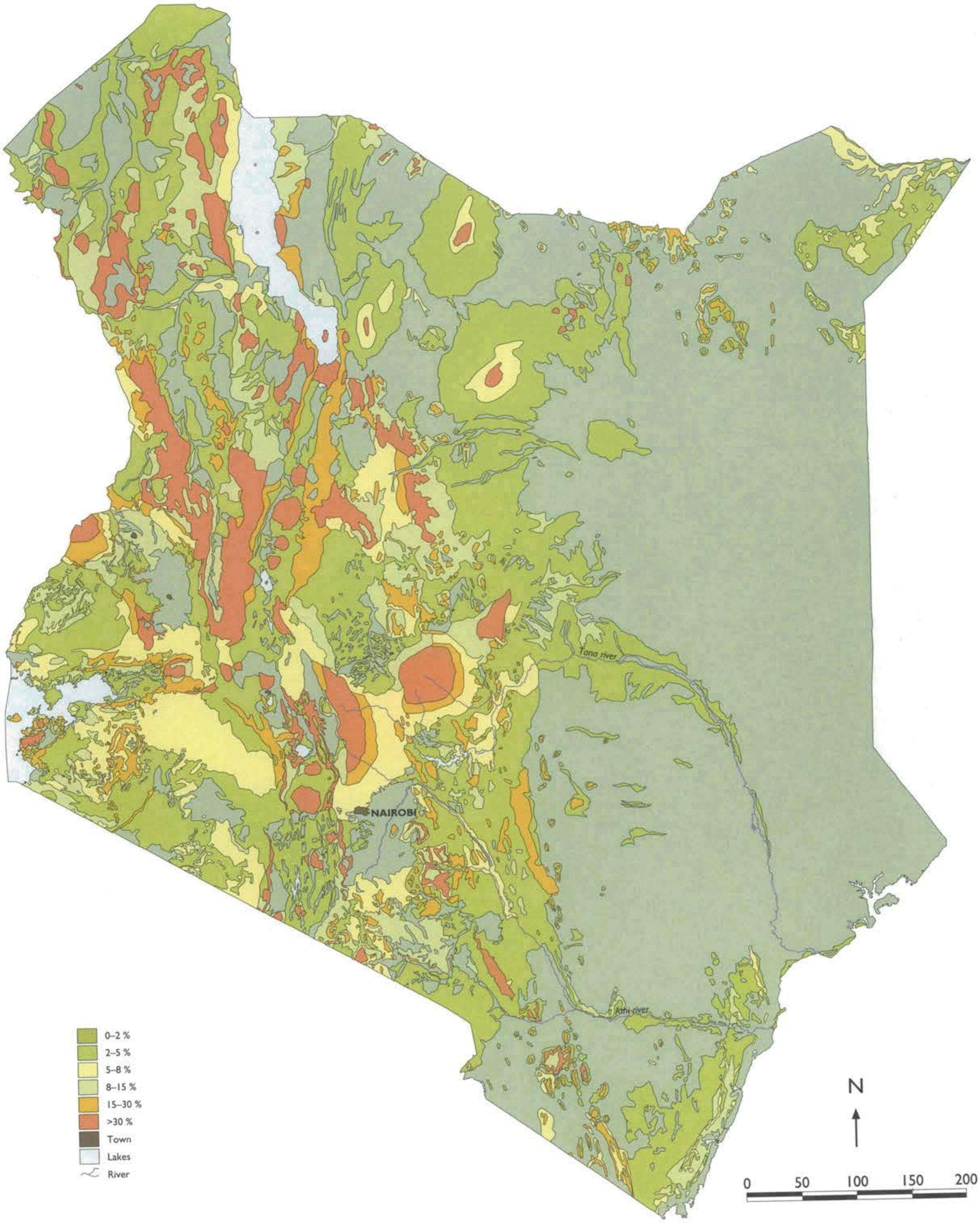
The use of a simple model at a national scale can give an insight into the risk of erosion over large areas. It can also indicate areas for further, more detailed analysis. The final map (Map 4.19) can be used at the policy level to determine priority areas for soil conservation action. However, the erosion risk classes cannot be used for quantification of remedial measures.

Based on original text supplied by V.W.P. van Engelen, J.W. Resink (ISRIC) and P.T. Gicheru (Kenya Soil Survey).

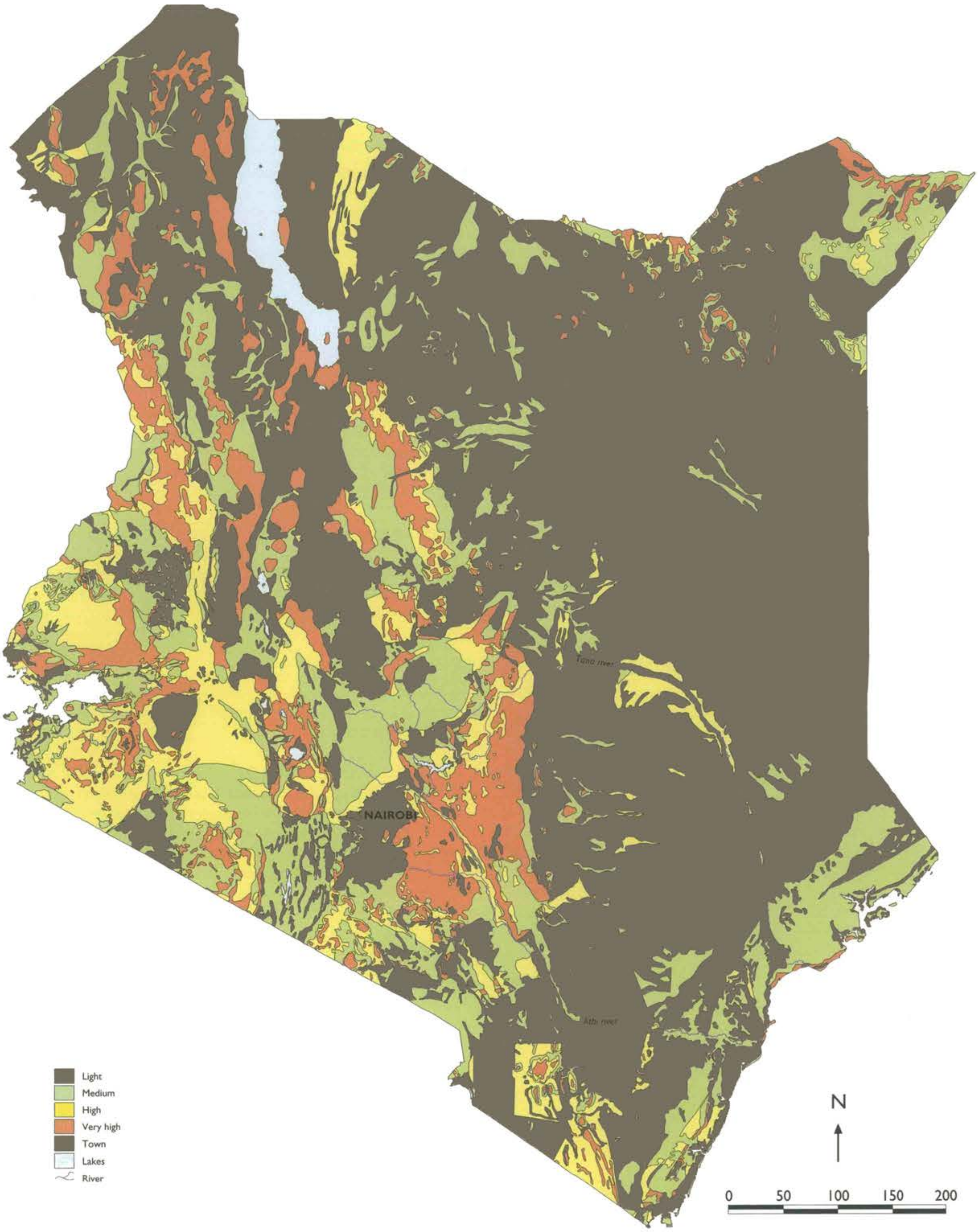
Map 4.17 Soils



Map 4.18 Slope class



Map 4.19 Water erosion risk



WOCAT: Regional Example of Eastern and Southern Africa

Introduction

Degradation due to unsustainable land and water use has been reported world-wide, but this atlas has focused on the threat of this phenomenon to the future use of drylands. The GLASOD programme has identified water and wind erosion as the most widespread soil degradation processes and the severity of their threat to future human livelihoods in the world's susceptible drylands is documented elsewhere in this atlas. However, numerous efforts have been made to combat erosion and other land degradation processes. Many local land users employ soil and water conservation (SWC) methods on their land and these efforts to improve soil productivity are often assisted by SWC specialists, land use planners and decision-makers. However, valuable experience based on these activities is usually not available to people in other locations. In the search for better land and water management and sustainable resource use, experience must be shared on a national, regional and global basis to promote SWC and sustainable natural resource use. The aim of the World Overview of Conservation Approaches and Technologies (WOCAT) programme is to promote just such a sharing and exchange of experience. This section outlines the methodology used and the work done in eastern and southern Africa.

The WOCAT approach – a search for solutions

The WOCAT programme contributes to the sustainable development of natural resources world-wide by presenting lessons learned from successful soil and water management. WOCAT collects, analyses and distributes knowledge about proven and promising SWC practices, addressing all stakeholders in sustainable land management, including politicians, decision-makers, SWC specialists and land users. WOCAT was launched in 1992 and is an ongoing programme, organised as a consortium of international institutions (see Box 1), co-ordinated by the Centre for Development and Environment (CDE) in Berne, Switzerland.

WOCAT has developed a framework for the evaluation of SWC, which includes standardised questionnaires on SWC technologies and approaches (Liniger and Hurni 1997a and b, see Box 2), and the spatial distribution of SWC. Data are collected and experiences exchanged in regional workshops. Databases are being established in regional and national centres and a system is being set up to ease access to and exchange of information. WOCAT develops user-friendly tools for the analysis of data, including a decision support system. The main thrust is to open access to the data, to enhance exchange of information (e.g. through the Internet), and to produce outputs such as books on SWC technologies and approaches, and maps on SWC activities. In order to facilitate access to the SWC experiences collected by the programme, regional and national institutions are supported in setting up their own WOCAT database and analysis systems.

By 1997, WOCAT had collected data at the regional level from Africa and at the national level from Thailand. Initiatives have been prepared for Latin America and Central America, Asia, Australia and Eastern Europe. Depending on national and regional initiatives and funding, the programme will progress on national, regional and continental levels. WOCAT operates in all climate zones, but some of the preliminary results from the susceptible drylands of eastern and southern Africa are presented below. Although verification of these results is continuing, this presentation is designed to illustrate the ongoing activity and the need to collect further information on SWC.

Soil erosion in eastern and southern Africa

Soil degradation due to unsustainable land and water use reduces the productivity of cropland and grassland and thus threatens sustainable resource use and food security in many parts of the world. The results of the GLASOD survey indicated that soil erosion by water and wind are the most dominant processes of soil degradation, and hence these processes are the focus of the WOCAT programme.

Just over 600 million ha of land have been surveyed in 15 countries of eastern and southern Africa: Botswana, Eritrea, Ethiopia, Kenya, Lesotho, Malawi, Mozambique, Namibia, South Africa, the Sudan, Swaziland, Tanzania, Uganda, Zambia and Zimbabwe (Liniger *et al.* 1996). About 59% of this area lies in the susceptible drylands as defined using the timebound data set described on page 2–7 (see Map 4.20). Using the mapping polygons defined for the GLASOD Africa database (See Section 2), areas were classified by land use. As Figure 4.5 indicates, almost half of the susceptible drylands in this part of Africa are used for grazing, while nearly a quarter is cropland. WOCAT studies of SWC technologies and approaches have focused on these two land use categories.

The distribution of cropland in the region's susceptible drylands is shown in Map 4.21 and Map 4.22 indicates the severity of erosion on cropland using the GLASOD methodology. The 'not applicable' category on these maps,

BOX 1
Member and task force institutions (1997)

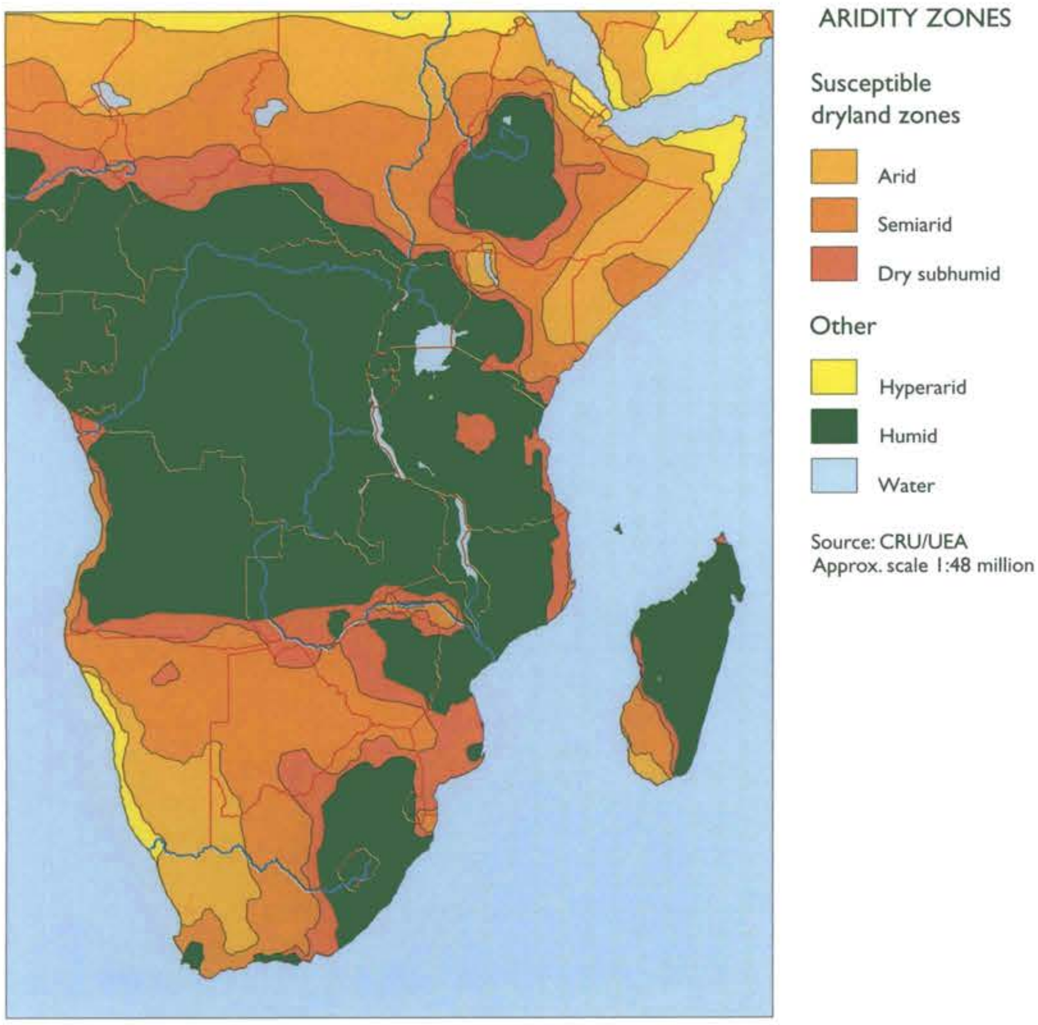
CDE (Centre for Development and Environment), University of Berne; FAO (Food and Agriculture Organization of the United Nations), Rome; UNEP (United Nations Environment Programme), Nairobi; ISRIC (International Soil Reference and Information Centre), Wageningen; CDCS (Centre for Development Cooperation Services), Vrije Universiteit Amsterdam; RSCU (Regional Soil Conservation Unit), SIDA, Nairobi; ASOCON (Asia Soil Conservation Network), Jakarta; GTZ (Gesellschaft für Technische Zusammenarbeit), Eschborn; OSS (Observatoire du Sahara et du Sahel), Paris; IRE (Institute for Resources and Environment), University of British Columbia, Vancouver; SOCOX Consult, Lochem.

Financing institutions (1997): SDC (Swiss Agency for Development and Cooperation), Berne; FAO; UNEP; RSCU; OSS; GTZ; IDRC (International Development Research Centre), Ottawa.
Secretariat: CDE, Bern.

BOX 2
WOCAT SWC definitions

SWC:	Activities at the local level which maintain or enhance the productive capacity of the soil in erosion-prone areas through: prevention or reduction of erosion, conservation of moisture, and maintenance or improvement of soil fertility
SWC technology:	Measures used in the field (agronomic, vegetative, structural and management)
SWC approach:	The ways and means used to implement a SWC technology on the ground

Map 4.20 Aridity zones



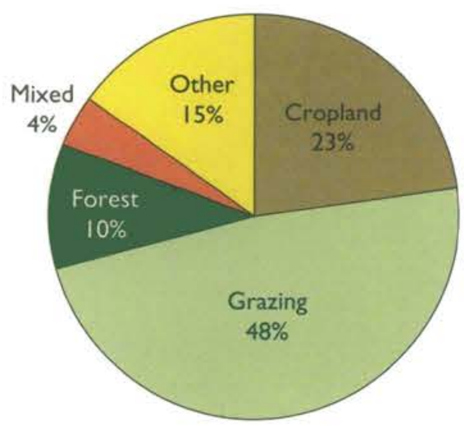


Figure 4.5 Land use types in susceptible drylands. Source: WOCAT

and others below, indicates areas that are either not in the susceptible drylands or not used for crops, where no erosion occurs, or areas without data. The most intensively farmed susceptible dryland areas (where more than 50% of individual polygons are used as cropland) tend to be in the semiarid and dry subhumid zones, including coastal Tanzania, southern Mozambique, central and western Zimbabwe, or along rivers such as the Nile and Orange. Most cropland in the susceptible drylands is unaffected by erosion (Figure 4.6), but none the less 17.3 million ha of eastern and southern Africa's susceptible dryland cropland is degraded by water and wind erosion, with the largest areas so-affected occurring in the semiarid zone (e.g. Figure 4.7).

The areas most extensively used for grazing tend to be in the drier parts of the susceptible drylands, in central Sudan, central Eritrea, eastern parts of Ethiopia and Kenya, much of Botswana and Namibia, and western and northern South Africa (Map 4.23). Erosion also tends to be most severe on grazing land in the more arid areas (Map 4.24), where the greatest areas are affected (Figure 4.8). In total, 48.5 million ha of grazing lands in eastern and southern African susceptible drylands are affected by erosion. Areas subjected to particularly heavy grazing pressure can, in extreme cases, become subject to severe gully erosion (Figure 4.9).

Soil and water conservation on cropland in eastern and southern Africa

Soil degradation due to agricultural practices and the clearance of land for agriculture would be worse without traditional and recently developed SWC technologies. Such technologies are commonly classified into the following categories.

- **Agronomic measures**, such as mixed cropping, contour cultivation and mulching, which are usually associated with annual crops. They tend to be routinely repeated each season or in rotational sequence and are therefore impermanent and of short duration.
- **Vegetative measures**, such as grass strips, hedge barriers and windbreaks, are more permanent approaches involving perennial grasses, shrubs or trees. These technologies often lead to a change in land profile and are often spaced according to slope.
- **Structural measures**, such as terraces, banks and bunds, also involve changing the profile of the land. These are permanent measures, implemented primarily to control runoff and erosion, and require substantial labour or economic inputs during construction.
- **Management measures**, such as land use change, enclosures and rotational grazing, involve a fundamental change in land use. They do not involve agronomic or structural measures, and often result in an improved vegetation cover and reduced intensity of land use.

Most of the implementation of SWC technologies in the region has been achieved by land users themselves without outside assistance, but in many cases incentives have been successful in encouraging farmers to adopt SWC approaches. Such incentives include food-for-work programmes, cash payments to land users, and other forms of support such as equipment, credits and compensation for labour. Land tenure and land use rights play an important role in investment in sustainable soil and water management. SWC was mainly applied on individually owned land and rarely on communal cropland. About half of the approaches reported had good involvement of the local community in the planning, implementation and evaluation phase. An economic analysis showed that in subhumid to semiarid environments, there was often an immediate benefit due to water conservation, and the costs could be recovered within a few years after implementation, after which SWC resulted in great benefits. In humid environments, by contrast, the total costs for SWC were often higher than the benefits, even 10 years after implementation.

The first analysis of SWC activities in eastern and southern Africa shows that most of these activities are concentrated on cropland. In the susceptible drylands as a whole, structural measures are by far the most commonly used technologies (Figure 4.10) but Map 4.25

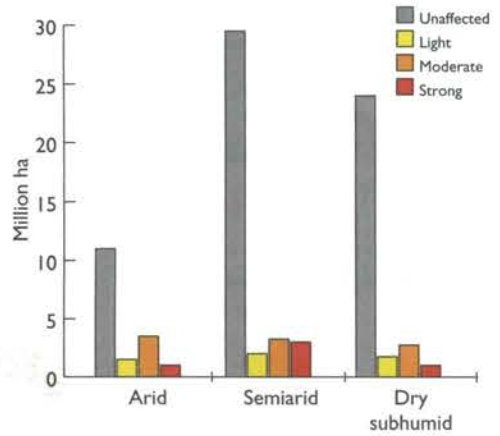
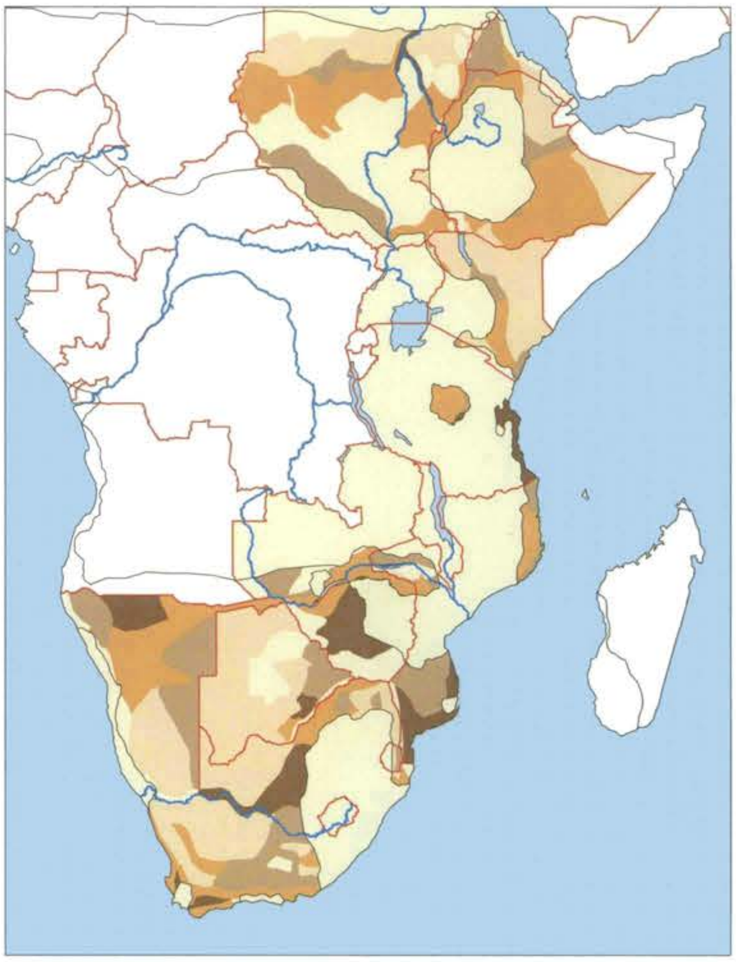


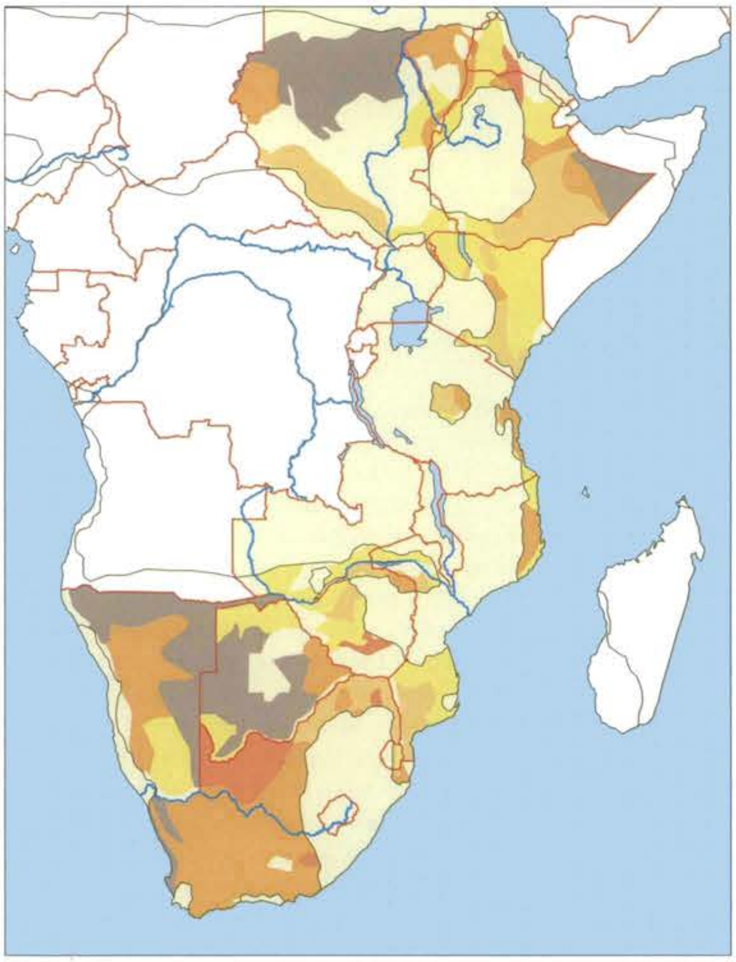
Figure 4.6 Water and wind erosion on cropland in susceptible drylands. Source: WOCAT

Figure 4.7 Soil erosion on ox-ploughed steeply sloping cropland in Ethiopia. Source: WOCAT

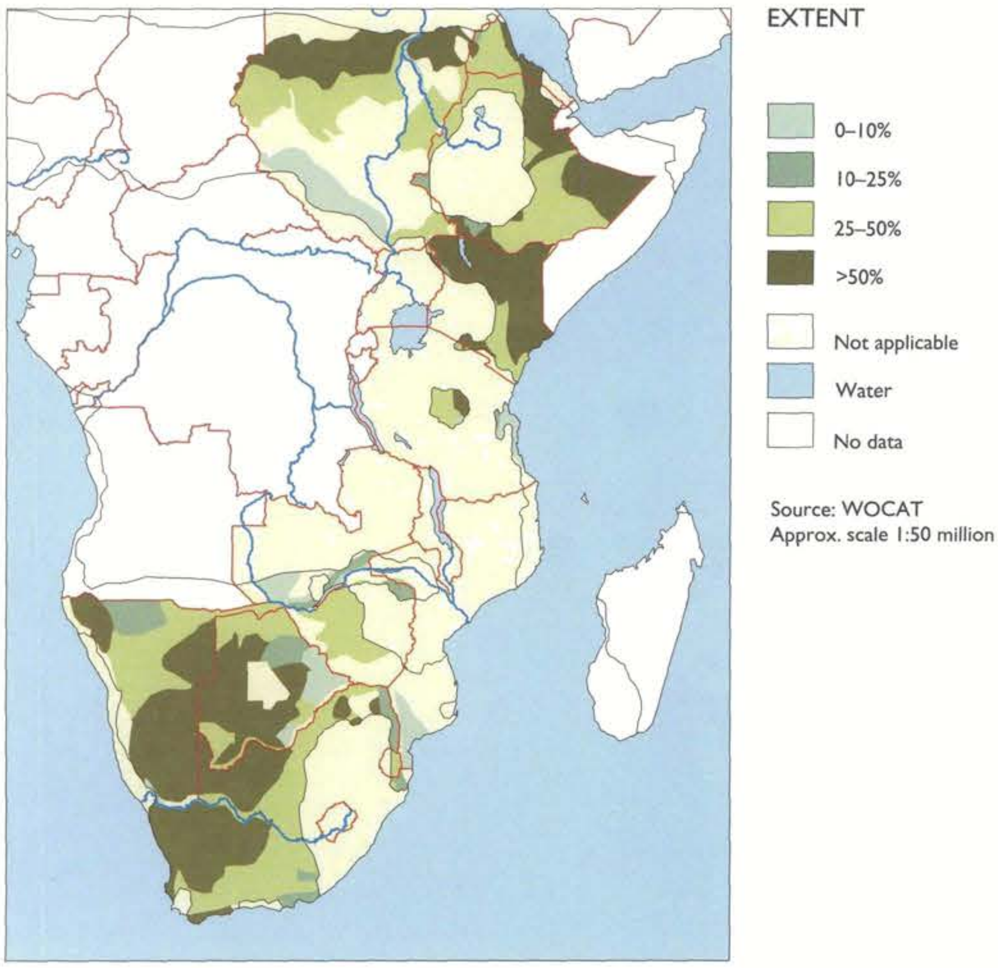
Map 4.21 Extent of cropland in susceptible drylands



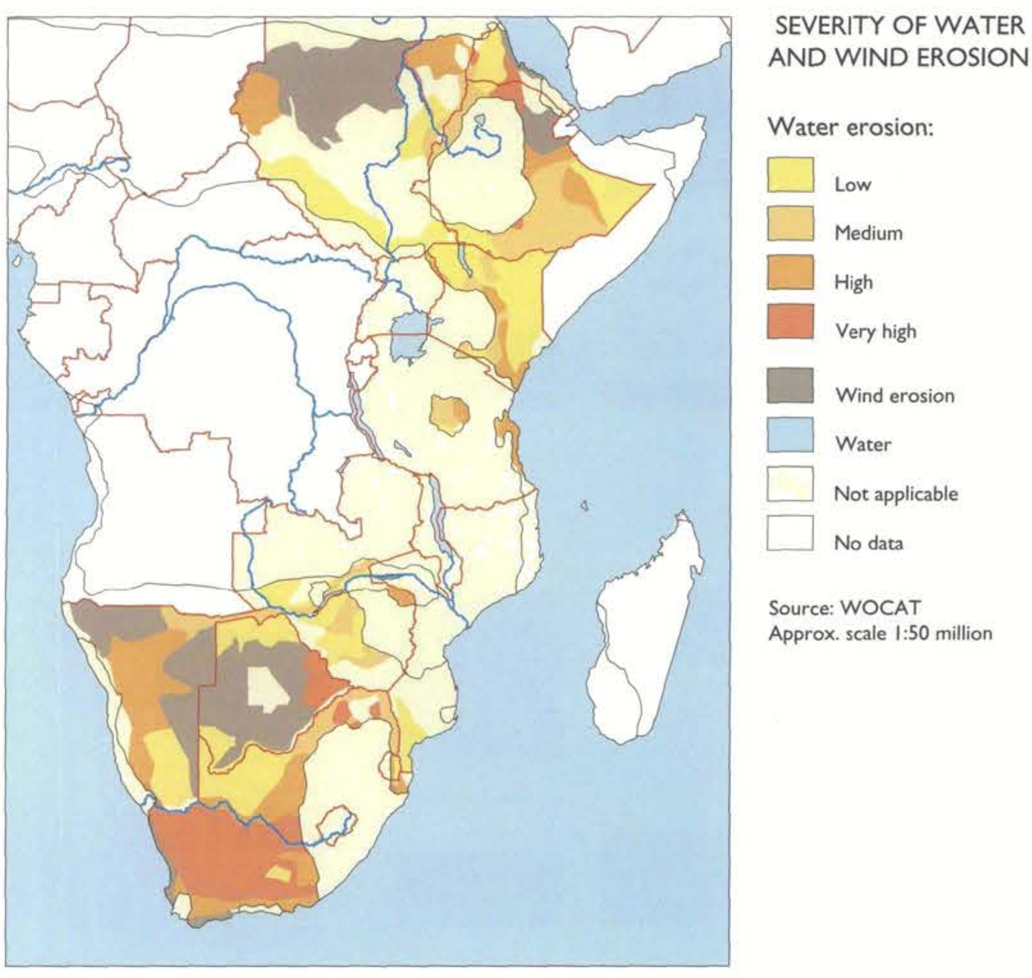
Map 4.22 Water and wind erosion on cropland in susceptible drylands



Map 4.23 Extent of grazing land in susceptible drylands



Map 4.24 Water and wind erosion on grazing land in susceptible drylands



indicates distinct regional differences. While structural measures predominate in eastern African susceptible drylands, agronomic measures, and to a lesser extent vegetative measures, are also common in southern Africa.

Assessment of the impact of SWC on cropland shows achievements in all of the countries (Map 4.26) and medium to high effectiveness was found on the large majority of croplands in all three susceptible dryland zones (Figure 4.11). Comparison of Maps 4.25 and 4.26 with Map 4.22 indicates the success of largely agronomic practices in keeping erosion to low or medium severity in southern Mozambique and western Zimbabwe, for example, and the successful application of structural measures in keeping water erosion at low severity in south-eastern Sudan. Combinations of technologies are also often used: both structural and vegetative measures are shown in Figure 4.13, an area in the Machakos region of Kenya.

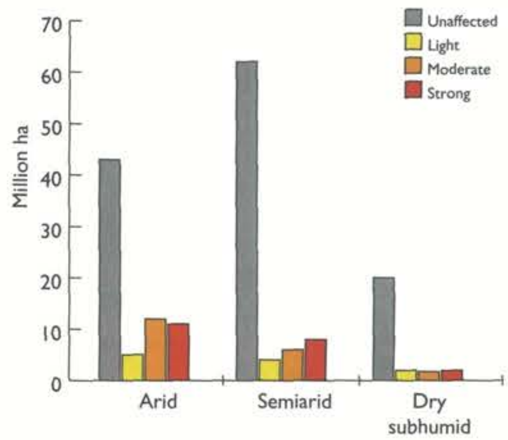


Figure 4.8 Water and wind erosion on grazing land in susceptible drylands. Source: WOCAT

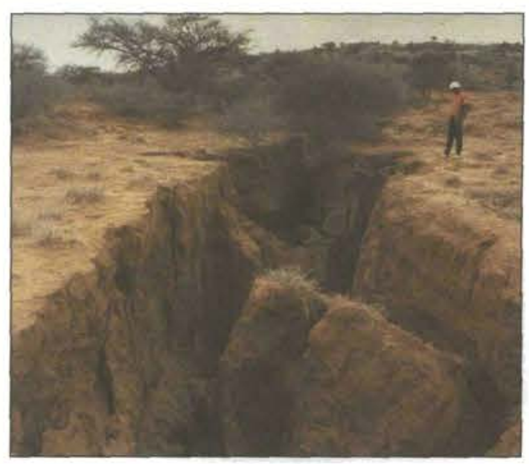


Figure 4.9 Gully and sheet erosion on heavily-grazed semiarid land in Kenya. Source: WOCAT

SWC on grazing land in eastern and southern Africa

Few SWC activities were reported on grazing land in eastern and southern Africa, and the overall effectiveness of such schemes was lower than for cropland, particularly in arid regions (Figure 4.12). Nevertheless, some were considered to be highly effective, mostly in southern Africa (Map 4.27). The few described technologies comprise management and vegetative measures (Figure 4.14), the aim being to improve rangeland mainly by controlling grazing, and thus improving vegetative cover. Even though many experiments have been done using structural measures, SWC specialists do not find them appropriate for the vast areas, especially considering the high costs compared with the productive value of the land.

The fact that most of the grasslands in eastern and southern Africa are open access areas, or areas under communal management, has often been cited as a key problem with regard to improving its management. Even though traditional systems have managed to use grazing land sustainably in previous centuries, many of these systems do not seem to work any more. The expansion of cropland at the expense of the best grasslands and population growth is usually cited as the reason for the failure of traditional systems today. New, innovative approaches and technologies face the challenge of finding management solutions that are supported by the local people and do not involve very high costs. The fact that large areas under grazing are already badly degraded also means high costs for rehabilitation. Grazing lands have been neglected in the past and major efforts will be needed to improve productivity and food security in the semiarid and arid grasslands. WOCAT therefore promotes GRASS: Grass cover for the Recovery of Arid and Semi-arid Soils (Liniger and Thomas 1996).

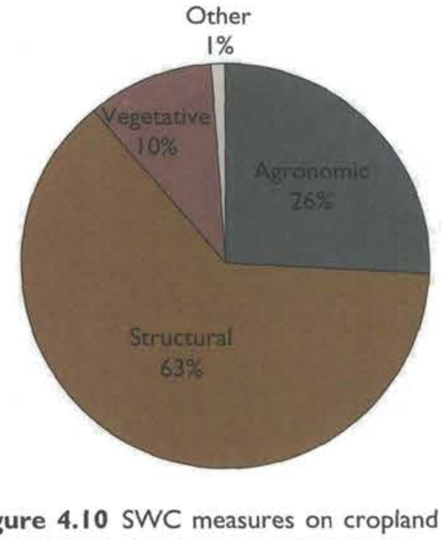
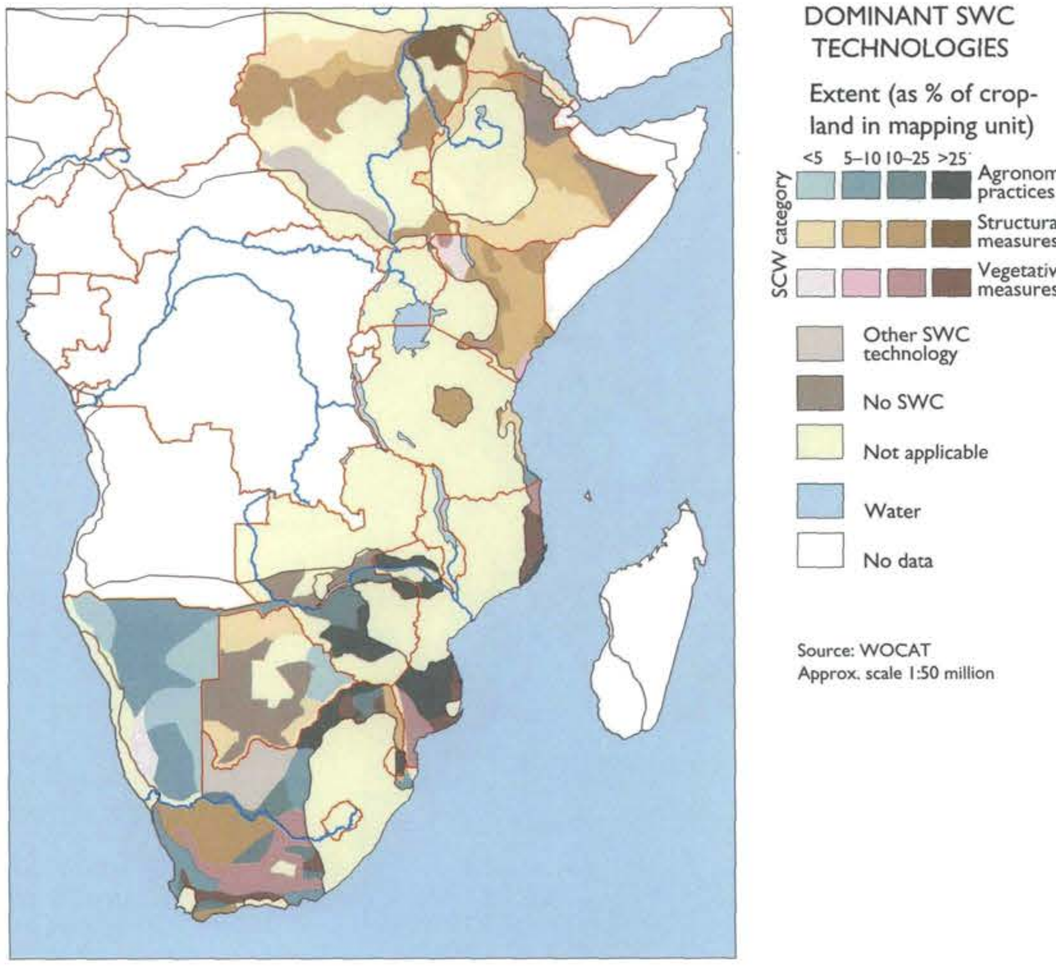


Figure 4.10 SWC measures on cropland in susceptible drylands. Source: WOCAT

Map 4.25 Dominant SWC technologies used on cropland in susceptible drylands



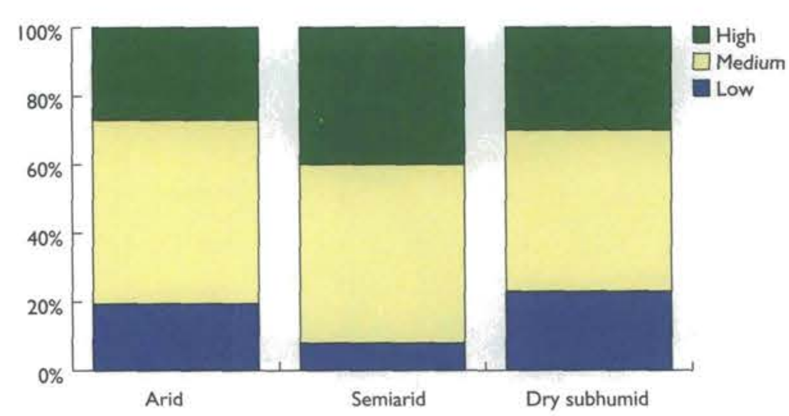


Figure 4.11 SWC effectiveness on cropland in susceptible drylands. Source: WOCAT

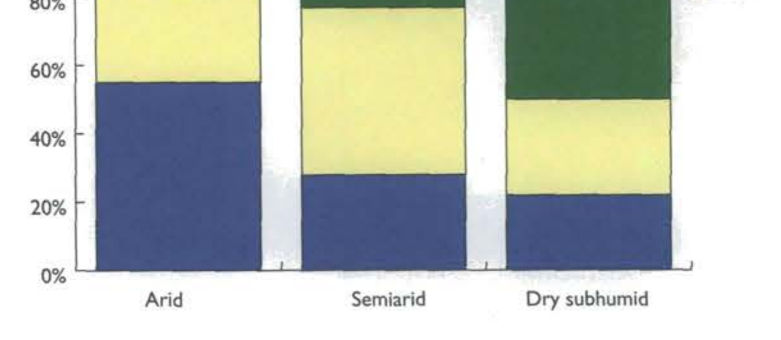
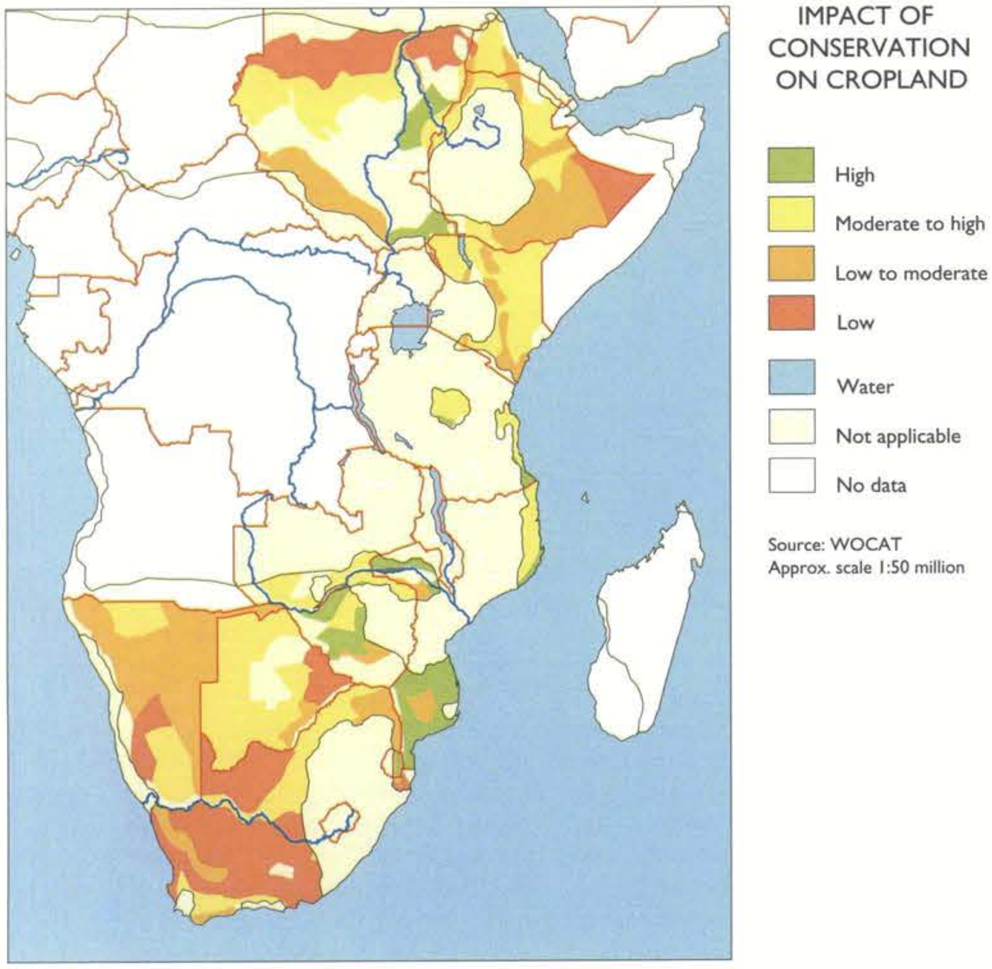


Figure 4.12 SWC effectiveness on grazing land in susceptible drylands. Source: WOCAT

Map 4.26 Impact of conservation on cropland in susceptible drylands



Map 4.27 Impact of conservation on grazing land in susceptible drylands

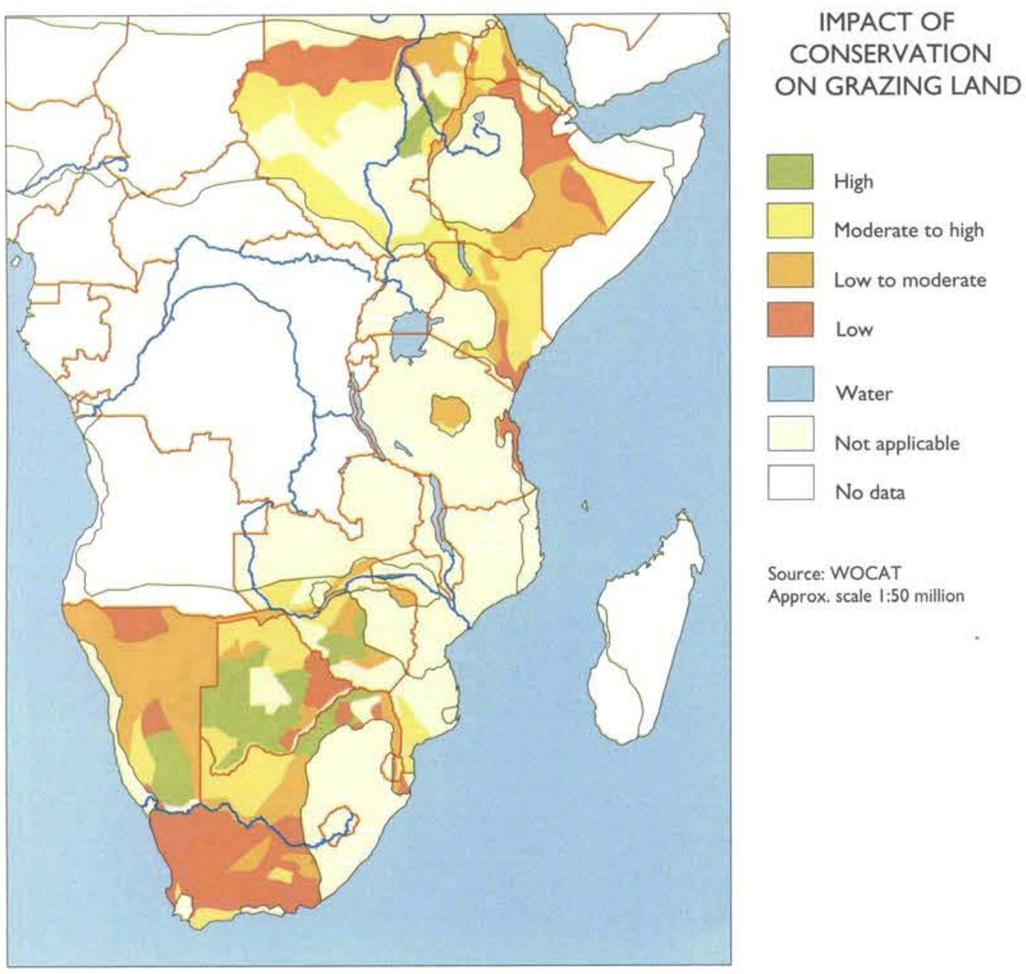


Figure 4.13 A combination of vegetative (grass strips and trees) and structural (terraces) measures used in Machakos, Kenya have successfully prevented erosion and runoff which still affect nearby fields

Outlook: the global programme

WOCAT has established a methodology for the collection, evaluation and dissemination of SWC experiences throughout the world, both inside and outside the susceptible drylands. As the programme advances, more and more proven and promising SWC technologies and approaches will be analysed and made available through a network of decentralised databases that are easily accessible to SWC specialists world-wide. Outputs such as handbooks describing and analysing SWC technologies and approaches, maps of SWC activities, and the database system have been clearly identified, and decision support systems are under development. National, regional and international institutions are invited to join the global programme of WOCAT and to carry out their own WOCAT activities.

Original text by H.P. Liniger.

Figure 4.14 Protection from grazing has allowed the vegetation cover to increase in this area of Baringo District, Kenya

Development of a Water Atlas to Understand Water Availability in the Middle East

The Water Atlas

Land degradation and poor environmental management, resulting from high population growths and the drive for food self-sufficiency, are features of most countries in the Middle East. These countries face increasingly acute water shortages as demand for water exceeds its availability, making water resource management, planning and allocation an increasingly important issue.

Water plays a fundamental, pervasive, and critical role in every national economy. In the Middle East, however, water takes on a more complex and strategic role due to its relations to religion, natural security, and economic and social well-being (Star and Stoll 1988, Trolldalen 1996). As in every semiarid nation beset with periodic droughts, the fundamental problem of water scarcity is both in terms of quantity and quality.

The agricultural sector consumes more than 70% of water in Jordan, Syria, Israel, West Bank, and Gaza. Though agriculture accounts for less than 10% of GDP in the countries in the region (and less than 5% in Israel) water for agriculture is heavily subsidised in Jordan, Israel, and in the Palestinian Authority in order to achieve their political, social, and strategic objectives. These concerns completely override economic considerations and incentives at the expense of depleting water supplies for future generations.

With water demand exceeding available supplies in the region (see Figures 4.15 and 4.16), it is imperative to find tools for effective water demand management, since increasing supplies, through the only currently available means of desalinization and recycling of effluents, are long-term and costly alternatives. Agriculture is culturally embedded in the economy and highly symbolic politically, hence agricultural practices have to be developed which use water efficiently (Figure 4.17) and crops promoted which are not heavily dependent on water (e.g. Gisser and Pohoryles 1977).

Water resources management has become the key issue in preventing further environmental degradation in the Middle East. In moving towards the sustainable utilisation of water resources, there is a need to improve the understanding of the water resource situation, in particular the relation between surface water discharge, aquifer recharge and their respective sustainable yields. Map 4.28 is an example of a digital hydrographic map showing major aquifers, their geographical extent, as well as the surface hydrological network, a tool to help assessment of the relation between surface and underground water. Where such existing resources are transboundary (Figure 4.18), the lack of agreement on their joint management, or on the joint search for new and additional sources can become a dangerous point of friction and an impediment to regional development (Lowi 1993, Reguer 1993, Elmusa 1993).

The Madrid Conference in 1991 established a number of multilateral working groups as an integral part of the Arab-Israeli peace process. The multilateral talks were intended to compliment and support the bilateral talks. The working groups were conceived as a means of broadening the scope of the peace process and dealing with long-neglected practical problems. Among the five working groups, the Working Group on Water Resources was set up to encourage closer co-operation on water issues such as water resources availability and its sufficiency to meet the economic, social and environmental needs of the parties to the peace process. Many of the most sensitive issues, including allocation, were reserved for the bilateral track and it was agreed at the first meeting of the group in Vienna in 1992 to collect information on regional data and water management practices. The second meeting in Washington also reached consensus on data sharing, water management techniques and water supply enhancement. With the support of the Norwegian Government a Water Atlas was produced. At a later stage it was realised by all parties in the region that conflicts of interest over the allocation and use of water resources would have to be dealt with in a comprehensive manner. This implied that a regional perspective would have to be taken in the framework of multilateral track, in addition to the topics addressed during bilateral discussions.

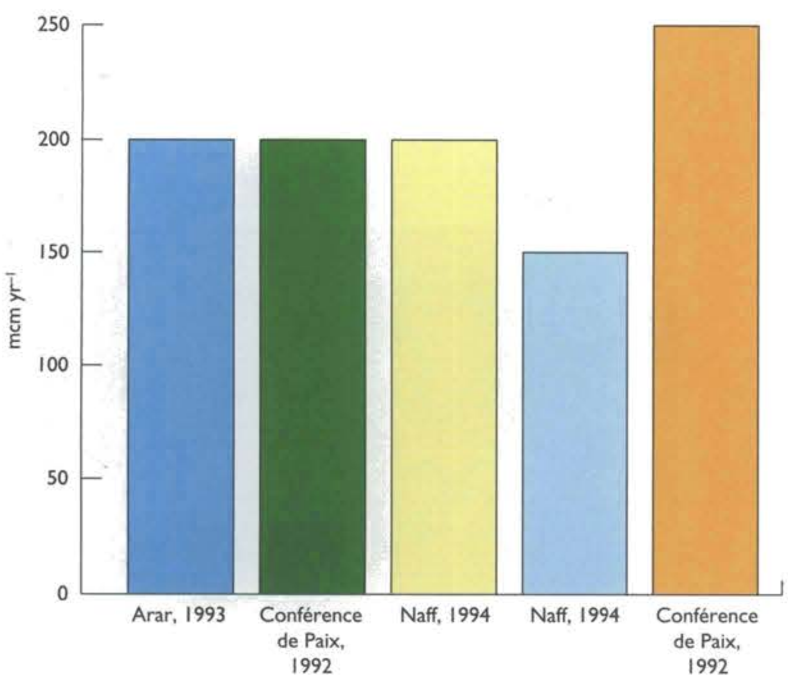


Figure 4.15 Estimates of the current annual water deficit in Israel

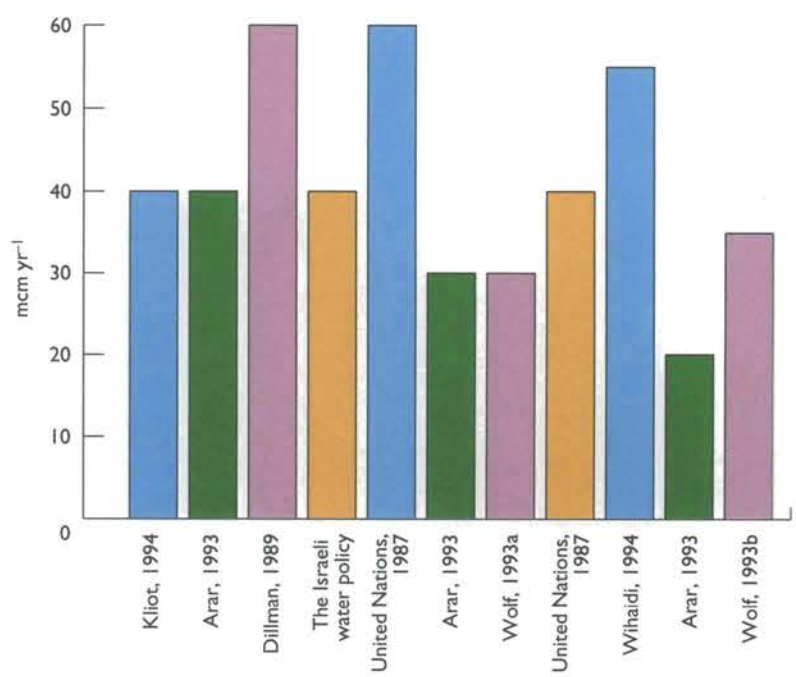


Figure 4.16 Estimates of the current annual water deficit in the Gaza Strip

The academic initiative leading towards a new negotiation process within the Mulitilateral Peace Talks

The conclusion of the new initiative was the first regional water agreement in the Middle East. After 2 years of intensive studies and negotiations, a final text of a water agreement was agreed on 13 February 1996. The agreement, entitled 'Declaration of Principles for Cooperation on Water-related Matters and New and Additional Water Resources' was made public on 12 June 1996 at a ceremony in Oslo.

There were four parts to the declaration:

- In a 'Joint Statement', the core parties agreed to combine their co-operative efforts in the development of newly-developed and additional water resources.
- The 'Common Denominators' listed eight items which were identified by the parties and form the major elements in their water legislation as a basis for co-operation.
- 'Principles of Cooperation on New and Additional Water Resources', which include detailed principles and provisions on co-operation among the participating parties. Of special relevance are agreements on mechanisms of co-operation; ownership and utilisation of new and additional water resources; technical, economic and financial issues; environmental management; operation and maintenance and areas of co-operation.
- Co-operation on other water-related matters, which outlines several ways for future co-operation such as data exchange, meteorological information, scientific and technical co-operation and early warning of flooding.

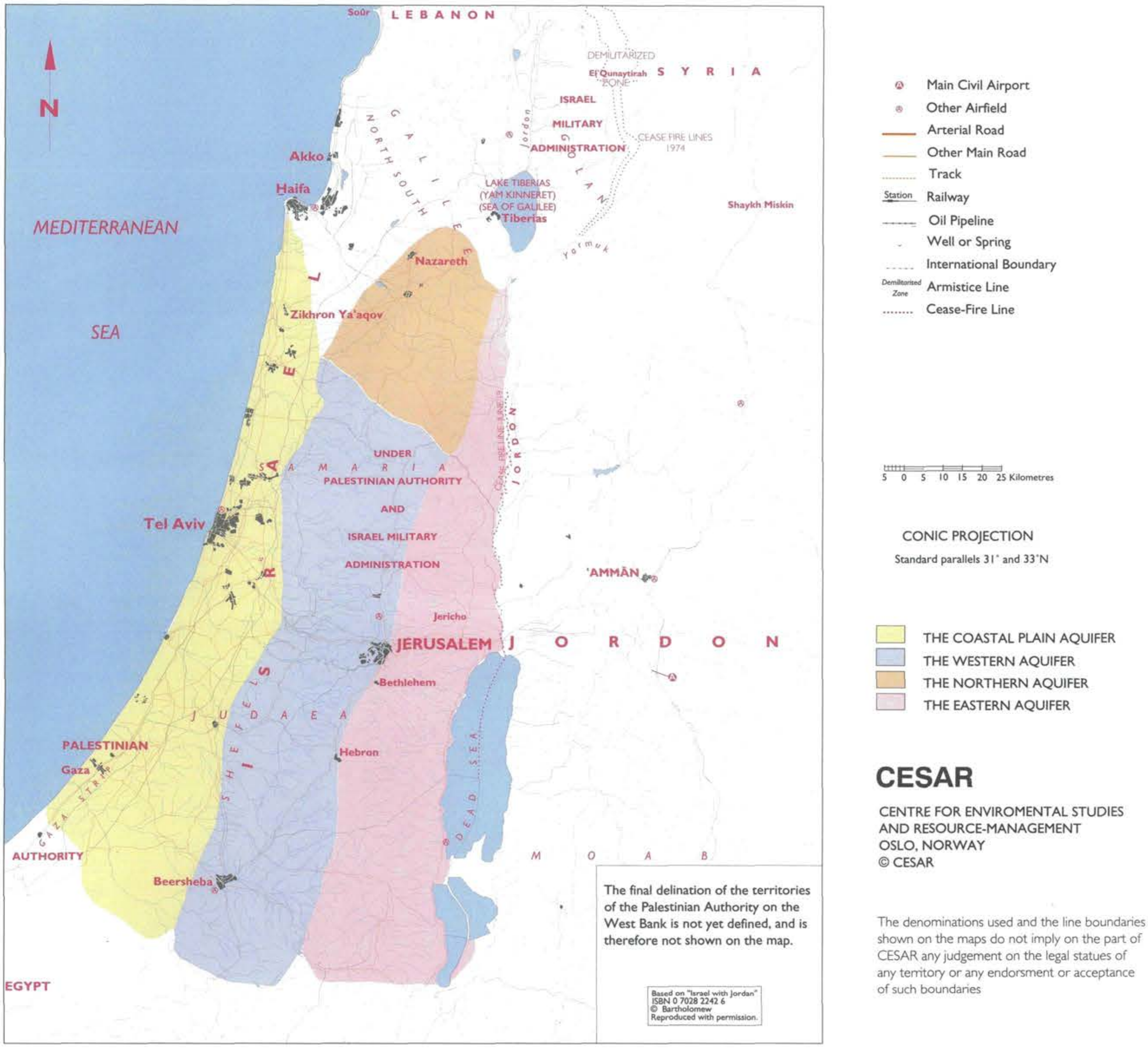
The voluntary agreement marks a significant step in the search for a just and lasting peace and paves the way for future co-operation in solving water resources problems in a region of the world where such problems have reached a high political dimension. The methodology adopted in facilitating the discussions which eventually reached consensus is based on non-judicial conflict resolution. A prerequisite was to reach basic understanding not only of the facts regarding the water resources situation in this part of the Middle East as they are presently available, but also to study jointly the water laws, water institutions and water supply economics in each of the affected territories.

Original text by Prof. J. Martin Trolldalen.

Figure 4.17 Plants grown under strips of plastic to conserve water on a West Bank kibbutz (Paul Harrison/Still Pictures)

Figure 4.18 Agreement on joint management for the various uses of water resources, such as the River Jordan which forms a political boundary along part of its course, is essential both to prevent environmental degradation and to ease political tensions (Paul Harrison/Still Pictures)

Map 4.28 Surface water resources and main aquifers of the Middle East study region



Desertification and Land Use in Mediterranean Europe

Introduction

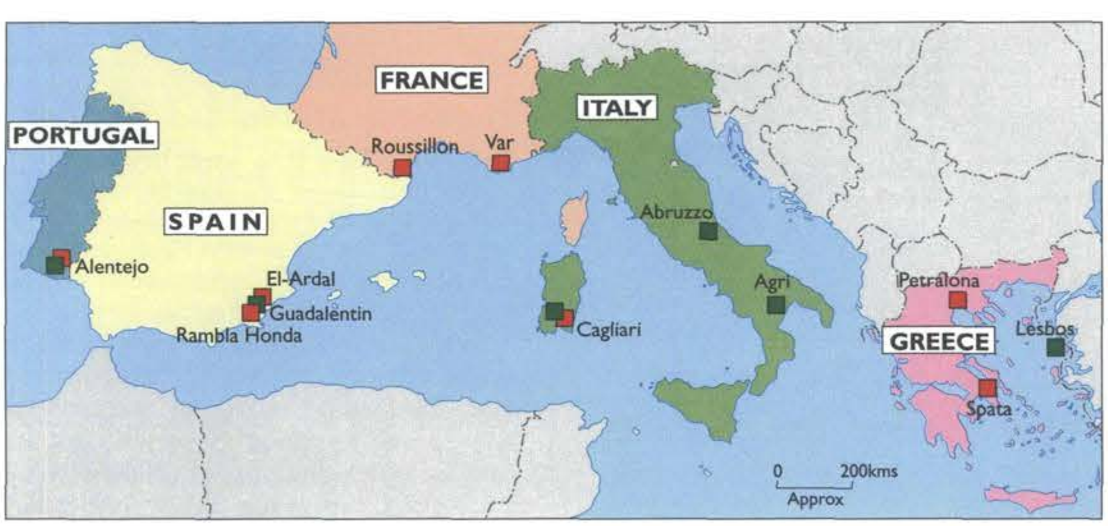
The Mediterranean countries of the European Union are experiencing significant problems of desertification and land degradation caused by a combination of factors (Perez-Trejo 1994). Some of these are related to climate and the underlying conditions of the soil, and others to inappropriate land use and policies at local to international levels. The good intentions of governing and policy-making bodies to generate jobs, work and wealth are leaving footprints of desertification behind them. The climate is highly seasonal throughout the Mediterranean basin (Conte 1995, Palutikof *et al.* 1996). July to September is dominated by hot dry conditions, with the winter wet season commencing in mid-October and extending through to late April. There is, however, notable spatial variability in the climate of the region. The wettest areas are southern France, the Balkan states and Italy. Parts of Greece and Turkey, southern Italy and the Iberian Peninsula are the driest areas. In Mediterranean Europe, true susceptible drylands only occur in Sicily, the heel of Italy, Sardinia, eastern Greece, southern Portugal and a large area of Spain (Map 4.29). Climate also displays marked temporal variability, for example a significant drought has affected many parts of the region in the 6 years since 1990.

The region has suffered from land degradation at least since the Bronze Age (Grove 1996), with significant landscape changes including marked erosion occurring during Greco-Roman times (Vita-Finzi 1969), though distinguishing climatic change impacts on ancient soil erosion from those resulting from human actions can be problematic. Landscapes throughout the European Mediterranean have been extensively modified through terrace construction over many centuries. Soils and vegetation have responded to, and evolved under, the impacts of anthropogenic fire and grazing (Blumler 1993). In recent years major changes in the population distribution have occurred with the abandonment of traditional dryland agricultural systems in areas away from the coast, the movement of people to the major cities and coastal areas and the development of irrigated agriculture and industry (Margaris *et al.* 1996). Changes have been accelerated by the incorporation of the region into the European Union, by the increasing demands of water from agriculture, industry and tourists and by higher standards of living. Flooding and erosion, groundwater depletion, salinization and loss of ecosystem integrity and function have attracted a response from the European Union which is trying to understand the underlying causes of desertification and provide the scientific basis for mitigation programmes. Several research programmes and many projects have been or are being conducted under the auspices of the European Commission Directorate-General for Science, Research and Development. The Mediterranean Desertification and Land Use project (MEDALUS) is one of these, and is now in its third phase of research.

MEDALUS – Mediterranean Desertification and Land Use

It is against this background that the MEDALUS project was started in 1991 (MEDALUS 1993). Since then, several hundred scientists have contributed to the overall project. In many cases research on desertification has had to commence with the collection of baseline data due to its initial absence. Information has been collected principally to allow the investigation of the underlying physical processes of desertification. This has been done at eight representative locations across southern Europe where harmonised data have been gathered (Cammeraat 1996). Due to the need for a broad European dimension to the project, some of the sites (Map 4.29) fall outside the susceptible drylands as defined in this atlas.

Map 4.29 The location of the MEDALUS Research sites in southern Europe. Those shown by red are the eight MEDALUS core programme sites. Target areas for research application are shown in green



Soil erosion and ecosystem models for projecting future desertification, including under the impacts of anthropogenically enhanced global warming, have been developed as part of MEDALUS research (Kirkby *et al.* 1996, Bathhurst *et al.* 1996). Fundamental climatological studies have been undertaken to establish past trends and to contribute to predicting future ones (Palutikof *et al.* 1996). Integrated studies using remote sensing and geographic information systems (GIS) have been carried out in target areas in Spain, Italy, Portugal and Greece, with a view to understanding landscape responses to disturbance (Boer 1996). The first phase of MEDALUS focused substantially on aspects of the physical environment. MEDALUS II and now MEDALUS III have greater socio-economic dimensions (Thornes 1996). Other major projects funded by the European Commission, such as the Anthropogenic causes of land degradation and desertification in the Mediterranean basin (ARCHAEOMEDES) programme (ARCHAEOMEDES no date) have human dimensions as their core components.

MEDALUS I consisted of foundation research on climatology, physical desertification processes, modelling, remote sensing and GIS and, to a limited extent, socio-economic factors (MEDALUS 1993). MEDALUS II, which was officially completed in 1996, built on these foundations (Table 4.10). The current MEDALUS III programme is an integrated study contributing to a concerted action on desertification and supporting the implementation of the Convention to Combat Desertification (CCD). It contains four subprojects the first of which continues the core activities of MEDALUS I and II. The second consists of regional case studies focusing on environmentally sensitive areas, the third is dealing with regionalisation in large areas and the fourth with river channel areas and floodplains.

The remainder of the summary of activities given here is devoted to some of the results and findings of MEDALUS I and II, to illustrate the nature of the desertification problem in southern Europe, the information being collected and the modelling and other tools that are being developed.

Table 4.10 The components of the MEDALUS II research programme

Project 1: The Basic Field Programme
General objective: *Continuation of MEDALUS I basic field programme and data archiving. Collection of field data necessary for quantifying and understanding the physical processes of desertification (mainly by water erosion) at the core programme sites.*

Actions:
1 Field monitoring, with routine measurement of 55 key environmental parameters.
2 Field studies of ecological dimensions of vegetation–water–grazing links.
3 Specific experiments related to desertification response units (see project 2) methodology.

Project 2: Environmental Analysis Modelling and Regionalisation
General objective: *Extension of physically based and agricultural system-based numerical models to the regional scale.*

Actions:
1 Development of sub-catchment scale models (Bathurst *et al.* 1996), including the use of the concept of desertification response units (DRUs) (Imeson *et al.* 1996).
2 Development of vegetation growth models (Kirkby *et al.* 1996).
3 Development of remote sensing methodologies for identifying land use (Harrison *et al.* 1996).
4 Application of a new GCM to provide climatic scenarios and the study of extreme meteorological events at the regional scale (Burton *et al.* 1993).

Project 3: Managing Desertification
General objective: *Investigation of problems of land and water resource management against a background of desertification and socio-economic change.*

Actions:
1 Examination of cultural, historical and socio-economic constraints on change.
2 Studies of land use management to control desertification.
3 Investigations of waste disposal dimensions of land degradation.
4 Implementation of models of water resource allocation.
5 Revegetation of abandoned sites.
6 Mitigation of salt water incursion to groundwater.

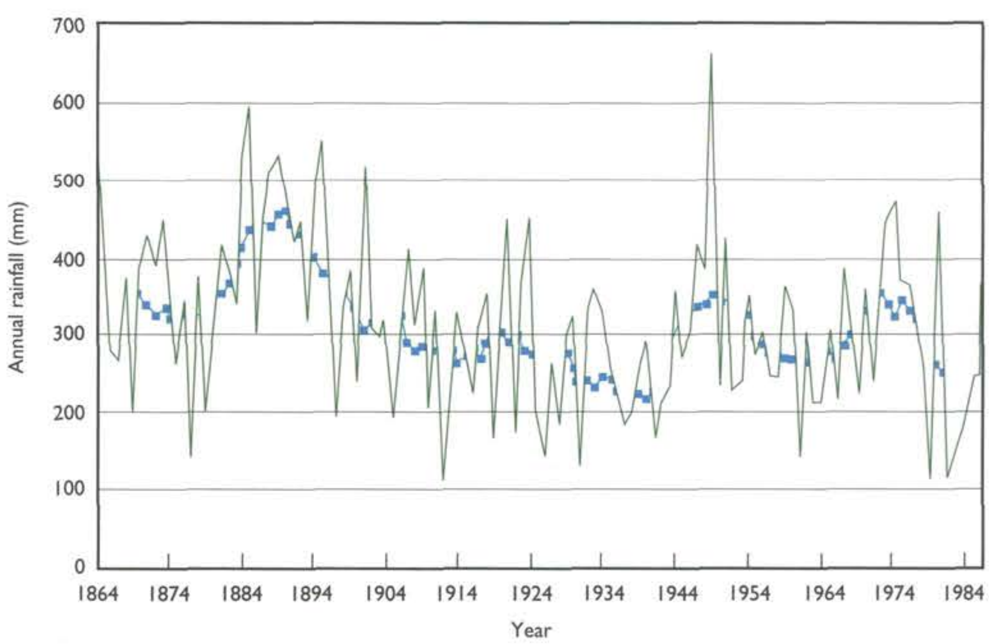


Figure 4.19 The trend of precipitation measured in the Guadalentin catchment, Spain

The MEDALUS research sites and target areas

The MEDALUS research sites are located in areas of southern Europe extending from the Alentejo region of Portugal in the west to Lesbos (Greece) in the east (Map 4.29). The areas are representative of major geo-ecological zones and land use types and histories and are all experiencing problems of land degradation. During the programme several of the study areas have been affected by severe drought and this is still the case for some parts of south-east Spain (Figure 4.19). At the eight sites indicated by the red squares, a common measurement programme was run between 1991 and 1996 designed both to collect data to develop and test the MEDALUS erosion model (Kirkby *et al* 1996), and to obtain data on key desertification processes specific to the site. At the green sites, integrated studies were carried out from 1994 or 1996 in specially selected target areas. The objective of research at the target areas has been to apply the findings from other areas and test the models that have been developed. In particular, environmentally sensitive areas are being used and efforts are being made to 'regionalise' findings and models; that is, to extrapolate findings and develop and test their applicability to large areas. The impacts of land use and climate changes are also being assessed.

The available data and information

The data and information collected at the eight field sites includes measurements of climatological, ecological, pedological, hydrological and soil erosion parameters (Table 4.11). These have been collected using agreed common protocols and methodologies, to allow genuine comparison of data. Together with maps, air photos and digital pictures of the research sites, much of this information is available with the MEDALUS soil erosion model on a CD-ROM. An example of the information for the Spata site near Athens in Greece can be seen in Figure 4.20.

Examples of desertification in the Guadalentin catchment

The Guadalentin Target Area, (Map 4.30) in the driest part of Europe provides good examples of the desertification problems occurring in Mediterranean Europe. Part of the research has involved establishing the area's sensitivity to erosion and desertification and collecting detailed data on relationships between land use change and erosion. This has involved applying the Desertification Response Unit (DRU) Methodology that was developed

Table 4.11 Environmental attributes being measured at the core field locations of the MEDALUS programme

ATMOSPHERIC PARAMETERS	SOIL PARAMETERS	VEGETATION AND LAND USE PARAMETERS
continuous	*continuous*	*seasonal*
autographic rainfall	open or bounded plot runoff	percentage cover
dry bulb temperature	micro-catchment runoff *	above ground biomass
wet bulb temperature	*one-off*	leaf area index
wind speed	bulk density	shoot elongation
wind direction	soil water retention curves	grazing patterns*
global radiation	soil profile description	grazing density*
event-based	soil depth	shoot and leaf arrangement
spatial distribution of rainfall	soil map	litter production
	infiltration characteristics	litter decomposition
SURFACE PARAMETERS	soil texture	primary production
continuous	soil chemistry	*One-off measurements*
nutrients	aggregation	species composition
periodic	soil fauna*	land use history
photography of surface	soil temperature*	vegetation cover type
site maps	*event based*	vegetation spatial pattern
plot maps	soil moisture	environmental sensibility
stone content/arrangement	surface runoff	
digital elevation model	sediment yield	
crusting	*periodic*	
cracking	soil moisture (weekly)	
roughness	soil organic matter*	
compaction	percentage soil covered by stones	
permeability of crust		(*)Not measured at all sites

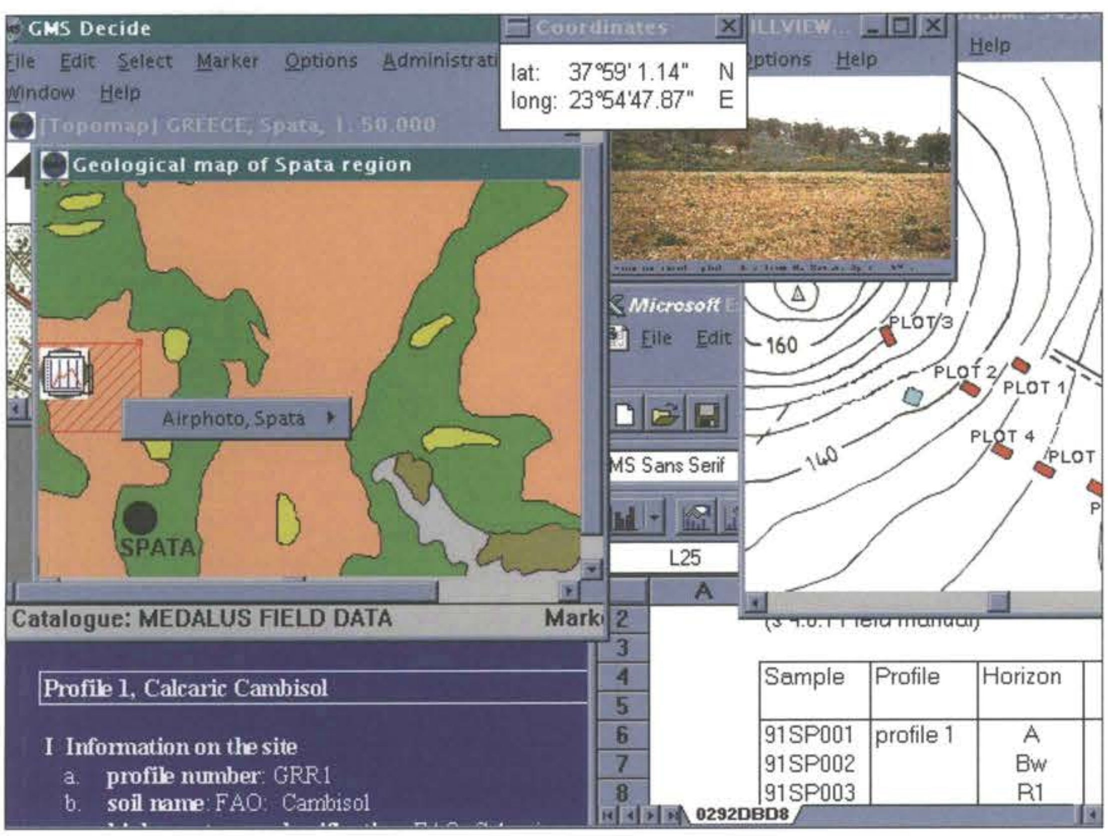
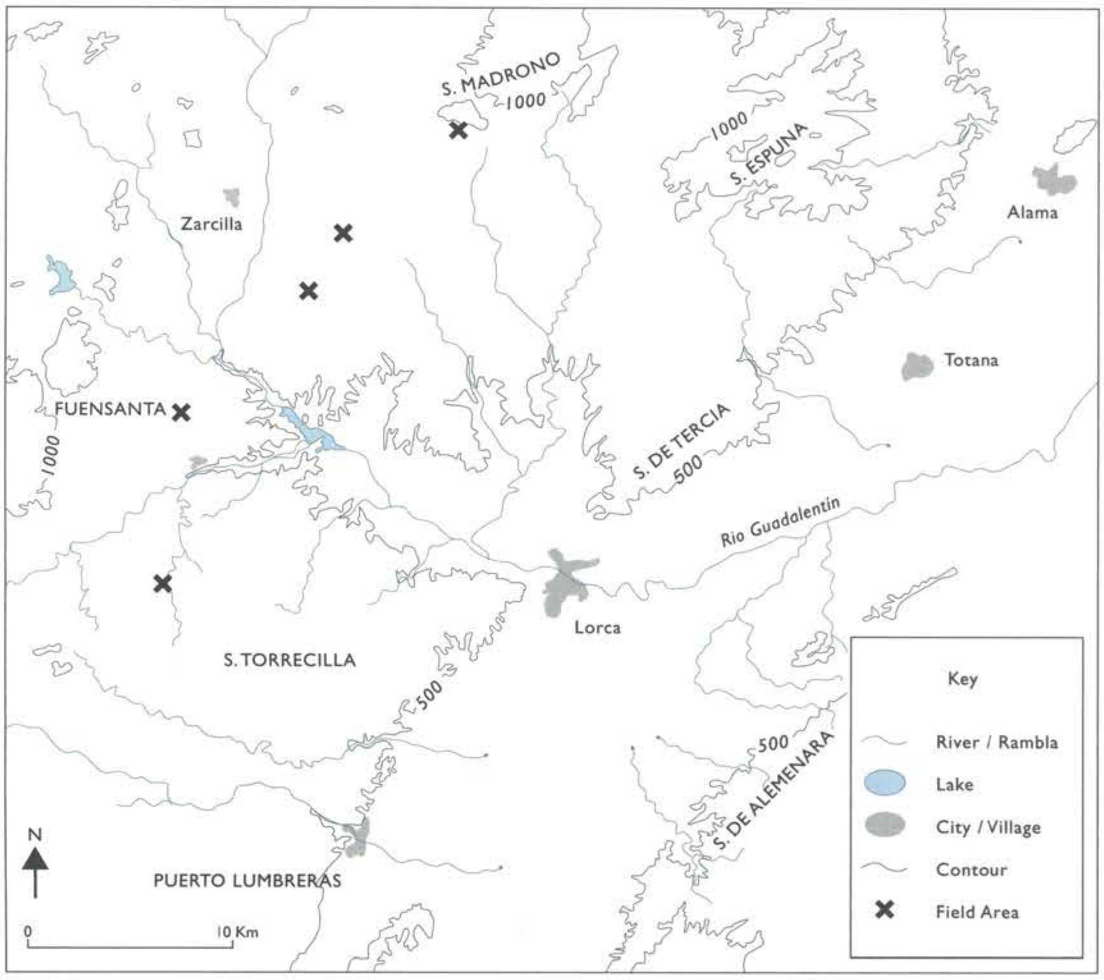


Figure 4.20 Example of data and information contained in the MEDALUS GeoManagement System, for the Spata Site, Greece

for the project (Imeson *et al.* 1996). Much of the physical research in MEDALUS has been at the patch scale, while environments actually evolve, and human actions take place, at the landscape scale. DRUs provide a link within the nested hierarchy of environmental units at which research and desertification occurs (Figure 4.21). An application of this is seen in Map 4.31, an area of marls and soft limestone that has experienced a complex history of land use change during the last four decades. Abandoned areas (Figure 4.22) often have thin soils and produce much runoff during extreme events and this forms a threat to downslope agricultural areas. Drought conditions hinder vegetation recovery and regeneration (Figure 4.23), but the problem is exacerbated by European Union agricultural subsidies that currently encourage pastoralism in the area. The most degraded and eroding areas are the former common grazing lands that were taken into cultivation due to an expansion of mechanised agriculture in the 1960s and which were abandoned, as systems failed, during the subsequent decades (Figure 4.24). Areas that have been used for irrigation also experience salinization problems (Figure 4.25). Soil degradation on some surfaces in unit C1 (Map 4.31) can be considered as irreversible, and the physical properties of the soils make them highly susceptible to gullying (Figure 4.26).

Map 4.30 The research area of the Guadalentin, showing the location of representative fieldwork sites selected for special study



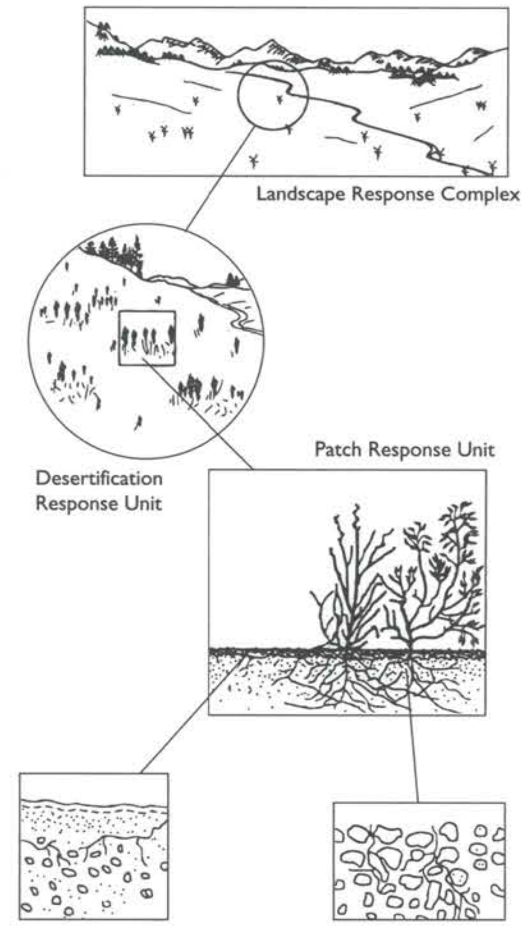
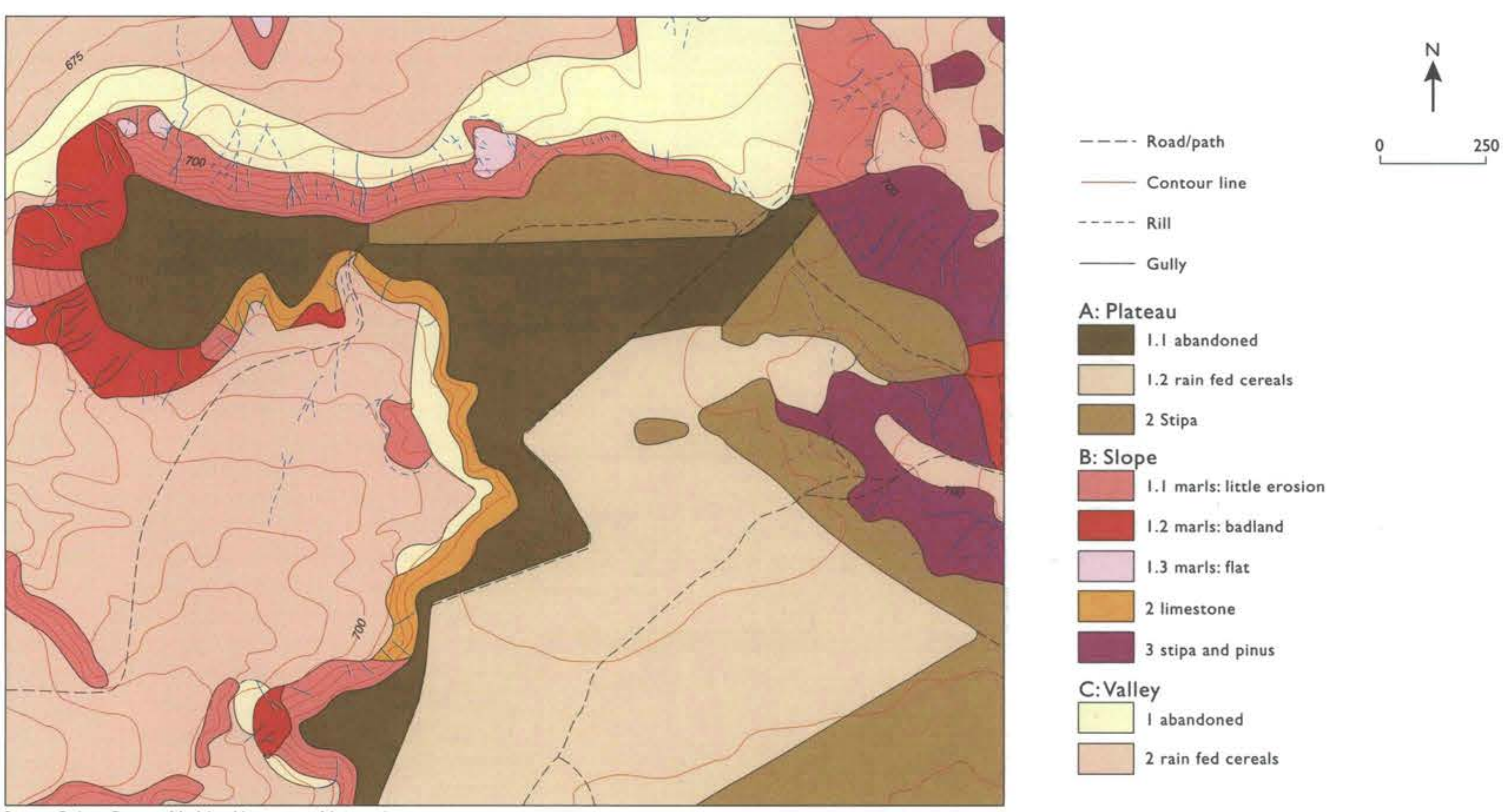


Figure 4.21 The Desertification Response Unit as part of a nested hierarchy of landscape units

Map 4.31 Soil erosion response units at the Canada de Cazorla research site



Source: Ruben Coppus, Medalus, University of Amsterdam

Figure 4.22 Effects of grazing and abandonment along lower river course in the Guadalentin

Figure 4.23 Area of marl and limestone affected by drought and overgrazing during the last decade

Figure 4.24 Land abandonment: an area previously used for wheat but now largely abandoned in the Guadalentin catchment (area of schist)

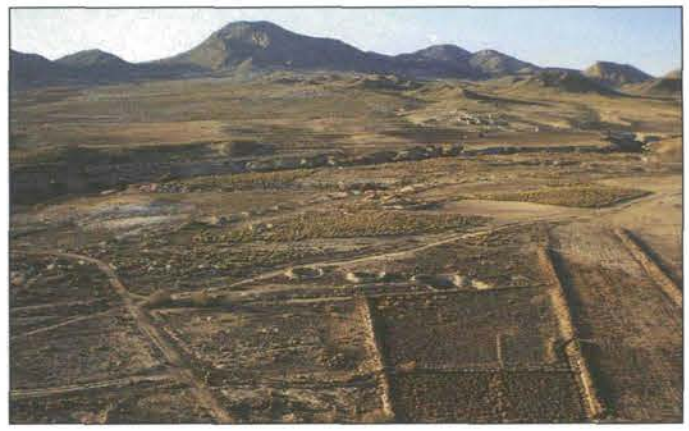


Figure 4.25 Desertified areas affected by salinization following irrigation in the Guadalentin

Figure 4.26 In Guadalentin marls have frequently developed badlands due to the chemical and mineralogical properties of the parent material

Figure 4.27 Example of plots at the Val Formosa soil erosion site that is in the Portuguese MEDALUS target area

The processes that cause desertification in the Guadalentin occur at different spatial and temporal scales. MEDALUS research has attempted to understand the development of, and linkages between, the patterns and structures in the landscape at different spatial and temporal scales. When process–pattern relationships can be understood, they can be used to identify any system stability and resilience. This understanding can generate important inputs to desertification rehabilitation programmes. These relationships are best investigated in small study sites, but the research is using remote sensing techniques to upscale findings to larger, regional scales. An example of a research site used to establish relationships between micro- and meso-scale desertification processes is shown in Figure 4.27.

Conclusions

The MEDALUS project is developing the scientific basis and modelling tools for understanding and evaluating the impact of the complex processes of desertification in southern Europe. The challenge during the coming decades will be to compare the knowledge gained and models developed in the programme with those obtained from studies in other regions, and to apply the findings within desertification mitigation programmes.

Developed from initial text and figures supplied by A.C. Imeson and L.H. Cammeraat with additional text by D.S.G. Thomas.

Biological Diversity in the Susceptible Drylands

Introduction

The biological diversity of susceptible drylands may be less well publicised than that of the tropical rain forest but many important crops and animals originate in the drylands and humans rely significantly on the biodiversity of these areas. Wheat, barley, sorghum, millet, many pulses and cotton, as well as many of the animals that have been closely linked to the development of human civilizations originated in the drylands. In the face of burgeoning human populations, the challenge is to maintain the species richness of the susceptible drylands within the context of sustainable environment management.

Some areas of the susceptible drylands are in fact wetlands (e.g. the Aral Sea). Wetlands play key roles in the local biophysical conditions and also in the global migratory patterns of birds. They have a significance far beyond their local expression. They also have unique and highly susceptible biological characteristics of their own. Large parts of many critical wetland habitats (including estuaries, mangroves, open coasts, flood plains and swamps) and the species they support, have been lost due to a wide range of human activities (UNEP 1995).

The biota of the drylands consists of a series of dynamic and delicate ecological balances. Dominant among these are the balances that have been established between herbivores, pollinators and vegetation. Vegetation requires nutrients; predators require prey; and herbivores need vegetation.

Productivity of the soil depends on a balance being maintained between vertebrates, invertebrates, microbial activity and nutrient fluxes related to seasonal changes, moisture and solar energy availability. The balances that have been established are not only bilateral ones, but complex interactions that fluctuate with seasons and vary from place to place. These have been referred to as 'symphonic guilds' of interacting organisms (UNEP 1995: 350). They are part of a complex web of life in the susceptible dryland ecosystems.

Biological diversity in the drylands is characterised by a high degree of within-species variation representing adaptation to the variable and sometimes extreme conditions (see page 136). There is a moderately high diversity of species in the drylands, except in the driest areas where specially adapted species predominate. Dryland species are highly adapted to environmental stress. This makes them a vital source of genetic material for improving crop varieties by increasing their resistance to drought and disease.

Predominant among the species in the dryland ecosystems are the micro-organisms, annual plants and the ground-living creatures such as predatory arthropods, ants and termites, grasshoppers, snakes, lizards, and rodents (UNEP 1995). There is also considerable variation in species richness among the drylands of different continental areas.

Some of the dryland species such as the large game animals are well known but other species are known only to specialists. The role of fungi, for instance, in the maintenance of the productivity of the soils is indispensable. The sub-surface life in the drylands vastly exceeds that above ground. Dryland plant species are also important sources of commercial and industrial products (see page 138–139).

Human impact on biodiversity

While the human use for commercial purposes of some dryland species has resulted in the loss of some and significant extensions in the range of others, the most widespread human-induced impacts on dryland biodiversity stem from the introduction of fire for hunting, clearance of natural habitats for cultivation and soil fertility improvement, and excessive grazing of livestock. Introductions of domestic and game animals have been accompanied by the creation of water points, encouraging concentration of livestock. The introduction of non-native plant species, the removal of non-palatable plants, and the removal of predators and of burrowing and herbivorous animals have all had impacts on the natural biology of the drylands. Construction of roads, canals, fences, dams and irrigation schemes has fragmented and even obliterated natural areas, replaced established species, and interfered with or blocked natural migratory routes.

Among the impacts on species diversity are the following:

- Disturbance of 'symphonic guilds' has had direct influences on the structure and functioning of dryland ecosystems. Changes in plant root systems affect the underground decomposers. Termites and nesting or burrowing mammals provide micro-environments that enhance decomposition and nutrient cycling. Their removal slows decomposition and increases the chances of loss or transport of nutrients from the surface (Whitford 1991).
- Introduction of hoofed livestock to regions lacking a recent evolutionary history of grazing is often accompanied by reduction of populations of native burrowing herbivores, thus reducing the soil disturbing activities of these animals (UNEP 1995).
- Conversion to agriculture may increase local nitrogen values but native plant species may be displaced and are notoriously difficult to replace (Jackson *et al.* 1991, UNEP 1995).
- Reductions in soil crusts may reduce nitrogen fixation, increase soil erosion and alter local moisture infiltration rates since microbial crusts play significant roles in nitrogen cycling and in stabilising the soil surface against erosion (Eldridge and Greene 1994).
- Replacement of native plants with non-native plants, to improve forage, or as invasive weeds, reduces local plant and animal diversity. Aquatic habitats are especially vulnerable to invasions of non-native plants.
- The loss of large woody species, overused for fuelwood or as carving material, negatively influences the persistence of many typical species of drylands plants (Franco and Nobel 1989, UNEP 1995).
- Introductions of large animals as game or livestock have often established wild or feral populations (e.g. horses, camels, oryx) that affect native vegetation and deplete or compete with native herbivores.
- High fire frequency reduces the number of tree species and the numbers of individuals per species in most savanna sites (San José and Fariñas, 1991). Fire frequency has increased considerably under human influence. As a result, tree/grass ratios have changed markedly.

Valuing biodiversity

Biological resources can be valued economically under two headings: direct values and indirect values (McNeely 1988). Direct values include values for consumptive use (e.g. fuelwood, wild animals hunted for food) and productive use values (e.g. plant-based drugs). In many rural drylands, wild foods form an integral part of everyday diets, as well as providing insurance against crop failure, pest attack or drought. The harvesting of wild resources also represents a ready source of income to cash-poor families which may amount to a significant proportion of total household incomes, particularly where farming is marginal (IIED 1995). The value of all wild resources to local people, for subsistence consumption or sale, was calculated to be more than US$120 million in Tanzania in 1988, representing 8% of the total agricultural contribution to GDP that year (Kiss 1990).

Wild resources also have indirect value which can be categorised into non-consumptive uses (e.g. wooded land which protects against flooding and may help to regulate local climate), option value for some future use (e.g. wild relatives of crops represent a storehouse of genetic diversity for future cross breeding: see Table 4.12), and the aesthetic value of a species by its very existence. Assigning realistic economic values to some of these indirect benefits can be particularly difficult. Although economic valuation is a useful way of making wild resources financially visible, it must be recognised that not all of these resources can be given a price tag. Nevertheless, such resources remain essential, at either local, national, or both scales (IIED 1995).

The Global Biodiversity Assessment (UNEP 1995: 890) tackled the problem of the assessment of the economic value of biodiversity in depth and concluded: 'Effective biodiversity conservation depends on the valuation of all goods and services provided by ecosystems in order to determine the configuration and combination of uses that best satisfy the interests of society.' As a recent IIED study (IIED 1995: 14) found:

> Combining economic concepts with participatory research allows for a more comprehensive valuation of wild resources, recognising not only the financial value, but also the indirect and non-use values. The local level valuation methodologies being developed should be made accessible to local communities to enable them to negotiate with powerful external interests and to enhance local natural resource management structures.

Policy responses

The drylands have been the bread basket of the world for centuries and many successful efforts have been made to avoid degradation at the same time as increasing productivity. In the last few decades, however, grand development schemes and mechanised agriculture have swept away the hedgerows and windbreaks, and the small mixed farms, and have fenced pastures and settled many nomads. Now it is realised that this trend has to be arrested and perhaps reversed.

Conservation of biodiversity is not necessarily incompatible with sustainable agriculture, since 'much of the genetic diversity on which the improvement and future sustainability of agriculture must depend is found in and around farmers' fields, in village woodlands and in grazing lands' (IIED 1995: 11). Good practices can and do increase sustainable productivity, reduce risk, maintain soil productivity, increase carbon storage, protect or restore biodiversity, prevent desertification and even restore areas which have become degraded.

Among the prime causes of biodiversity loss in drylands, as in other major world biomes, has been the destruction of habitats and trade in certain dryland plants and animals (or parts thereof). International trade has been curbed with legislation under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES – see page 139), while the conservation response has long been at the forefront of strategies to combat the threatened loss of biodiversity by habitat destruction. Conservation efforts have ranged from the lobbying of conscientious activists, through the designation of certain areas as protected areas, right through to draconian enforcement of Scientific Reserves/Strict Nature Reserves where people were excluded (sometimes after being displaced) and nature protected by armed guards or the military.

The conservation approach has achieved much in certain areas, and has led to increased understanding of the importance of biodiversity. In the drylands where 1.8 billion people live and where more than a billion of these people are directly dependent on agriculture and the land for their survival, conservation efforts have faced major economic and livelihood hurdles. So it has been realised, for example, that exclusion of indigenous people from the conservation areas is neither productive nor sustainable. Unless the people also benefit in economic terms, effective conservation or sustainable use of biodiversity is unlikely to become a reality.

As in other cases where emerging issues are identified, high quality, reliable assessments of the problem, monitoring of its progress and the success of efforts to overcome it are essential. A first Global Biodiversity Assessment was carried out by UNEP and partners and is drawn on extensively here, while the Survey of Economic Plants for Arid and Semi-Arid Lands (SEPASAL – see page 139) has taken this work further for dryland flora. But much more needs to be done in the drylands, which have not yet attracted the attention of the global conscience leaders nor of the financiers.

Table 4.12 Examples of the productivity contributions of wild relatives of crops

Crop	*Found in*	*Effect on production*
Wheat	Turkey	Genetic resistance to disease; valued at US$50 million per year
Barley	Ethiopia	Protects California's US$160 million per year crop from yellow dwarf virus
Beans	Mexico	Genes from the Mexican wild bean used to improve resistance to the Mexican bean weevil which destroys up to 25% of stored beans in Africa and 15% in South America
Grapes	Texas, USA	Texas rootstock used to revitalise the European wine industry in the 1860s after louse infection

Source: after WCMC (1992)

Conclusions

Land degradation and desertification are intricately linked with people's utilisation of productive natural resources and the only viable key to the successful maintenance of dryland biodiversity in the long term is to modify the human use of these environments. As the IIED study concluded:

> Incorporation of indigenous crops and other native plant germplasm in the design of self sustaining agro-ecosystems should ensure the maintenance of local genetic diversity available to farmers. *In situ* management of wild genetic resources is likely to be the most effective conservation method in the long term. (IIED 1995: 11)

Since the key to changing policy is so often the demonstration of the economic valuation of the policy options, their costs as well as their benefits, the Global Biodiversity Assessment concluded:

- The allocation of biological resources on the basis of current market signals is inefficient and inequitable. It leads to losses in social welfare. Moreover, these losses are distributed in a way that bears most heavily on both the poorer members of this generation and all members of future generations. An appropriate strategy for biodiversity conservation should address both the efficiency and equity issues. Valuation is an essential element of this process.
- Efficiency and equity both require the development of effective institutions and incentives that will (a) confront resources users with the full social cost of their behaviour, and (b) enable those who invest in conservation to appropriate the benefits.
- Traditional approaches to protected areas have sometimes worked against the interest of local populations by removing traditional rights of access to the resources in protected areas and the benefits of that access, thereby taking responsibility for management of the area away from local people.
- Preserving biological resources through nature reserves and other protected areas may be an important short-term step where biological resources are under immediate threat. But it is not feasible to protect critical ecological systems by excluding human users of wild resources.

The conclusions, recommendations and options for maintaining biodiversity in the susceptible drylands are thus very similar to those for successfully combating desertification in general. As each element involved in effective sustainable environment management is studied, so the commonality of need and approach becomes clearer. In order to combat desertification and conserve biodiversity effectively, sustainable environmental management must be achieved.

Original text by Franklin Cardy.

Dryland Plants and Their Use

Introduction

The climatic characteristics of drylands contribute to the survival strategies of plants. Despite moisture deficits at a range of temporal scales, and the harsh temperature regimes and high variabilities, there are normally plants of some form in most dryland settings, perhaps invisible but present none the less as seeds or as dormant tissue below ground. Even the Rub' al Khali, the Empty Quarter of Arabia and one of the most inhospitable places on Earth, has as many as 37 species of flowering plants. The focus here is on the plants of tropical and subtropical drylands, excluding anywhere with a mean temperature of < 0°C in the coldest month (such as much of Central Asia and Central North America).

Dryland plants have their own communities, structures and characteristics, some of which are far-ranging whilst others are more closely associated with particular areas – for example cacti in the Americas, acacias in Sub-Saharan Africa and the white-barked Ghost Gum (*Eucalyptus papuana*) in Central Australia. Many dryland peoples, especially in developing countries, rely significantly on indigenous plants for food and livelihoods, but the resource base may be far smaller than in humid areas. While many dryland plants are harvested and used locally, some also enter the market economy at some level, whilst a few even reach international trade.

In drylands, as in other areas, there are pressures affecting the relationships between people and plants. Political measures constrict the movements of nomadic peoples; increasing human and livestock populations diminish plant resources; dryland rainfall regimes change, perhaps because of human activity elsewhere; and traditional knowledge about plants and ecosystem management gradually disappears in the face of external pressures. The special needs of drylands are recognised in the United Nations Convention to Combat Desertification (CCD). Links between people and plants clearly underlie one of CCD's two objectives: 'improved productivity of land, and the rehabilitation, conservation and sustainable management of land and water resources, leading to improved living conditions, in particular at local level'.

Plant communities and coping strategies

The least known dryland plants are small ones that live in soils, rocks and even under light-transmitting stones. They comprise cyanobacteria, algae, lichens (associations of algae and fungi), and bryophytes (mosses and liverworts) and together they commonly form crusts over extensive areas of drylands (fungi too are present – but are not plants). Along the coastal strip of the Namib Desert, for example, lichens are so extensive and dominant a life-form that they can be detected by remote sensing. All these micro-organisms have a great impact on both physical and ecological processes such as soil nutrition, erosion control, nitrogen fixation, and the establishment of the seeds of higher plants. Indeed the crusts that they form on the soil surface are increasingly believed to be indicators of a healthy land condition.

Higher plants, including ferns, gymnosperms (such as conifers) and flowering plants, and their life cycles are better known. The conservation of water is not a problem for annual plants in drylands, which may complete their entire life cycle within a few weeks and can offer spectacular displays of flower colour, for example in Namaqualand in South Africa (Figure 4.28). Perennial plants have a number of quite different means of surviving the season of drought. The Creosote Bush (*Larrea tridentata*) of North America and the Mesquite (*Prosopis juliflora*), a widespread tree native to Central and South America, both have deep roots tapping underground water sources. Succulent plants store water in specialised tissues and often lack or have only rudimentary leaves. Shedding all leaves at times of water stress is a very common adaptation. Many species have spines which reduce incipient radiation as well as offering protection against browsing animals. Stomata, through which plants lose water by evapotranspiration, may lie in grooves or furled up leaf surfaces or may even be closed by day and open by night in those species which photosynthesise by fixing carbon at night. The living stone plants (*Lithops*) of southern Africa reduce exposure by being almost entirely underground, and have translucent, flattened leaf tips which allow light to reach the subterranean parts of the leaves. In the coastal Peruvian Desert, bromeliads (*Tillandsia* spp.) dispense with roots altogether and obtain all their moisture from fogs. The fogs of coastal Namibia, where mean annual rainfall is less than 50 mm, are the main source of water for plants such as *Trianthema hereroensis* and *Stipagrostis sabulicola*, but the uptake method is quite different for each of them, respectively by direct foliar absorption and by a lattice work of shallow roots exploiting moisture condensed on the surface of the dunes where they grow (Louw and Seely 1982). One adaptation common to virtually all dryland plants is the ability of their seeds to withstand desiccation and survive from one growing season to the next.

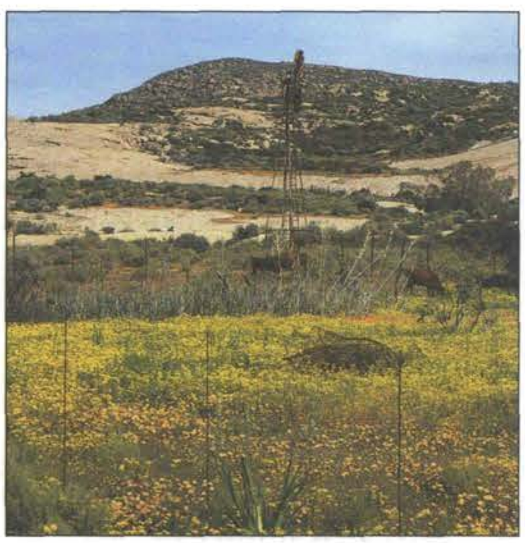


Figure 4.28 Flowering annuals in Namaqualand, South Africa, are an important tourist attraction in this dry region. The best displays are provided in recently ploughed or disturbed areas (DSG Thomas)

Centres of dryland plant diversity

The Centres of Plant Diversity (CPD) project (WWF and IUCN 1994–97) has set out a basis for conserving plant communities and biodiversity. Worldwide, areas have been identified which, if conserved, would safeguard the greatest number of plant species. Some 234 'first order' sites are included, selected on the basis of the total number of native and/or endemic higher plant species. Other criteria for site selection included the presence of important gene pools of useful plants, the range of habitats represented, and the degree of threat to the site. As the criteria for selection focused on floristic richness, the vast majority of CPD sites are in the wet tropics. However, a number of dryland areas qualify (Table 4.13). It should be noted that many of the sites contain a range of different habitats, including humid areas within dryland areas. The next challenge is to ensure the floras of these sites are adequately conserved. Some, such as Hobyo in Somalia, are reasonably well safeguarded by their isolation and low human population density, whereas others, such as Madagascar, are under severe pressures. Conservation prescriptions will vary from site to site, and will need to be formulated with local people's input and with respect to traditional land management practices and resource rights.

Unless political boundaries coincide with the bioclimatic boundaries of plants and plant communities, or there has been a specific project to find out, reliable numbers for species are generally difficult to obtain for most dryland areas. Over 1900 native higher plants

Table 4.13 Centres of Plant Diversity (CPD) sites containing significant areas of tropical drylands (excluding subhumid areas) (WWF and IUCN 1994–97)

Code[a]	*Site*	*Area (km²)*[b]	*Flora*[c]	*Endemism*[d]	*Type(s) of dryland vegetation*
Madagascar					
IO1	Madagascar (whole island treated as site)	587 000	9345	dry Southern Domain has highest level of endemism in the island's flora	dry deciduous forest and deciduous thicket in the south-west, including *Adansonia, Pachypodium* and Didiereaceae (endemic family)
Namibia/Angola					
Af50	Kaokoveld	70 000	952*	at least 116 (12%)	desert vegetation, including *Welwitschia*, savanna
Somalia					
Af42	Cal Madow	9600	1000	high species endemism	lowland semi-desert and bushland, to dry montane forest, with *Boswellia* (frankincense) and *Commiphora* (myrrh)
Af44	Hobyo	3000	<1000	high species endemism	dune vegetation, deciduous bushland
South Africa/Namibia					
Af51	Western Cape Domain (Succulent Karoo)	111 212	5000	1750 (35%)	mostly succulent shrubland with associated annuals, extremely rich in Aizoaceae, Crassulaceae and Euphorbiaceae; high succulent diversity, unparalleled worldwide
Australia					
Au3	Central Australian Mountain Ranges (and surrounding areas)	168 000	1300	120 (9%)	grasslands, shrublands, woodlands, rock and cliff communities; the site contains 65% of the known flora of Central Australia
Au7	South-west Botanical Province	309 840	5500	2472 (45%)	semiarid scrub in north and east of province
Mexico					
MA12	Central region of Baja California peninsula	36 000	>500	*c.* 100 (20%)	desert vegetation, including Cactaceae and 10 endemic genera
Mexico/USA					
MA11	Apachian/Madrean region	180 000 (whole region)	4000	–	thorn scrub and other desert vegetation, including Cactaceae, in Chihuahuan and Sonoran deserts
Ecuador					
PO7	Galápagos Islands	7900	541*	229 (42%)	xerophytic scrub, including endemic Cactaceae, in lowlands
Brazil					
SA19	*Caatinga* of north-eastern Brazil[e]	1 000 000		6 endemic genera	xerophytic deciduous forest to sparse scrub, savanna, *cerrado* and grassland
Chile, Peru					
SA42, 43	Lomas formations (including those of the Atacama Desert)	>7000	>930	>60% endemism in Chile; 42% in Peru	desert vegetation of annual, short-lived perennials and woody scrub
Iran					
SWA10	Touran Protected Area Biosphere Reserve	18 604	1000	contains most of the *c.* 150 endemics of the Central Iranian deserts	semi-desert, xerophytic and halophytic communities
Oman/Yemen					
SWA1	Dhofar Fog Oasis	30 000	900	*c.* 60 endemics; two dry endemic genera, *Dhofaria* and *Cibirhiza*	dry deciduous woodland, shrubland, semi-deciduous thicket and grassland to desert shrubland and open desert
Yemen					
SWA4	Socotra	3625	815*	230–60 (28–32%)	semi-desert and dry deciduous shrubland, including *Boswellia, Commiphora* and *Dendrosicyos*

Notes:

a Site codes follow WWF and IUCN (1994–97).

b Refers to the total area of a CPD site. For large regions this is sometimes an estimate to the nearest 100 km² or 1000 km².

c Estimates for the number of indigenous higher plant species for the whole CPD site based on current botanical knowledge. An asterisk (*) denotes exact number of indigenous higher plant species so far recorded from the site.

d Refers to the number of species whose distribution is restricted to the CPD site. Where a site contains a range of vegetation types, it has not been possible to determine endemism for the arid and/or semiarid component.

e The area covered by *caatinga* vegetation itself may in fact be closer to 600 000 km², and comprise *c.* 10 000 species.

are found in Australian dryland areas (Jessop 1985). 1200 species are found in the Sahara region from the Atlantic to the Red Sea (Ozenda 1977, Takhtajan 1985). Niger and Oman are entirely within drylands and coincidentally both support 1180 species (Davis *et al.* 1986, Ghazanfar 1992). Despite the apparently limited data for tropical drylands, put into context, their broad floristic composition is far better known than for tropical rain forest areas.

Use of dryland plants

Plants have long had great value to societies subsisting in drylands (Figure 4.29). There are many dryland plants that transgress geographical boundaries and occur in different regions and continents, and some have attained great utility for the populations of different areas, though precise uses vary from place to place. A good example of all this is *Dodonaea viscosa*, a member of a largely Australian genus. *D. viscosa* is found in many areas, including areas throughout the Pacific, South America, the Sahel, the Karoo, Arabia, east Asia and China. Depending on location, even within Australia it can vary from a multistemmed shrub 1.5 m high (in drier areas such as the Great Victoria Desert) to a tree of 6 m (for example in wet sclerophyll forests) (West 1984).

Its uses too are very diverse. Leaves are chewed like Coca (*Erythroxylum coca*) in Peru and it is known as Native Hop in Australia for its former use as a substitute in beer making. In Botswana it is an important bee plant. In many places its qualities as a good firewood, igniting readily, have been recognised, as has its potential for carving and as a hedging material. From Gabon and Nigeria, to the Sudan, India and the Philippines, *D. viscosa* is a well-known febrifuge, whilst an infusion of the roots has been claimed as one of South Africa's oldest remedies for the common cold. It is also an important fodder plant in Australia, but geographical variability may account for its apparently low palatability to livestock elsewhere.

The Argan (*Argania spinosa*) is a dryland plant whose ecological, economic and cultural importance is closely interlinked (Prendergast and Walker 1992), and it is the only species of its family north of the Sahara. To local people it is important in a number of ways (Figure 4.30). Its timber is dense and strong and makes a charcoal more highly prized than less traditional sources such as Australian *Eucalyptus* species. Despite an armament of thorns, Argan trees are heavily browsed by goats. The seeds provide a highly nutritious cooking oil which is three times the price of olive oil. The Argan is not threatened at the species level but its populations are as a function of clearance and land degradation pressures.

Some dryland plant species have assumed national or regional importance as trading commodities. Two examples show the relative novelty of such trade and how it is being threatened. In the Sonoran Desert of Mexico and USA the Ironwood (*Olneya tesota*) is a species of both ecological and economic importance. Ecologically it acts as a nurse plant for other species, including cacti, by creating favourable microhabitats for germination and seedling establishment and it is important too for the survival of many animals. Local people have traditionally carved Ironwood to make implements needed for their hunter-gatherer lifestyle. From the 1960s, the demand for Ironwood trees has increased as carving for the tourist trade has become an important economic activity. Now up to 3000 craftsmen are involved, using an estimated 5000 tonnes per year of Ironwood. However, land clearance for agriculture and charcoal production is threatening Ironwood availability.

In southern Africa the palm *Hyphaene petersiana* is an important species with a diverse range of uses. Its large strong leaves are used in basket making, its fruits are edible, and its timber used for building and fencing. In north-central Namibia baskets are almost exclusively destined for local or regional markets (Konstant *et al.* 1995). In the early 1990s the annual offtake of leaves amounted to 10%, within sustainable levels estimated at 30% per annum, but now severe browsing by livestock is a threat to the palm's regional survival. In Botswana subsistence basket making was turned in the 1970s into a commercial venture for the tourist and export market (Cunningham and Milton 1987). The effects of a seven-fold increase in the value of the industry from 1976–82 reduced both leaf availability, especially near settlements, and the possibility for the species to reproduce through seed.

Any destructive harvesting of dryland plants has to be closely reviewed given the low natural productivity and long regeneration time. In Western Australia, the highest quality incense oils from Sandalwood *Santalum spicatum* are produced from trees in semiarid areas (Loneragan 1990). Exports worth US$10 million/year are made to the Far East. Whole trees (including their root systems) are harvested but it takes from 50–90 years in these areas for them to reach a commercial size. The sustainability of the trade depends on controlled exploitation and, eventually perhaps, cultivation.

Of the quarter of a million or so species of higher plants, relatively few have become so valued that they are traded globally. Among dryland plants one of the most important is Frankincense (*Boswellia sacra*). The Ancient Egyptians were using incense (the tree's resin)

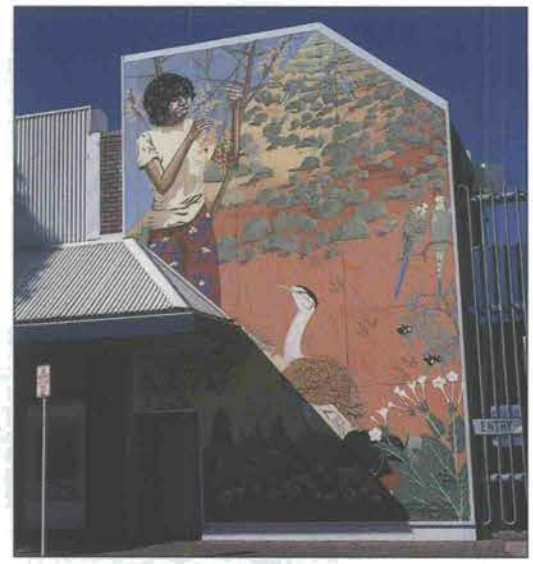


Figure 4.29 Mural depicting the gathering of wild foods, Alice Springs, Central Australia (HDV Prendergast)

by the 5th dynasty (*c.* 2800 BC); Greek and Roman physicians, as well as those of India, applied it to an impressive array of illnesses; and today it is still burned in religious ceremonies and used medicinally. Originally Frankincense was traded from the hills of Dhofar in southern Oman where, within Islamic times, the local kings controlled the trade and commanded extraordinary wealth (Miller and Morris 1988). Although official trade statistics are now scarce, Somalia and Ethiopia have been the main exporters since the 1970s, with China the leading market (> 1000 tonnes in 1984). The 1994 price for top quality incense from another *Boswellia* species (*B. frereana*) was US$6/kg (Coppen 1995).

Another internationally traded dryland tree resin, but of far higher commercial value, is

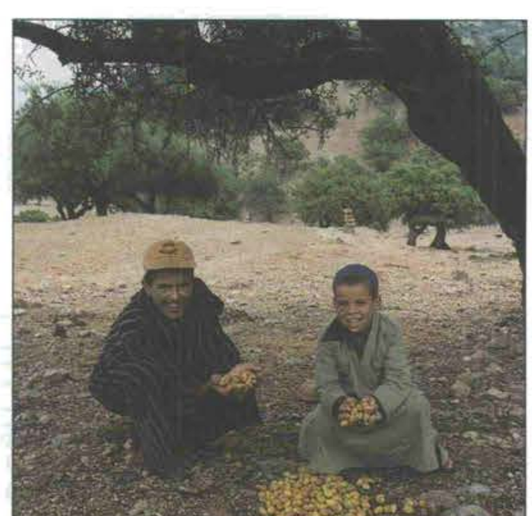


Figure 4.30 Argan fruits near Tamanar, Morocco (HDV Prendergast)

Gum Arabic, a polysaccharide produced by *Acacia senegal*. Its high water solubility and low viscosity confer much prized emulsifying, stabilising, thickening and suspending properties which are exploited in many food products, in the pharmaceutical industry for the manufacture of tablets, in the printing industry for treating lithographic plates, and in ceramics for strengthening clay. The production of Gum Arabic is greatly affected by the vagaries of climate, such as the severe Sahelian drought of 1973–74 which halved Sudanese exports in 1975 to about 20 000 tonnes (Coppen 1995). In 1991 the European Community, the largest market for Gum Arabic, imported a total of 32 100 tonnes, 17 100 tonnes from the Sudan, whilst the USA imported a further 8300 tonnes. Since top quality Gum Arabic from the Sudan has a market price of about US$5000 per tonne, it is a considerable foreign currency earner. The source is still 'wild' although exploitation is now also taking place of the plantings of *A. senegal* established for desertification control. To collect the gum a strip of bark is levered up and off the wood, causing minimal damage, and the tears of gum are subsequently picked by hand. Although yields are variable, *c.* 250 g/tree/year is cited usually as an average (Coppen 1995). The development of the Gum Arabic industry has focused on establishing new countries, like Kenya, as suppliers but there is still a need for research on a number of agronomic aspects, including assessments of yields in both wild and planted populations. A potential threat to the trade is the manufacture of synthetic alternatives.

The Economic Botany Data Collection Standard (Cook 1995), developed by the International Working Group on Taxonomic Databases for Plant Sciences, provides a system whereby plant uses (in their cultural context) are described, using standardised descriptors and terms, and attached to taxonomic data sets. The 13 LEVEL 1 states (Table 4.14) cover all uses of plants, and are divisible into a variable number of Level 2 states (there are a total of 107). The Survey of Economic Plants for Arid and Semi-Arid Lands (SEPASAL, Davis *et al.* 1997) uses this standard scheme. The sorts of plants it deals with are now being internationally recognised for their importance as traditional resources (D. Posey in Hinchcliffe 1995). By early 1997 SEPASAL contained information on about 6100 dryland species worldwide. The top four families represented are the Leguminosae (1152 species), Gramineae (769), Compositae (352) and Chenopodiaceae (217) and the top four LEVEL 1 uses are *animal food* (2689 species), *food* (2306), *materials* (2173), and *environmental uses* (1986). Among the latter's 11 Level 2 states, Erosion Control has the most species currently ascribed to it (571) apart from Ornamentals (762), with 158 and 153 species from the Gramineae and Leguminosae respectively. An important feature of SEPASAL is its ability to search for particular keywords and combinations of characters, and its application to answering enquiries about dryland plants. As well as data on plant uses, there are other fields such as plant descriptions, vernacular and trade names, sources of seeds and details on soils and climate tolerances.

Conservation legislation

International trade in certain plants has reached critical levels. Between 20–30 000 species worldwide are now covered by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES, see Mathew 1994). Among them are many groups of plants with characteristic adaptations to dryland environments, such as succulence. Many of these plants are highly prized, and their wild populations often threatened, by plant collectors. CITES has two lists of species: Appendix I species whose trade is prohibited except in exceptional circumstances (for example to promote conservation); and Appendix II species whose export or re-export requires certification. Appendix I species include all species in the cactus genera *Ariocarpus*, *Discocactus* and *Turbinicarpus*; *Agave arizonica* and *A. parviflora* from North America; and all 50 or so species of cycads *Encephalartos* from Sub-Saharan Africa. Appendix II is by far the bigger for it includes all *c.* 2 500 species of Cactaceae, all 700 or so succulent species of Euphorbiaceae, all *c.* 340 species of the largely African genus *Aloe* except *A. vera* (originally from the Canary Islands and now widely cultivated for its medicinal properties such as wound-healing) and all six species of *Alluaudia* which are endemic to the dry thorn forests of south and south-west Madagascar. In addition to CITES, many species are covered by special national or regional legislation; for example Madagascar has a 1983 decree banning the export of many succulent *Euphorbia* and rare *Pachypodium* species and the European Union has its own more rigorous regulations. *Guaiacum officinale* and *G. sanctum* (Figure 4.31), important for timber and resin in the Americas, are now listed in Appendix II as commercial and local demands have depleted stocks.

Conclusions

The loss of local plant knowledge, and its close connection with the loss of the plants themselves, is a key issue facing drylands. This is acknowledged in the CCD: for example Article 17 (Research and Development) binds parties to support activities that 'protect, integrate, enhance and validate traditional and local knowledge, know-how and practices'. Traditional land management techniques, now attracting the attention of ecologists and land managers, are part of this knowledge, as is the ability to find, harvest and process those wild' (but probably partly tended) plants needed for foods, medicines, fuels, fibres and other uses on a daily or seasonal basis. Such plants can be vital to the survival of people at particular times, for example during drought, and especially for women, children and the poor. They may also have significant values in local economies and contain gene pools of cultivated dryland plants. Yet social and environmental changes are threatening the continuity of traditional knowledge. If desertification and other changes are to be reversed, such knowledge, from ecosystem level down to species level, will need to be recorded for the benefit of people, plants and the places where they live.

Original text by H.D.V. Prendergast, S.D. Davis and M. Way.

Table 4.14 LEVEL 1 states

Level 1 states	Level 2 states (environmental uses)
Food	Unspecified environmental uses
Food additives	Erosion control
Animal food	Shade/shelter
Bee plants	Revegetators
Invertebrate food	Indicators
Materials	Soil improvers
Fuels	Ornamentals
Social uses	Boundaries/barriers/ supports
Environmental uses	Agroforestry
Vertebrate poisons	Firebreaks
Non-vertebrate poisons	Pollution control
Medicines	
Gene sources	

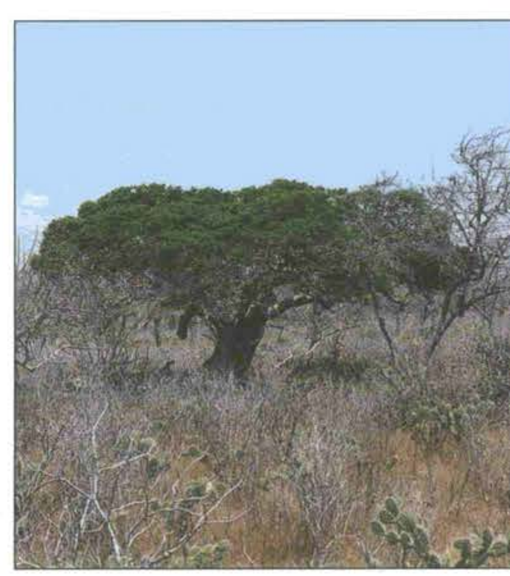


Figure 4.31 Guaiacum in Venezuela (MF Newman)

Carbon Sequestration in Drylands

Introduction

Desertification and global warming are two major environmental issues that have some significant linkages. Not only may global warming in the twenty-first century contribute to increased stresses in dryland areas, but poor land-use practices, especially those leading to vegetation destruction and soil loss, can contribute to the processes leading to atmospheric warming. Therefore stategies that lead to the amelioration of both problems are likely to be of great global importance.

The consequences of human-induced global warming, discussed on page 13, are only just beginning to be understood (Idso and Idso 1994). Likely climate changes caused by the enhancement of so-called greenhouse gases, particularly carbon dioxide (CO_2), in the atmosphere include not only increasing temperatures but also changes in total rainfall and its seasonality, and systematic increases in rainfall intensity (Solomon *et al.* 1993). Along with the direct effects of increasing CO_2 concentrations on plants, these climatic influences will interact strongly with the grazing impacts and other land-use pressures that are already being placed on drylands (Sombroek *et al.* 1993, West *et al.* 1994). Fortunately, there are potential opportunities for mitigation of the rate of increase of atmospheric CO_2, through absorption and storage of carbon in plants and soils, called *carbon sequestration.* Mitigation strategies involve two possibilities: the conservation and/or protection of existing carbon sinks, and efforts to increase the capacity of the land to sequester carbon.

The principal biological sinks for CO_2 have previously been thought to be the forested regions of the world, notably tropical rainforests, and much effort has been concentrated there (Trexler 1991, Kinsman and Trexler 1993). It is now clear that drylands are also a prime candidate for major carbon sequestration efforts (Glenn *et al.* 1993, UNEP 1995). However, any effort to sequester large amounts of atmospheric carbon in drylands involves significant scientific and organisational challenges. Not the least of these challenges is to find enough land. To absorb even 25% of the atmospheric CO_2 emissions into dryland soil and vegetation would require an area of about 2 to 5 billion ha. While management systems in the susceptible drylands could be altered to sequester more carbon (Glenn *et al.* 1993), significant incentives may be required to get land users and owners to participate in sequestration programmes.

Table 4.15 Estimates of carbon sequestration potential of some major land-use types with projected annual carbon storage and time frames

Option	*Area (million ha)*	*Rate ($tC\ ha^{-1}\ yr^{-1}$)*	*Period (yr)*	*Cost (US\$ tC)*	*Total ($MtC\ yr^{-1}$)*
Dryland crop management	450	0.3–1	5–20	1–5	135
Halophytes	130	0.5–5	Indefinite if harvested 5 yrs if not	170 (irrigated and harvested) 20 (dryland not harvested)	65
Bush encroachment	150	0.1–0.5	15–50	10–20	37
Energy crops	20 (5% of dryland crop area)	4–8	indefinite	150	80
Domestic biofuel efficiency	not applicable	not applicable	indefinite	2–5	75
Agro-forestry (arid)	50	0.2	30	2–10	10
Agro-forestry (semiarid)	75	0.5	20	2–10	38
Agro-forestry (subhumid)	150	1.5	15	2–10	225
Improved pasture (semiarid Asia)	10 (2500 degraded globally)	0.1	30	10	1
Savanna fire control	900 (globally)	0.5	30	1–5	450
Woodland management	400 (globally)	0.5	30	1–5	200

Source: UNEP 1995

Rationale for sequestering carbon in drylands

At first glance, the possibility of large-scale carbon sequestration in drylands might seem unlikely. Compared to other biomes, drylands accumulate only a fraction of the hundreds of tonnes of carbon per hectare that can accrue in temperate and tropical forest systems, and at a fraction of the annual rate. But the world's drylands store about 60 times more than is added to the atmosphere annually by fossil fuel burning. Small unit changes in the rate at which carbon is emitted or sequestered in these soils can have relatively large impacts on the atmospheric carbon budget, given the significant proportion of the total global land area that are drylands. Drylands cover 6.1 billion ha world-wide, 5.2 billion ha of which are susceptible to desertification. These susceptible drylands cover 40% of the world's total land area, a greater portion than is covered by cropland (1.4 billion ha or 8%) or closed forest (4.4. billion ha or 25%).

Estimates of the potential productivity of world ecosystems are based on the type of native vegetation they supported before human land-use systems were imposed on them (Oldeman *et al.* 1991). Primary productivity is very low in hyperarid areas (approximately 250 kg $ha^{-1}\ yr^{-1}$ of carbon), but increases in the arid and semiarid areas (Whittaker 1970), reaching levels as high as 4000 kg $ha^{-1}\ yr^{-1}$ of carbon) in the dry tropical forests (Table 4.15). These rates are nearly as high as those in temperate regions. Increasing carbon storage in the drylands would involve converting degraded lands, which are performing well below their potential, into land-use systems that perform closer to natural production levels. Obviously, the greatest potential for carbon storage lies in the regions with the highest potential productivity, while hyperarid areas have little potential for increased carbon storage.

In general, it seems that global dryland systems without effective management will become much stronger carbon sources under a doubled CO_2 climate (Ojima *et al.* 1993). Whether from a global perspective or from a dryland perspective, it is imperative that they become sinks. Over 1 billion people currently live in susceptible drylands, and any effort to restore the productivity of these areas will benefit their inhabitants.

The carbon story

Soils of the world's drylands hold 300–369 $\times 10^{15}$ grammes (or Pg) of C (carbon) as soil organic carbon (SOC), and 473–546 Pg C soil carbonate carbon (CAC). This corresponds with about 20–25% and 68–79% of the estimated world's total terrestrial reserves (Batjes 1996). A feature of drylands is that they have low SOC contents and high CAC reserves (Grossman *et al.* 1995, Sampson *et al.* 1993). The relatively large contribution of CAC to soil carbon reserves of dryland systems is illustrated by the fact that the value is as high as 77% in hot deserts and only 7% in the boreal forest. This difference in the proportion of SOC and CAC has implications for the potential of drylands as a sink for carbon. Although reserves of carbonate carbon globally are large, this source of carbon does not participate in the carbon flux to other carbon systems as rapidly as organic carbon (Batjes 1996).

The soil organic carbon (SOC) stored in the world's soils as fresh organic matter, stable humus or charcoal, is two to three times higher than the carbon stored in the natural vegetation and in standing crops (Ojima *et al.* 1993). The soils of grasslands and cropped drylands store up to 10 times as much carbon as the plants growing on them (Schimel 1993). Soil carbon storage is one the largest pools of carbon in the ecosystem (Batjes 1966).

Soil organic carbon cannot be considered as a homogeneous carbon form. Instead it must be viewed as a mixture of labile and more resistant material. This affects the dynamics of soil carbon relative to climate and land management changes. Soil organic carbon is divided up into three major components which include active, slow, and passive soil carbon (Parton *et al.* 1993). Active SOC includes live soil microbes plus microbial products (total active pool is ~2 to 3 times the live microbial biomass level), the slow pool includes resistant plant material (lignin derived material) and soil stabilised plant and microbial material, while the passive material is very resistant to decomposition, and includes physically and chemically stabilised SOC.

The short-term fluxes of carbon from the soils are derived primarily from changes in the labile soil organic matter pool. The size of this pool is relatively small but it accounts for more than 60% of the soil carbon respiration under 'steady-state' conditions (Ojima *et al.* 1993). Natural ecosystems may have large stores of carbon in soil or vegetative compartments. The net flux of carbon from natural ecosystems at steady-state conditions to the atmosphere are essentially neutral. When these ecosystems are disturbed through natural disturbances, for example, fire, pest outbreaks, storm damage and floods, or converted to croplands or a semi-managed state by modifying land use practices large fluxes of carbon to the atmosphere may result. Release of carbon may come from soil stores or from vegetation reservoirs (Schimel 1993, Raich and Schlesinger 1992).

In the short term, the carbon balance of terrestrial ecosystems is particularly sensitive to the impact of human activities, including deforestation, biomass burning, land use changes and conversions, and environmental pollution. During the period 1850–1980 soil carbon pools have decreased by 40Pg C from the original 1471 Pg C and carbon held in vegetation is down by 80 Pg C from 672 Pg C in 1850 (Houghton 1995). The global release of carbon to the atmosphere from land use changes during the 1990s has been between 1.1 and 3.6 Pg C each year, as compared to 5.5–6.5 Pg C each year from fossil fuel combustion. Large amounts of carbon are displaced annually from soils due to global soil erosion and land degradation (Lal 1995).

The potential of drylands to store carbon will be limited by degradation of natural vegetation and soils in response to human population growth and agricultural expansion (Biswas 1994, Oldeman *et al.* 1991). As the twenty-first century approaches, it has become increasingly clear that the drylands of the world will be subjected to even greater land-use pressures as a result of the continued growth of population. Soils of drylands are particularly vulnerable to degradation in view of the slow speed of their recovery after a disturbance. Human activities have led to about 1035 million ha of degraded soils in the susceptible drylands (see Section 1).

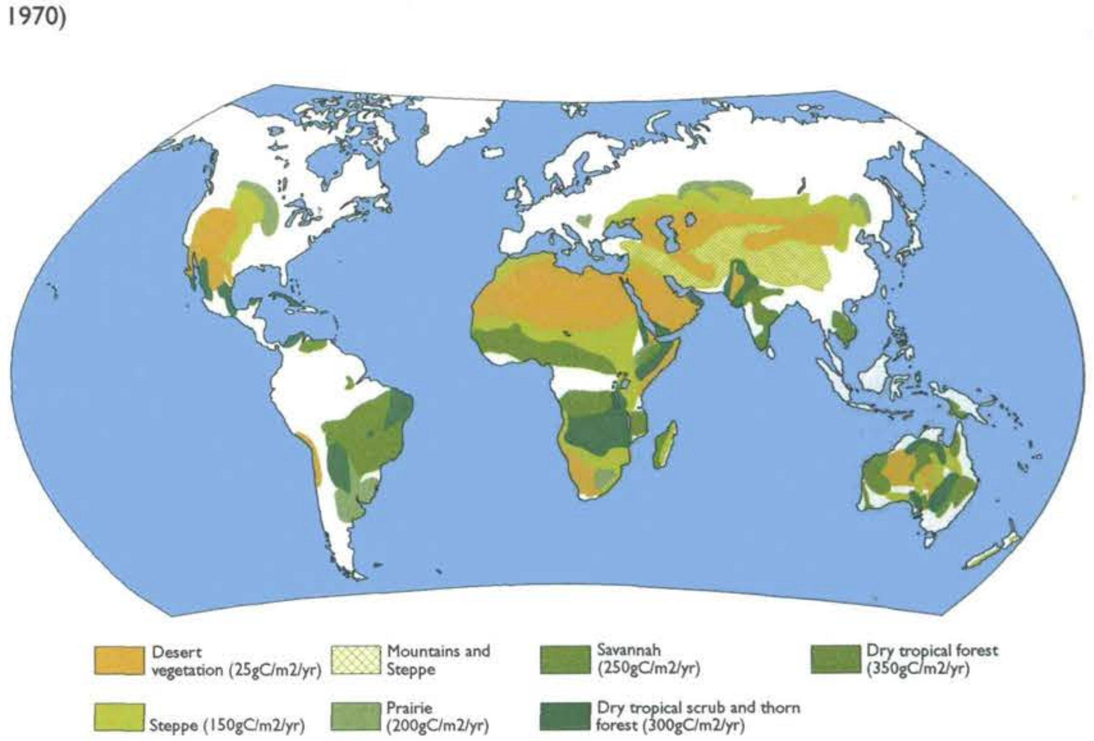
Evidence for carbon storage

Only part of the carbon pool in soils, namely the SOC in topsoils, is dynamic or labile and contributes to CO_2 exchange and nutrient cycling in the soil–water–atmosphere system (Ojima *et al.* 1993). The SOC status in natural ecosystems is closely related to the type and age of above-ground vegetation. The projected change in global climate is thought to be accompanied by higher soil surface temperatures, increased drought conditions and larger erosion hazards (Neilson and Marks 1994, Gifford *et al.* 1990).

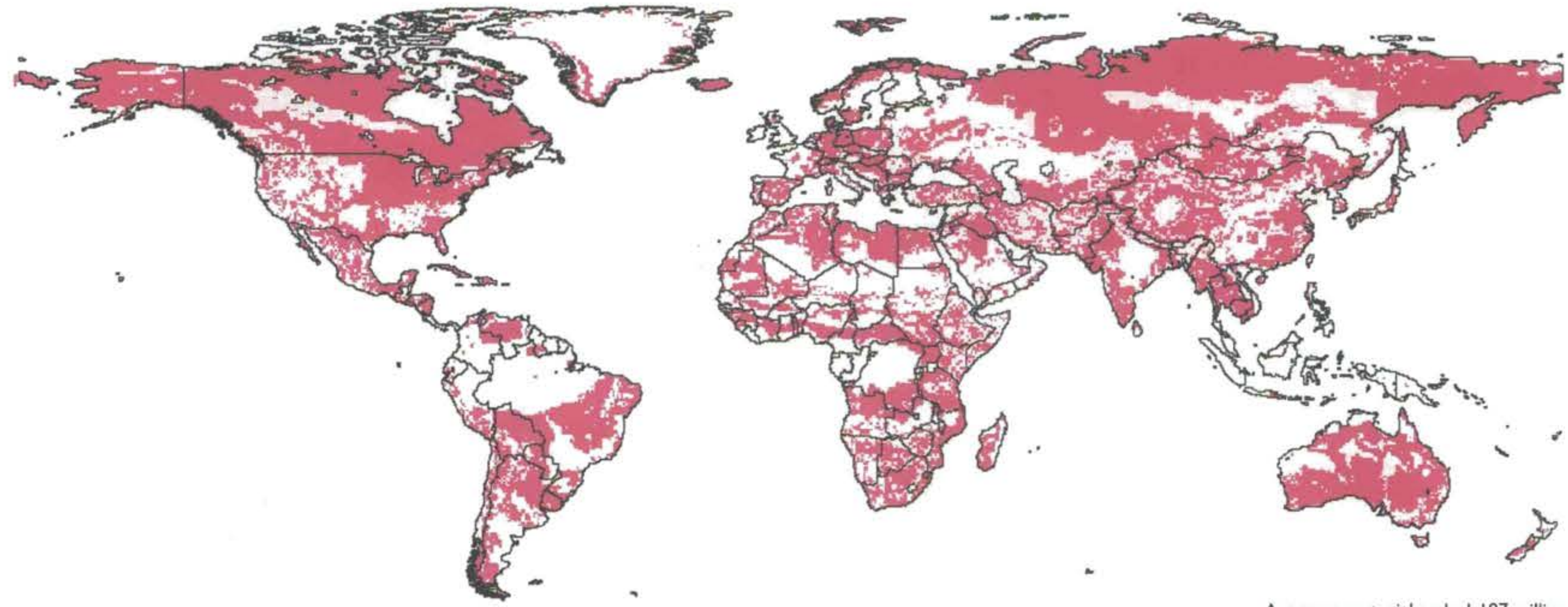
In the long term the most important determinants of the rate of decomposition of SOC are the rate of input of litter, soil moisture content and temperature. There is a tight linkage between the rate of plant productivity and soil respiration rate, with the mechanisms behind the linkage working in both directions (Owensby 1993, Schimel 1995).

The majority of the SOC is stored in more recalcitrant material, and these soil carbon pools also have different degrees of reactivity, and, as mentioned, have been defined as either the 'slow' or the 'passive' SOC pool (Parton *et al.* 1993). Together, the slow and passive pools constitute about 90% of the total soil carbon,

Map 4.32 Potential carbon sequestration by vegetation type (from Eyre 1968 and Whittaker 1970)



Map 4.33 Projected changes in leaf area index (LAI) from a doubled atmospheric CO_2 scenario. Pink areas have higher LAI, white areas the same or lower LAI (from Neilson and Marks 1994)



with an estimated ratio of 3:2 between the two pools respectively. The turnover rates in the various pools are a function of both abiotic (climatic and soil edaphic factors) and biotic factors and are affected by management, including grazing and fire management. The flows of carbon between these pools are controlled by decomposition rate and microbial respiration loss parameters, both of which may be a function of soil texture (Davidson 1994). The turnover time of these pools varies with the soil abiotic decomposition parameter which is a function of monthly precipitation and temperature (Parton *et al.* 1993, Ojima *et al.* 1993).

In general there is a grossly uneven partitioning of carbon between above- and below-ground fractions in the dryland soils. Ratios of about 4:1 have been reported (Marshall 1977). Soils under shrubby vegetation also show a higher below-ground fraction than those under grasslands (Gibbens *et al.* 1983, Owensby 1993). It is projected that as climate change proceeds, shrubs will invade grasslands. Grass to shrub species transition shifts below-ground litter input from fine root biomass (distributed in surface horizons) to deeply rooted, structurally resistant woody material (Connin *et al.* 1997).

These structural changes may enhance soil carbon storage lower in the soil profile, for example due to carbon allocation to deep roots by woody plants and deep rooted grasses (Nepstad *et al.* 1994). In drylands, higher mass-loss rates are often associated with fine root biomass relative to coarse roots and decreased microbial biomass with soil depth suggests that shrub invasion may result in greater long-term carbon storage in soils. But soil erosion and associated loss of soil carbon may balance these inputs (Lal 1995).

When desertification occurs, net changes in the carbon pool reflect a balance between fluxes in above- and below-ground biomass and soil organic carbon. For example, in semi-desert rangelands in New Mexico, USA a shift from grassland to shrubland resulted in a slight increase in soil carbon storage over the 110 year period, 1853-1963 (Connin *et al.* 1997). In many dryland regions there has already been a shift in vegetation composition toward a greater dominance of shrubs and other woody plants due to grazing pressure. This bush encroachment (see page 50) has, in some areas, been designated a 'woody weed problem', for example in parts of Australia and the south-western USA. Projections of climate change suggest that woody plants will come to dominate a larger area of land as CO_2 levels rise and water relations alter.

Global climate change, as currently simulated, could result in broad-scale redistribution of vegetation across the planet (Map 4.33). Vegetation change could occur through drought-induced 'dieback and fire'. It is predicted that grassland and shrublands (dryland ecosystems) could expand and that the tundra and boreal forests would contract most. A net result is that under the new equilibrium conditions the terrestrial biosphere may store up to 30% more carbon above ground than it currently does and this would act as a negative feedback to climate change (Neilson and Marks 1994, Sombroek 1995).

Changes in plant communities associated with changes in climate will affect litter quality. This will lead to either positive or negative feedbacks depending on whether lignaceous perennials or non-lignaceous annuals take over. In some drylands there may be a decrease in shrub abundance, an increase in half-shrubs and herbaceous species, an increase in C4 plants, an increase in the carbon:nitrogen ratio in plant tissues, and a decrease in succulents under all scenarios of climate change (Owensby 1993).

While a range of possible climatic change predictions for the twenty-first century exist, including their possible impacts on dryland areas (Williams and Balling 1995), it is difficult to predict some of the impacts that will affect biotic systems. For example, different microbial responses to rainfall and temperature changes are reasonably well known, but complex interactions such as effects on N-fixation, N-mineralisation, denitrification, cation leaching and ratios of trace gas emissions remain difficult to predict (Davidson 1994).

Possible effects of climate change on carbon storage in dryland soils

Drylands may be among the earliest systems to exhibit vulnerability to the effects of climate changes (OIES 1991), due to their low reserves of water and soil nutrients. Temperature increases and precipitation changes will modify processes such as evapotranspiration, decomposition and photosynthesis (Gifford *et al.* 1990). However, understanding how soil organic matter and nutrient status change in dryland soils in response to climate change requires a knowledge of several biogeochemical input and output processes (Schimel 1993). The effect of global climate change on soil organic matter content, soil organic matter quality and nutrient pools depends on the relative sensitivity of photosynthesis, autotrophic and heterotrophic respiration to climatic changes. There is increasing evidence that water- or temperature-stressed plants are more responsive to CO_2 increase (because higher CO_2 reduces transpiration) than unstressed plants. Rates of carbon gain, decomposition and nutrient cycling are all sensitive to temperature and moisture (Ojima *et al.* 1993). Projected rises in global temperature and the associated changes in rainfall distribution could have serious implications for the drylands, especially in the tropics (Sombroek *et al.* 1993).

It appears, from experimental work, that the relative growth-enhancing effects of atmospheric CO_2 enrichment is greatest when resource limitations and environmental stresses are most severe (Idso and Idso 1994, Solomon *et al.* 1993). It could well be that the percentage growth response of natural ecosystems to atmospheric CO_2 enrichment will be greater than that of managed agricultural systems (Tinker and Ineson 1990). Whether these experimental trends apply also to ecosystems remains to be assessed.

Feasibility of carbon storage in drylands

At present on severely degraded lands, release of CO_2 due to overutilisation of plant production, ensures that drylands are a net source of CO_2 (Sombroek 1995). The benefits of turning this around are obvious. If all the land restoration measures proposed by UNEP (1992) were adopted, the net effect on carbon sequestration would be that over 37 Pg C per year would be sequestered. This represents about 15% of the atmospheric CO_2 emissions (Glenn *et al.* 1993, Squires and Glenn 1995). This would be a significant contribution to the mitigation of global warming. Some regions will have the potential to sequester more CO_2 than others (Map 4.32).

Dryland soils are low in carbon but there is scope to augment this via better management. Specific sequestration opportunities were calculated for a number of major land use/ecosystem types. The major options considered are shown in Table 4.15, along with a time frame and costs.

The option of absorbing excess CO_2 into biomass through global-scale revegetation programmes seems attractive despite problems of cost, availability of land and the difficulty of achieving and monitoring long-term carbon storage (Trexler 1991, Squires and Glenn 1995). Possible carbon offset programmes to remove CO_2 via living vegetation or to store it in the soil have been proposed for every major type of ecosystem. Projected costs of such carbon offsets range from US$5 to 200 per tonne, which is actually considerably lower than the cost of some carbon source limitation measures (Flour 1991, Trexler 1991). Wisely chosen projects have beneficial social and environmental effects in addition to carbon removal, especially in many parts of the world's dryland where population pressure is high and quality of life is low. Action to increase biomass on drylands will protect biodiversity, ameliorate the living conditions of local people as well retain carbon (Trexler and Meganck 1993).

Conclusions

Carbon sequestration, the process of carbon stock protection and aggradation, is being looked at as a viable option by a world increasingly worried about the potential impact of global warming. The world's drylands have the potential to reach an annual carbon sequestration rate of over 1.0 Gt (UNEP 1995). This is the figure cited as the minimum to be considered as relevant to the efforts to mitigate the build-up of atmospheric carbon.

There are, however, significant risks with carbon sequesterisation strategies. These arise because of the small differentials between the degraded and rehabilitated land and because of the vagaries of the climate. Carbon is easily gained but just as easily lost. The risks associated with carbon sequestration projects inevitably increase along the aridity gradient, due to increasing climatic variability and because of the complex land tenure and community structures. The only ways to manage carbon are the more efficient production and use of energy and in better land management.

The links between drylands and climate change mitigation are established. Stopping land degradation will slow the rate of release of CO_2 to the atmosphere; rehabilitating degraded lands can help sequester carbon in plants and soils (Figure 4.32). Carbon sequestration is compatible with techniques adopted to mitigate the effects of land degradation through increasing land cover and improving soil organic matter content to restore productivity to benefit the local inhabitants and the ecosystem (Squires *et al.* in press).

Achieving carbon storage will require careful planning, however, as not all rehabilitation options increase soil carbon storage. Some dryland soils have a finite storage capacity for carbon which cannot be increased by boosting biomass production alone. Improved carbon storage will also require careful consideration of the local economic conditions and must be compatible with the needs and aspirations of the local peoples. Sequestration opportunities in the world's drylands may be categorised as follows:

- increasing the standing biomass of dryland plant communities, either through more conservative grazing/browsing of rangelands, rehabilitation and revegetation of degraded lands, or afforestation of areas devoid of trees.
- Increasing the storage of carbon in long-lived woody plants (trees and shrubs).
- Substituting non-biomass fuels (solar stoves, biogas, etc.) for fuelwoods.
- Utilising biomass energy as replacement for fossil fuels.

Revegetation projects appear to be one of the most cost-effective ways to increase terrestrial carbon storage, and many countries are considering or have implemented such programmes as part of their strategy to combat desertification. In addition soil carbon can be increased too (Trexler and Meganck 1993).

Sequestration can occur in natural woodlands, grasslands and shrublands. Natural vegetation presents a wide variety of opportunities, both in terms of physical situation and the social change that may be needed in order to sequester and store additional carbon. Here the challenge may be less with the physical context of the dryland region and more with the social and cultural changes needed to affect the carbon dynamics in the desired manner. These lands, while they are widely diverse, are usually home to people who have cultural roots deep in the drylands and their method of use. Where those uses have grown unsustainable, or where carbon stocks are being needlessly depleted, it may be difficult to cause real change to occur.

Adapted from original text provided by V. Squires and E. Glenn.

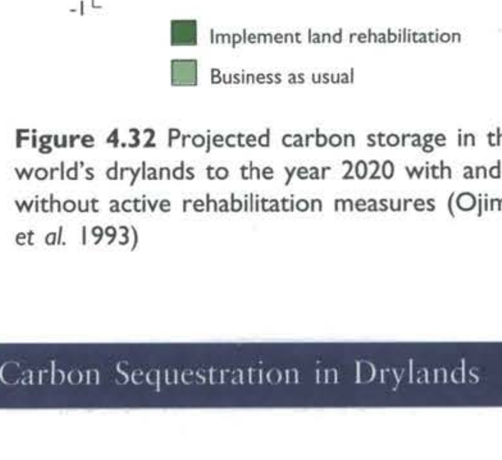


Figure 4.32 Projected carbon storage in the world's drylands to the year 2020 with and without active rehabilitation measures (Ojima *et al.* 1993)

Saline Soils in the Drylands: Extent of the Problem and Prospects for Utilisation

Introduction

Natural, or *primary*, salt-affected soils are widespread in drylands because the potential evaporation rate of water from the soil exceeds the amount of water arriving as rainfall, allowing salts to accumulate near the surface as the soil dries (Szabolcs 1979, 1989). Vast tracts of saline soils limit the amount and quality of pasturage available in the drylands. *Secondary*, or human-induced salt-affected soils cover a smaller area than primary salt-affected soils (Oldeman *et al.* 1991, Ghassemi *et al.* 1995) but secondary salinization represents a more serious problem for the human use of drylands because it mainly affects cropland.

Arable land is a scarce and valuable resource in dryland regions yet it is frequently abandoned when it becomes salinized, due to the very high cost of repair (Dregne 1995). The problem is aggravated by the low salt tolerance of major agricultural crops (Abrol *et al.* 1988) compared to wild salt-tolerant plants (halophytes) which are adapted to saline soils (Glenn 1995, see Figure 4.33). Salt buildup is perhaps the biggest enemy of irrigated agriculture in the drylands (Postel 1990, van Schilfgaarde 1993, Ghassemi *et al.* 1995, Gardner 1997). In the past several decades progress has been made in understanding and avoiding the practices that lead to soil salinization, and in developing new crops and agronomic techniques for salt-affected soils so they can remain in production without requiring complete restoration (Lieth and Masoom 1993). In recent years even sea water has been used to produce halophyte crops on an experimental basis (Glenn *et al.* 1997).

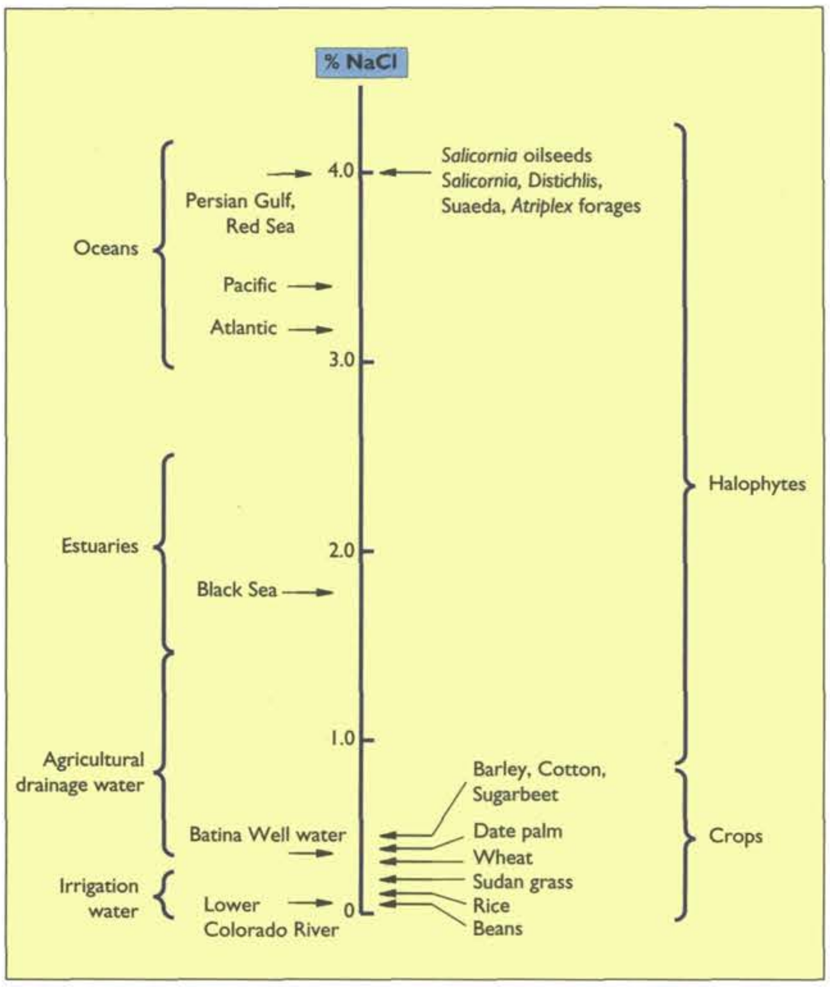
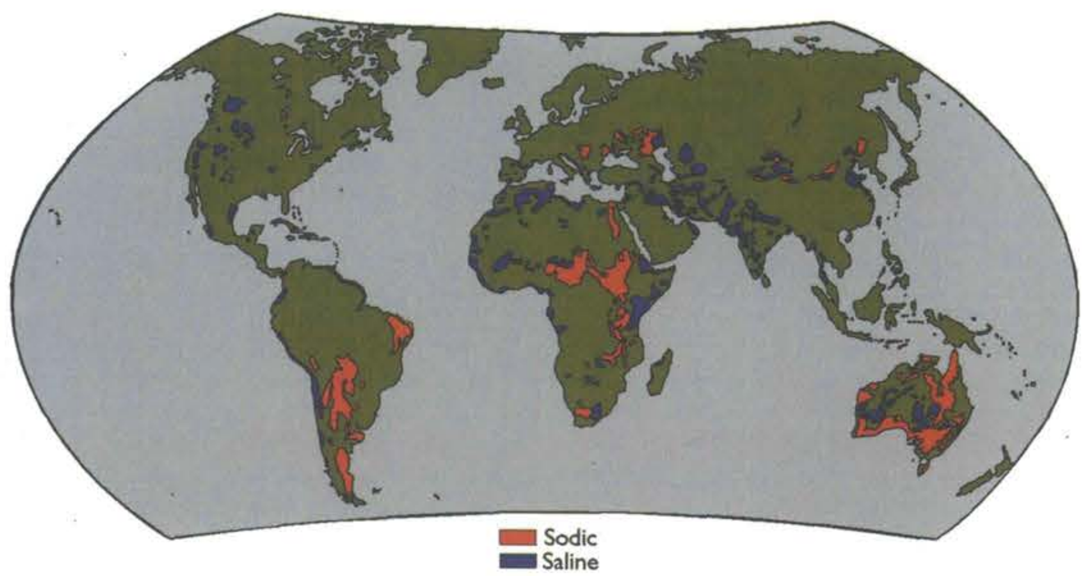


Figure 4.33 The salt tolerance limits for acceptable yields of crops and halophytes. Source: Glenn, E.P., Environmental Research Laboratory, University of Arizona

Map 4.34 Salt-affected soils. Source: Szabolcs (1979, 1989)



Global extent of salt-affected soils

There are two main types of salt-affected soils (Abrol *et al.* 1988). The first are saline soils, which contain sufficiently high levels of NaCl, $NaSO_4$ or, more rarely, other neutral salts, to inhibit the growth of crop plants. All types of soils can become saline. The second type are sodic, or alkaline, clay soils. They generally have low levels of total salts but contain enough of the alkali salt, Na_2CO_3, to damage heavy soils. Na_2CO_3 causes the clay particles in soil to disperse, or defloculate, by ion exchange processes, resulting in a deterioration of soil structure. A sodic soil has a low permeability to water and air and a pH above 8.2; plant growth is inhibited by negative effects of sodium on the soil and by the high pH, which reduces nutrient availability to the plant. Soils can become saline or sodic through natural or human-induced processes.

Accurate statistics on the extent of salt-affected soils are not available for all of the drylands, despite the importance of the problem, but some estimates of the extent of damage have been made. Map 4.34 shows the broad distribution of saline and sodic soils around the world, both natural and human-induced (Szabolcs 1979) while Map 4.35 shows the distribution of human-induced or secondary saline soils as identified in the GLASOD survey (Oldeman *et al.* 1991). Although salt-affected soils often have a

Map 4.35 Human-induced saline soils. Source: GLASOD

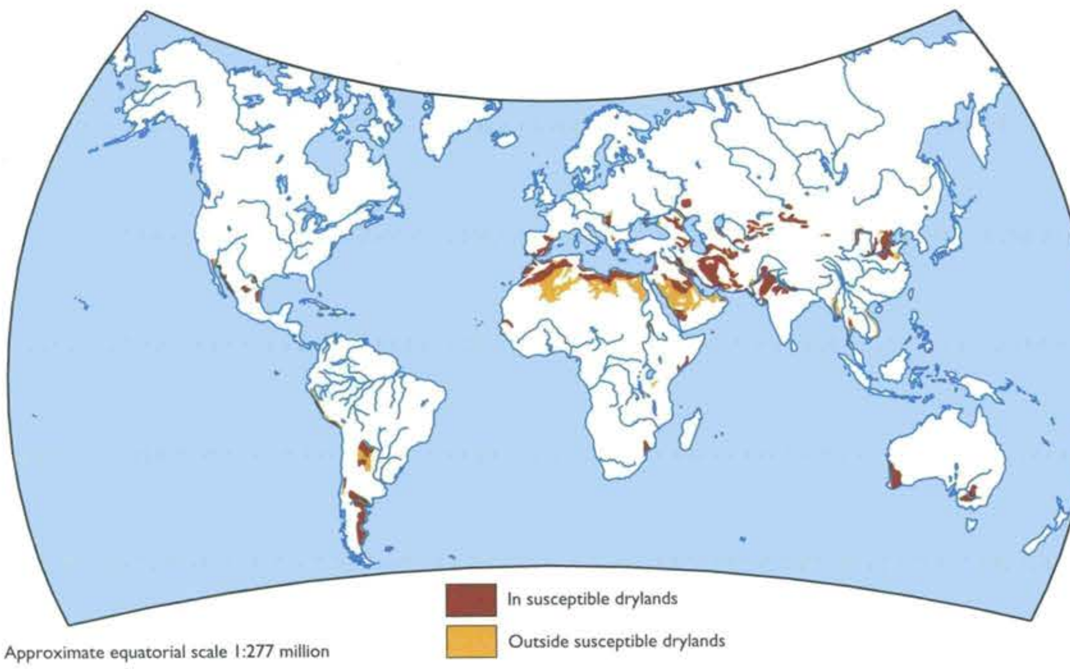


Table 4.16 World distribution of salt-affected areas (million ha)

Continent	*Saline*	*Sodic*	*Total*
Africa	122.9	86.7	209.6
South Asia	82.2	1.8	84.0
North & Central Asia	91.4	120.1	211.4
South-East Asia	20.0	–	20.0
South America	69.4	59.8	129.2
North America	6.2	9.6	15.8
Mexico/Central America	2.0	–	2.0
Australasia	17.6	340.0	357.6
Global total	411.7	617.9	1029.5

Source: Abrol *et al.* (1988)

Table 4.17 Global extent of human-induced salinization in the susceptible drylands (million ha)

Continent	*Light*	*Moderate*	*Strong*	*Extreme*	*Total*
Africa	3.3	1.9	0.6	–	5.8
Asia	10.7	8.1	16.2	0.4	35.4
South America	0.9	0.1	–	–	1.0
North America	0.3	1.2	0.3	–	1.8
Europe	0.8	1.7	0.5	–	3.0
Australasia	–	0.5	–	0.4	0.9
Global total	16.0	13.5	17.6	0.8	47.9

Source: GLASOD

patchy distribution, with salt problems affecting from 10% to 50% or more of the soils in a region, Table 4.16 indicates the best current estimates of all saline and sodic land areas while Table 4.17 shows data taken from the GLASOD database on human-induced salt-affected soils in the susceptible drylands.

The maps and tables illustrate four main points about the global salt problem: first, salt-affected soils cover a very large area of land; second, the dryland regions are disproportionately affected; third, saline and sodic soils are approximately equal problems; and fourth, human-induced salinity problems occur throughout the dryland countries, in both irrigated and dryland farming districts. Altogether about 1 billion ha of land, or 20% of the dryland area, have saline or sodic soils (Table 4.16, see also Thomas and Middleton 1993). Human-induced salinization affects a much smaller area than natural salinity but still affects approximately 77 million ha (Oldeman *et al.* 1991), 48 million ha of which are in the susceptible drylands (Table 4.17). Salt problems affect rich and poor countries alike, but Africa and Asia are disproportionately affected.

Land-use practices that lead to the salinization of cropland

The major factors responsible for the development of human-induced saline and sodic soils are illustrated in Figure 4.32. Four main forms of poor management can be recognised (Abrol *et al.* 1988, Ghassemi *et al.* 1995):

1. Use of saline groundwater for irrigation. Dryland groundwater is frequently saline, and prolonged irrigation with such water leads to the build-up of salts in the root zone which can eventually render the land too saline for crop growth. If the groundwater is high in Na_2CO_3 rather than NaCl and the soil has a high clay content, sodic rather than saline soil conditions result. In dryland regions aquifers are rarely recharged as fast as they are pumped, hence the water-table tends to be lowered and becomes more saline over time, because water is evaporated during crop production but the salts in the water are returned to the soil and aquifer. This is a common problem in inland irrigation districts throughout the drylands.

2. Ingress of sea water. Coastal arid zones often have sandy soils overlying shallow, freshwater aquifers which have accumulated over geological time spans. When these aquifers are pumped for irrigation or other uses, the water-table can be quickly lowered to below sea level, allowing sea water to seep into the aquifer through the sand. Coastal irrigation districts often develop unusably high salt levels in their well fields within 10–20 years of installation. On the Batina coast of Oman, hand-dug wells which sustained date gardens for centuries became salinized within a few years after the introduction of motorised pumps which extracted water from deeper levels, thereby lowering the water-table below sea level and permitting sea water to enter the wells (Speece and Wilkinson 1982).

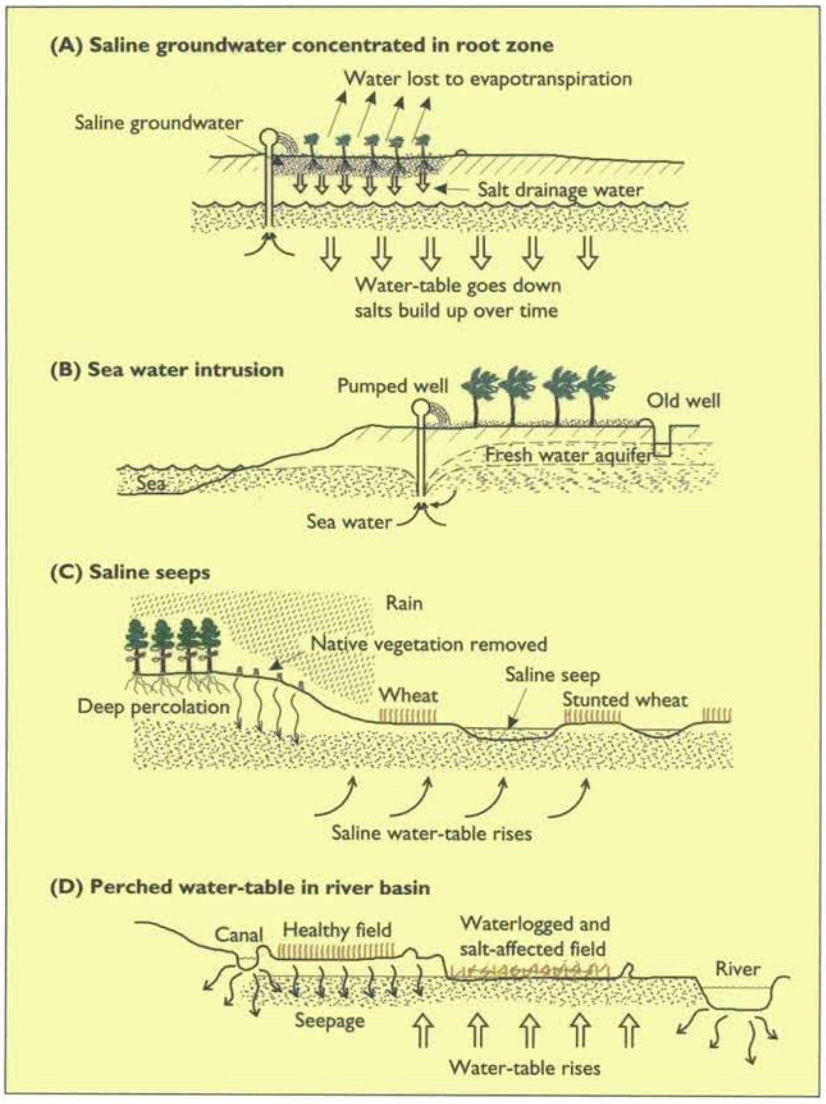


Figure 4.34 How soils become salt-affected. Source: Glenn, E.P., Environmental Research Laboratory, University of Arizona

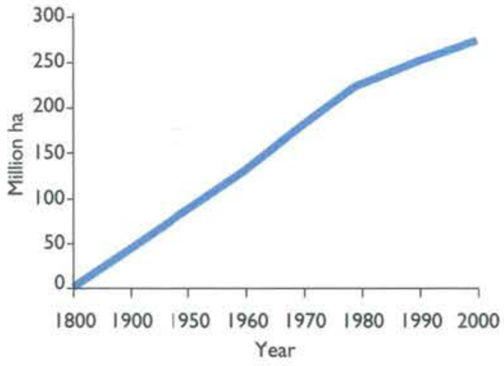


Figure 4.35 World gross irrigated area. Source: Glenn, E.P., Environmental Research Laboratory, University of Arizona

3. Saline seeps in non-irrigated dryland farming regions. When native shrubs, trees and grasses are replaced by annual grain crops, the evapotranspiration rate of the landscape is lowered. Rainfall that would have been used up by the native vegetation instead percolates through saline subsurface sediments to impermeable horizontal layers and is conducted laterally to low spots in the landscape, producing extensive areas of salty, waterlogged soil. Large areas of dryland wheat farms in Australia, the USA and Canada have been salinized by this process of saline seepage (Ghassemi *et al.* 1995).

4. Perched, saline water-tables under irrigated fields. The most intractable salinity problems occur in the large river basins that support vast dryland irrigation districts around the world. In its natural state a river basin has a balance between rainfall, stream flow, groundwater level and loss of water to evaporation and transpiration. When large quantities of extra water are distributed throughout the basin for irrigation, the natural balance is disrupted. Excess water seeps into soil from unlined canals, drainage ditches and from over-irrigation of the farm fields themselves. The excess water creates a high water-table throughout the basin, which rises into the root zone of the crops, waterlogging the soil and inhibiting plant growth. Salts build up in the root zone over time because there is no drainage to carry them away. Glistening white salt patches in irrigated fields are, unfortunately, a common sight in many irrigation districts. This problem affects irrigation districts all over the world, from the lower Colorado River of the USA to the Nile and Indus valleys (Ghassemi *et al.* 1995).

A crisis for dryland irrigated agriculture

Irrigated agriculture has become more and more important in feeding the world's growing population. The amount of irrigated land in the world doubled every 15–20 years from 1800 to 1980 and two-thirds of the world's irrigated area has been developed since 1950 (Figure 4.35, see also Postel 1990, Brown 1997). By 1990, one-third of the global food harvest came from irrigated fields, which represented only 17% of total cropland. Many of the new irrigation districts have been developed in dryland countries through the damming of rivers to provide irrigation water and electricity.

Since 1980, however, the trend towards irrigated agriculture has been slowing. Per capita irrigated area actually peaked in 1978 at 53 ha per 1000 people and has decreased since then; by 2000 it is projected to decrease to 43 ha. Lending by major international donors for new irrigation projects has fallen sharply.

There are several explanations for this recent trend (Postel 1990, Brown 1997): the best sites for irrigation have already been developed; the costs of adding irrigation capacity have risen; and irrigated drylands have been found to be extremely vulnerable to degradation from waterlogging and salt build-up, so further expansion of irrigation into new dryland districts is seen as a risky investment. The amount of salinized land in the irrigation districts can only be estimated since exact statistics are not kept for all countries. By one estimate, 38 million ha or 24% of the irrigated land of the top five irrigating countries has already been damaged by salt, and extrapolating to the world at large, 60 million ha are thought to have been damaged (Table 4.18). Another estimate puts the amount at 45.4 million ha, representing 20% of the total irrigated area (Ghassemi *et al.* 1995). Other countries with large amounts of salt-damaged land in irrigation districts, not shown in Table 4.18, include Afghanistan, Egypt, Iraq, Mexico, Syria and Turkey.

Salt damage is progressive, with more land lost to production each year in most irrigation districts. One estimate of the amount of new land that becomes salinized each year is 1–1.5 million ha (Kovda 1983). The statistics for total irrigated acreage in Figure 4.35 do not deduct for the amount of land lost to salt damage. Hence, a point will be reached, if it

Table 4.18 Irrigated land damaged by salinization: top five irrigators and world estimate, mid-1980s

Country	*Area damaged (million ha)*	*Share of irrigated land damaged (%)*
Pakistan	3.2	20
India	20.0	36
China	7.0	15
USA	5.2	27
Soviet Union	2.5	12
Total	37.9	24
World	60.2	24

Source: Postel (1990)

hasn't already, when the total *effective* area under irrigation will actually decrease. The lost income from salinized land in the irrigated drylands is estimated to be US$11.4 billion per year (Ghassemi *et al.* 1995).

Methods of preventing and repairing salt-damaged soils

Preventing salt damage is less expensive than repairing it. Most salt problems are caused by attempting to irrigate marginal land, or by irrigating more land than the natural or man-made drainage system can handle (Abrol *et al.* 1988). Low-lying, heavy soil that lacks adequate drainage is usually the first to become damaged and should probably not be irrigated from the start. However, social and economic pressures often result in the creation of irrigation districts that initially contain more land than can be sustainably farmed. The switch from seasonal to perennial irrigation after construction of the Aswan High Dam has raised soil salinity levels throughout the Nile Valley (White 1988). In the Nile Delta an ambitious irrigation scheme was developed for the reclaimed Mansour and Zawia polder areas (Boumans and Mashali 1983). About half of the land that was intended for irrigation has either been abandoned or never put into production due to salt problems.

Technically, both sodic and saline soils can be repaired (Arbol *et al.* 1988) but this may not always be cost-effective. Sodic soils can be reclaimed by applying gypsum ($CaSO_4$), calcium chloride ($CaCl_2$) or other calcium salts to the soil. Calcium replaces sodium on the clay particles and partially restores the soil structure. Sulphuric acid, elemental sulphur, iron sulphate and aluminum sulphate are also affective amendments, which react to produce calcium sulphate from calcium carbonate already in the soil. Adding an organic mulch such as straw or manure can also aid reclamation. To be effective, several tons per hectare of such inputs is required; it must be ploughed into the soil and irrigated prior to planting a crop. The restoration of soil structure is usually temporary, and gypsum or other amendments may be needed every few years in some sodic soils. A local, low-cost source of soil amendment is required for this method to be economical. An alternative method is to flood the land with high-salinity water after gypsum application then gradually dilute it with fresh water; this keeps the soil structure open during reclamation (Oster 1993). The land can be used for salt-tolerant crops during reclamation.

Saline soils can present an even more serious challenge. The usual method used to reduce soil salinity is leaching, in which large quantities of water, in excess of the amount needed by the crop, is added to the irrigation schedule or ponded onto the field between crops (Arbol *et al.* 1988). In theory, the excess water dissolves salts in the root zone and moves them down the soil profile where they will not damage the crop. In practice, however, leaching requires good soil drainage, and poor drainage is often one of the very reasons for salinization in the first place. Before leaching can be effective, therefore, a surface or subsurface drainage system must be installed, and a mechanism for the collection and disposal of the saline drainage water introduced. Irrigation canals must be lined to prevent seepage and control measures implemented to prevent overirrigation of crops. This often requires reworking the infrastructure throughout an entire irrigation district, because the water-table is likely to be high throughout the district.

Installing a subsurface drain system costs from US$1000 to US$2000 per hectare of farmland in the USA, and the disposal system for the drain water, requiring collection sumps, pumps and lined canals to carry away the brine, involves additional costs. Finding a place to deposit the brine has become a problem in its own right. Selenium and other toxic elements accumulate in the water (Presser 1994). If the water is discharged into surface ponds it can poison wildlife and even people, and basin-wide drainage projects often succeed only in displacing salt damage to adjacent ecosystems. The Aral Sea, for example, was once the world's fourth-largest freshwater lake but is now saline and toxic from the diversion of river water for agriculture and the deposit of irrigation drainage in the sea (Micklin 1988, see page 96). In the USA, California's Salton Sea is also becoming hypersaline and toxic from the deposit of agricultural waste water (Boyle 1996). Elsewhere in California, the San Joaquin Valley lacks a drainage canal to the sea because of concerns that the drainage water might damage the estuarine ecosystems. Instead, saline drain water is being temporarily stored in evaporation ponds in the valley with no clear permanent solution in sight (Presser 1994).

Potential solutions to the toxic drainage dilemma are all expensive; chemical treatment, filtration or bioremediation would cost US$30–100 million per year in California alone and would be required for an indefinite period (Postel 1990). Because of the expense and difficulty of installing drain systems and disposing of the output, only the most valuable land is likely to be rehabilitated this way. Much more frequently around the world, fields and sometimes whole irrigation districts are abandoned when they become too saline to grow crops.

New solutions to salinity problems

Increasing irrigation efficiency can prolong the life of an irrigation district, make water available for other uses, and extend the salinity limit at which crops can be grown (Letey 1993, Miyamoto 1993, Rhoades 1993, van Schilfgaarde 1993). Farmers using traditional flood basin or furrow methods of irrigation often apply 50% more water than is actually used by the crop due to the inefficiency of these application methods. It is difficult to add a precise amount of water when an entire field must be flooded at once. The excess water is not just wasted, it contributes to raising the water-table under the fields, bringing up salts and creating the need for a drainage system. More efficient irrigation methods are now in widespread use in dryland irrigation districts all over the world. These include drip irrigation, in which a precise amount of water is trickled into the soil at the base of each plant through a plastic tube (Figure 4.36); and moving boom irrigation, in which a motorised, wheeled irrigation machine travels over the crop, applying a predetermined amount of water as a simulated gentle rain from an overhead boom (Figure 4.37). Even flood irrigation has been improved by the use of precision, laser-guided land planes to level fields so that water spreads over them more evenly.

More efficient irrigation techniques have been accompanied by a better understanding of crop water requirements and better methods

Figure 4.36 Drip irrigation emitter (Agricultural Communications Systems, University of Arizona)

Figure 4.37 Centre-pivot boom irrigating the oilseed halophyte Salicornia with seawater (Jim Riley, Environmental Research Laboratory, University of Arizona)

of detecting water stress, for example by the use of infrared imaging of the crop. When the soil water supply becomes low, the plants close their stomata to conserve water. This results in an increase in leaf temperature because the leaves are no longer cooled by water evaporating through their stomata. This temperature increase can be detected by infrared sensors in the field or on satellites. A fully equipped, modern farmer potentially knows just when and how much to irrigate a field, and has the irrigation technology to accomplish the task.

These technologies are effective but expensive. Surface irrigation methods such as furrows or basins cost US$100–400 per hectare to install, compared to US$1000–2500 per hectare for self-moving systems or drip irrigation (Ghassemi *et al.* 1995). Although the economic costs of such technologies can be offset against their water savings and the benefits of continued crop production, they cannot be expected to solve all the salinity problems affecting the world's croplands. An alternate or complimentary approach is to shift towards more salt-tolerant crops. Crops that can tolerate high salinities can be grown on saline soils and water supplies, thereby extending the life of an irrigation district. They can also be used as secondary crops to be irrigated with drainage water from conventional crop fields. This second use of the irrigation water reduces the amount of drainage water that must be disposed of, an environmental benefit.

Intensive breeding and selection programmes have been carried out over the last two decades to improve the salt tolerance of rice, wheat, barley, alfalfa and other major crops (Shannon and Nobel 1990). A few improved cultivars have been released, but in general the results have been disappointing. Few conventional crops can be irrigated with water even 10% as salty as sea water, and drainage water often exceeds this salinity. More rapid progress has been made in domesticating wild halophytes as domestic crops (National Research Council 1990, Glenn *et al.* 1997). Halophytes such as *Atriplex* and *Distichlis* have been established on thousands of hectares of salinized land to provide forage for sheep and cattle. Animals often avoid halophytes in natural rangelands because they tend to be less palatable than grasses, but when halophyte biomass is incorporated into mixed rations, it can completely replace conventional grass hays in fattening diets. The animals need no special inducement to eat halophyte material if it is mixed with the other diet ingredients. They do, however, consume more feed and water per unit weight gain due to the high salt content of the halophytes (Swingle *et al.* 1996).

One of the most promising halophytes is an annual, succulent salt-marsh plant, *Salicornia bigelovii* (Glenn *et al.* 1991). It produces an oilseed that can be pressed to provide human-edible oil and protein meal for animal diets, while the straw can be used for forage (Swingle *et al.* 1996). It can be grown using undiluted sea water in coastal desert soils. Using sea water for irrigation requires special irrigation techniques, since the soil must be kept continuously moist and an excess of sea water (above consumptive use) must be added to keep salts from accumulating in the root zone. Altogether, halophytes grown with sea water require about 35% more irrigation per unit of biomass production as conventional crops (Glenn *et al.* 1997, see Figure 4.38). In coastal regions this disadvantage can be outweighed by the lower lift required to irrigate with sea water compared to deep wells. Although sea water irrigation produces a large amount of saline drainage water, in coastal regions it can be drained back to the sea by gravity, whereas inland irrigation basins often have no outlet. Sea-water-irrigated halophyte crops might become cost-effective in coastal communities which lack fresh water for crop production, or wish to conserve their fresh water resources for human use. Halophytes may also become cost-effective as crops to reuse saline water and soils within existing irrigation districts.

Conclusions

Saline soils represent a lost opportunity for crop production and pasturage throughout the world's dryland regions. Secondary salinization of cropland is perhaps the most expensive form of land degradation to repair, costing thousands of US dollars per hectare and frequently resulting in off-farm environmental damage through the disposal of saline drainage water. The best available estimates suggest that 45–60 million ha of irrigated land have already been damaged by salt build-up (Postel 1990, Ghassemi *et al.* 1995) and the GLASOD data indicate that the global extent of human-induced salinization on all farmland is 77 million ha, including 48 million ha in the susceptible drylands. The problem is being attacked by developing better irrigation and drainage technologies, taking more care in the initial design of irrigation districts, and by developing new crops that can be grown using highly saline water. Nevertheless, salinity will continue to be a serious problem throughout the arid regions for the foreseeable future. Population growth and the need for more food will put more, rather than less, pressure on dryland cultivated areas in the future. Finding ways to bring salinized soils into agricultural production must continue to be an important part of the international agricultural research agenda.

Adapted from original text supplied by E. Glenn, V. Squires and J.J. Brown.

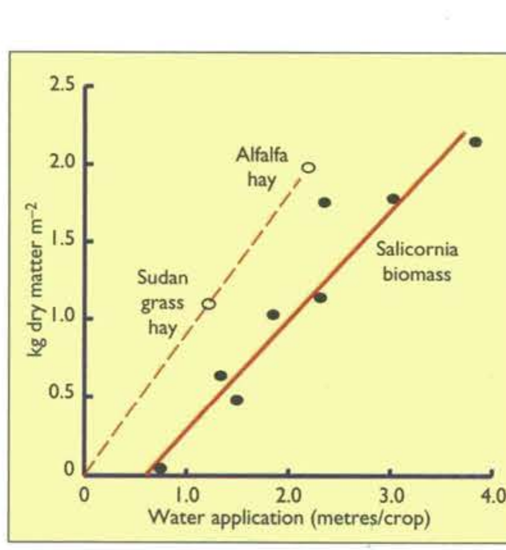


Figure 4.38 Sea-water-grown Salicornia yields as much biomass as conventional crops but needs 35% more water in field trials. Source: Glenn *et al.* (1997)

The North American Dust Bowl and Desertification: Economic and Environmental Interactions

Introduction

The Great Plains region of the USA and Canada suffered a decade of drought and crop failure during the 1930s, comparable in some respects to Africa's Sahel drought of 1968–73 (Hurt 1981, Kassas 1987). A major characteristic of the 1930s drought period was human-induced wind erosion, which by 1936 affected over 25 million ha of land (Lockeretz 1978, Figure 4.39). Dust storms were so intense that Great Plains topsoil was deposited on Washington, DC, New York City and ships 2000 kilometres out at sea in the Atlantic. A reporter from the *Washington Evening Star*, covering the Oklahoma dust storms of 1935, coined the term Dust Bowl to describe the region, though the term is also used to describe an event and period of time. The Dust Bowl years coincided with the decade of the Great Depression. Hundreds of thousands of people migrated from affected areas of the Great Plains, to the west coast to work as itinerant field hands or to northern cities where they swelled the ranks of the unemployed. The families that stayed on the land endured a decade of poverty and hardship. In some Dust Bowl counties half the families survived on federal welfare payments. The Dust Bowl was the worst environmental disaster in the history of the USA.

In the 1950s, drought and erosion returned to the Great Plains, affecting an even larger area than before (Hurt 1981, Lockeretz 1978, 1981, McGinnies and Laycock 1988, Easterling *et al.* 1992). The contrasts between the environmental, economic and social outcomes of the 1930s and 1950s droughts were a consequence of changing relationships between people and the land and differences between the antecedent conditions relating to each drought period. In the 1970s, drought returned once more, but by then farming was much more dependent on groundwater irrigation. This again led to differences between the ensuing outcomes and those of earlier droughts. The history of agriculture on the Great Plains over the last 150 years is, therefore, a good example of the complex relationship between people, policies, the environment and desertification.

Settlement and agricultural change preceding the 1930s

The events that occurred during the 1930s well illustrate the potential linkages between drought and desertification. While drought by no means leads to desertification *per se*, the nature of exploitation of the Great Plains by European settlers from the mid-nineteenth century set in place conditions that led to this semiarid area losing its natural resilience and becoming vulnerable to degradation, a vulnerability subsequently exposed by the onset of drought.

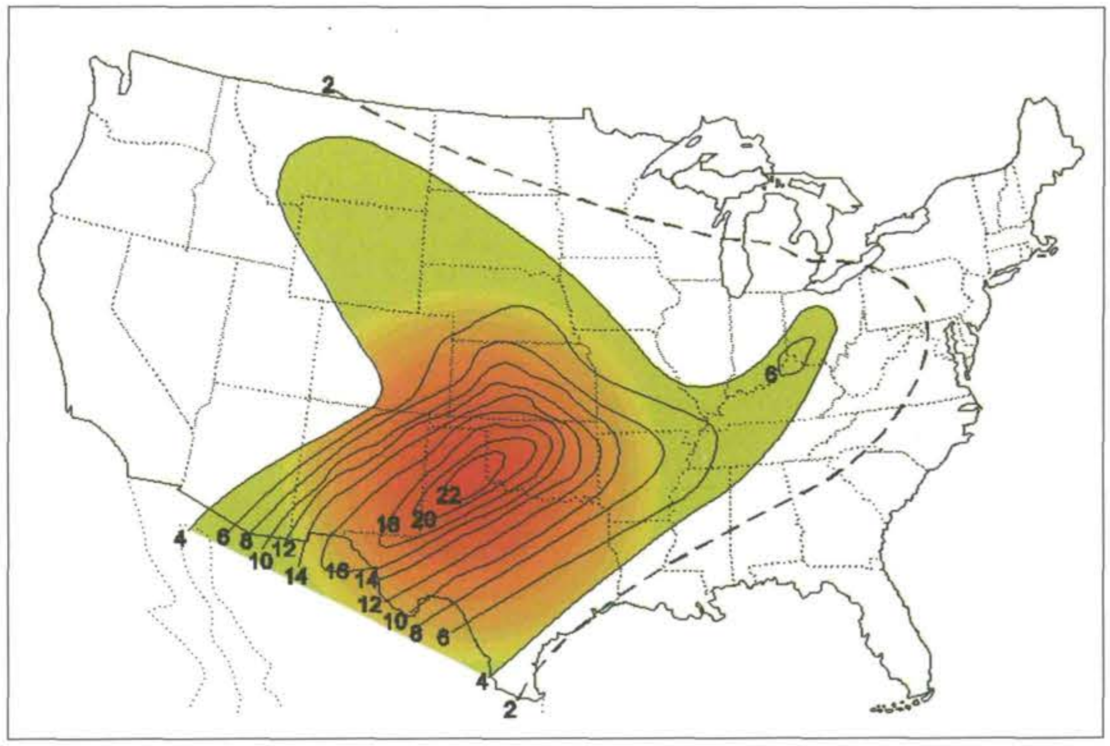


Figure 4.39 The North American Dust Bowl: number of days of dust storms during March, 1936

Droughts and dust storms are a normal occurrence on the Great Plains, and for example occurred during 1860-64, 1870-80 and 1910-18. Periodic droughts, followed by lightning fires which burn off dry grass and kill emerging woody plants, are probably important elements of ecosystem behaviour that maintained the region's natural grasslands. Grasses are able to re-establish quickly from seeds and underground rhizomes when rain returns, while burning is a trigger mechanism for the germination of some seeds. Wind erosion, to a limited degree, is also likely to have been a feature of system behaviour. While 'black blizzards', the raising of dust and ash into the atmosphere,

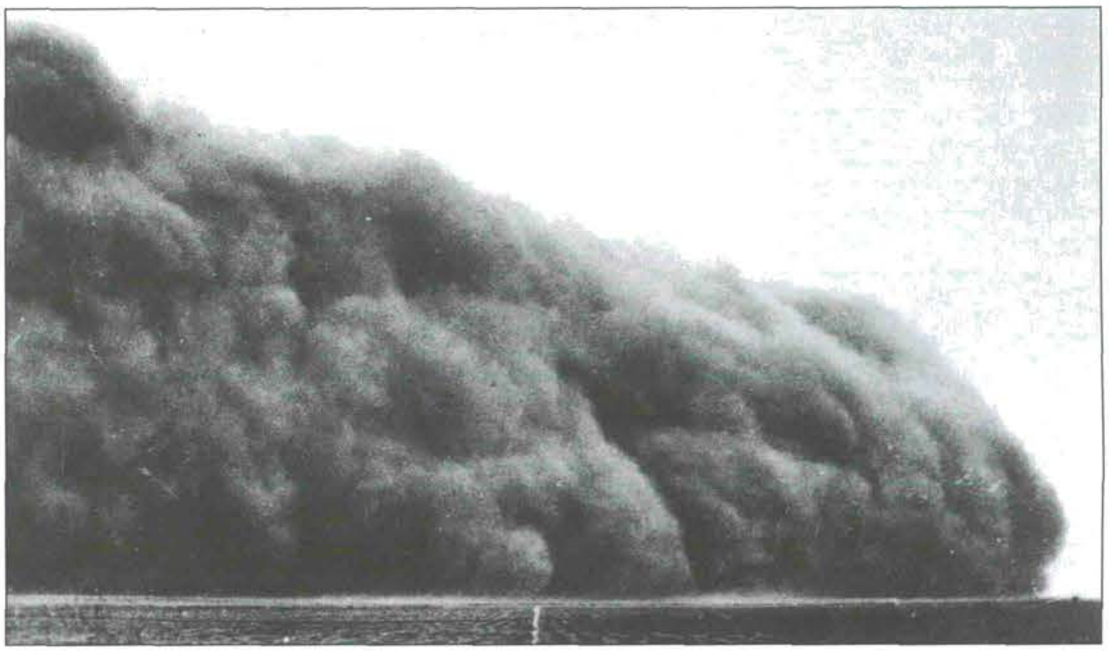


Figure 4.40 Dust storm south-east of Lamar, Colorado (Nebraska State Historical Society)

were a feature of the Dust Bowl decade (Figure 4.40), such events were also noted by early European arrivals in the area, prior to settlement and cultivation (Hurt 1981).

The Great Plains were commonly known as the Great American Desert during the early years of European settlement (Lockeretz 1978). The semiarid region was considered too harsh to farm, lacking surface water and trees. After European superiority had been gained over indigenous peoples, who were either killed or displaced, and following the virtual elimination of large bison herds, the grassy plains were perceived to be highly suited for cattle production.

Large-scale ranching began in the 1860s after railways had been constructed and it became possible to transport cattle to markets in the more populated, increasingly urbanised, eastern USA. These were the days of the so-called 'Cattle Kingdom'. Large ranching operations were frequently established in the plains through investment from Europe. A ranching company typically owned only a small amount of acreage that controlled access to water, but utilised extensive grassland areas that were public domain. Typical was the Prairie Cattle Company, a British company that controlled 2 million ha in three states and owned 140 000 cattle. High-intensity livestock use in some areas created problems of trampling and soil compaction, while grazing pressure removed the short, wiry grass species that gave protection against wind erosion. Cattle numbers increased from approximately 1 million in 1870 to over 8 million in 1886, but then collapsed precipitously due to drought, winter blizzards and a depression in cattle prices, such that by 1887 most of the large ranches had been bankrupted.

The second, and more damaging, land-use practice that led up to the 1930s Dust Bowl was dryland farming (McGinnies and Laycock 1988). The Homestead Act of 1862 granted individual settlers 65 ha of land with the provision that they make it productive. The small size of these land holdings was insufficient for livestock rearing in a semiarid area, so the settlers attempted crop farming (Lockeretz 1978, 1981). These 'sodbusters' were attracted not only by the promise of free land, but by the promotional efforts of interest groups that stood to profit from large-scale settlement, particularly the railroad companies. The name Great American Desert was dropped from maps, and promotional brochures declared that 'rains follow the plow'. The railroads offered free one-way tickets to potential settlers. Most came from the eastern USA and Europe, where reports were circulated of record crop yields in the plains. Starting in the 1870s, settlers came in great numbers, such that by 1890, 6 million people were living on the plains and 40 million ha were under cultivation, although recurrent drought forced many to leave (McGinnies and Laycock 1988).

By 1900, however, several key technologies had been developed which led to a more rapid expansion of plains farming. Barbed wire kept free-ranging cattle out of farm fields; windmills extracted water from shallow wells; and the labour of growing a wheat crop was reduced through the use of technical developments including ploughs that furrowed, deposited and covered seed in one operation, and harvesters that allowed one person to cut and bundle crops simultaneously (Hurt 1981, Lockeretz 1978). By 1920, the use of tractors and combine-harvesters dramatically reduced the labour involved in wheat cultivation, such that a crop required only about 6 weeks of work per year by the farmer. As farming became more mechanised the average farm size increased through the consolidation of small holdings, and land owners were either absent through much of the year or leased out the land. By 1930, 38% of the farms were run by tenant farmers who had no stake in the long-term sustainability of the land.

Market forces also contributed to the expansion of wheat cultivation in the Great Plains. During World War I, wheat prices rose to over US$70 per tonne (Lockeretz 1978), and 'wheat will win the war' was the patriotic rationale for ploughing up more and more native grassland for crop production. After 1920 wheat prices began to fall, decreasing to under US$35 per tonne by 1929. Paradoxically, this had the effect of stimulating production. Farmers could only stay in business if they both mechanised and increased the amount of land they farmed in order to pay for capital outlays. This contributed to the expansion of cultivation, at the expense of remaining areas of native grassland, and into the driest areas at the margins of areas suitable for wheat.

A number of cultivation practices also gained prevalence during this period of enhanced cultivation (Lockeretz 1978, Hurt 1981, McGinnies and Laycock 1988). Fields were commonly left fallow in alternate years, with the view that this would increase soil moisture content. However, during fallow periods ploughing usually took place several times, to destroy weeds, but also to create a dust mulch that was believed to enhance the ability to adsorb moisture. In reality, the opposite impact was achieved. Frequent ploughing actually lowered soil moisture content and broke up clods, both factors contributing to the potential for wind erosion.

The Dust Bowl decade

In 1931, wheat prices collapsed to US$7 per tonne and at the same time the rains failed over large areas of the Great Plains (Lockeretz 1978). Farms were put into fallow or abandoned, increasing the area of bare soil susceptible to erosion. The first large dust storms began in the Texas Panhandle in 1932 and moved east into Oklahoma and Kansas (Hurt 1981). Drought conditions, created by higher than average temperatures which increased evapotranspiration, and enhanced in many areas by below average rainfall, continued for the rest of the decade. In each

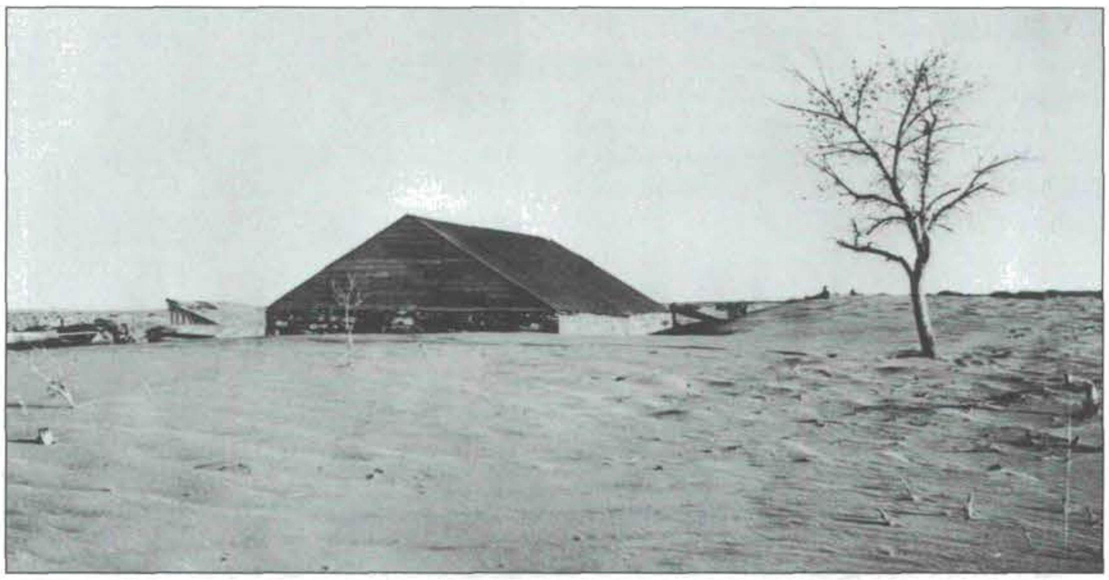


Figure 4.41 Windblown sand and dust not only caused on-site problems of erosion but off-site problems including the burial of buildings and fields (Nebraska State Historical Society)

year up to 1937, more farms were abandoned and more soil was left unmanaged and available for wind erosion. The fine soils, which had been broken down by the dust mulch tillage method, were mobilised in huge dust storms. Sediment was transported over great distances, both out of the affected region, and within the Great Plains. In extreme cases blowing dust covered over or uprooted crops and even houses (Figure 4.41). Even if an individual farmer practised good land stewardship, his land was susceptible to damage by dust picked up from his neighbours' farms, or from abandoned land. The US Soil Conservation Service estimated that by 1937, 43% of land at the heart of the Great Plains had suffered serious wind erosion damage (Thomas and Middleton 1994).

Many tenant farmers abandoned the land. These 'Dust Bowl Refugees' constituted the largest group of displaced persons in United States history. The migration was not just confined to the USA; in the Canadian part of the plains, a quarter of a million people left their farms. Perhaps more remarkable is how many people stayed on the land. The vast majority of farmers who owned their own land, stayed throughout the Dust Bowl years, despite repeated crop failures (Hurt 1981).

During the 1930s a realisation about the causes of the Dust Bowl and the need for a new land ethic began to develop. The Great Plains Committee released a report documenting how the climate, soils, plants and animals of the undisturbed Great Plains were impacted upon by the social, economic and technological forces during settlement to ultimately produce the Dust Bowl (Great Plains Committee 1937, Lockeretz 1978).

In 1936, the Resettlement Administration commissioned an influential film called *The Plow that Broke the Plains* (Hurt 1981). The film opened with soft music and a view of a rolling sea of grass extending to the horizon. A narrator explained that this was how the Great Plains looked before European settlement. Then the film showed cattlemen and farmers arriving, gang ploughs turning the soil, and the first puffs of dust began to blow on the screen. Then a newspaper headline announced World War I and rising wheat prices, and a row of tractors appeared on the screen, breaking sod, and more dust blew. The music became loader, then finally deafening, and the screen flashed to an exploding stock ticker then the screen went black. After a few seconds the scene changed to sand drifts, a cattle skull and a house blown over with dust. The narrator concluded, 'Fifteen million hectares of plains totally ruined by the plough and 70 million hectares badly damaged. What is America going to do about it?'

Response to the Dust Bowl

Events in the 1930s in the Great Plains of North America engendered a new awareness of the need for more sensitive agricultural practices and a need for soil conservation measures. A number of policies and actions at national and local levels contributed to improvements in the spheres of both pastoralism and crop production.

The Taylor Grazing Act of 1934 implemented common sense provisions that had been recommended by a federal commission 55 years earlier (Kassas 1987). Under what became the Bureau of Land Management, the number of animals that could be grazed on public land was set by the condition of the rangeland, and restoration of overgrazed lands was undertaken. The general problem of soil erosion was tackled by creating the Soil Conservation Service (SCS) in 1935 (Helms and Woodman 1990). In addition to conducting research on ways to prevent soil erosion, the SCS also became an extension service and activist force for preventing erosion. It worked with state governments to draft land-use regulations, and prepared a model state law entitled *A Standard Soil Conservation District Law*, which created state conservation districts that bound farmers together to combat soil erosion. Colorado, Kansas, New Mexico and Oklahoma quickly passed the law.

The SCS and local conservation districts worked with farmers to implement specific, soil-conserving practices (Nall 1975, Lockeretz 1978, Hurt 1981). These included terracing and contour ploughing (Figure 4.42), both of which reduced erosion potential and enhanced runoff infiltration, thereby improving soil moisture content. All other things being equal, Hurt (1981) indicates that in some locations 50 mm of rainfall could add as much soil moisture to a contoured and terraced field as 200 mm of rain to a dust-mulched field. In 1935, terracing cost about US$5 ha but increased the value of land by US$25 ha. Strip cropping was introduced to reduce the potential for wind erosion. This entailed planting contoured strips of soil-holding crops, such as maize, within wheat fields (Figure 4.43) to reduce the distance blowing dust could travel. The shelter-belt project of the 1930s planted a total 30 000 linear kilometres of land with over 200 million trees to act both as wind breaks and as a buffer to the long distance transport of sediment that was liberated by the wind.

Practices employed during fallow periods and during ploughing prior to crop sowing were modified. Instead of burning off wheat stubble after harvesting, it was incorporated into the soil where it stabilised the soil surface. Ploughs were improved to throw up large, overlapping ridges of large clods which helped maintain soil structure and soil moisture. Pasture land throughout the Great Plains was reseeded with native grass mixes selected for the soil type and rainfall. Dams and farm ponds were built to reduce runoff from heavy rains.

Figure 4.42 Contour ploughing (Natural Resources Conservation Service, USDA)

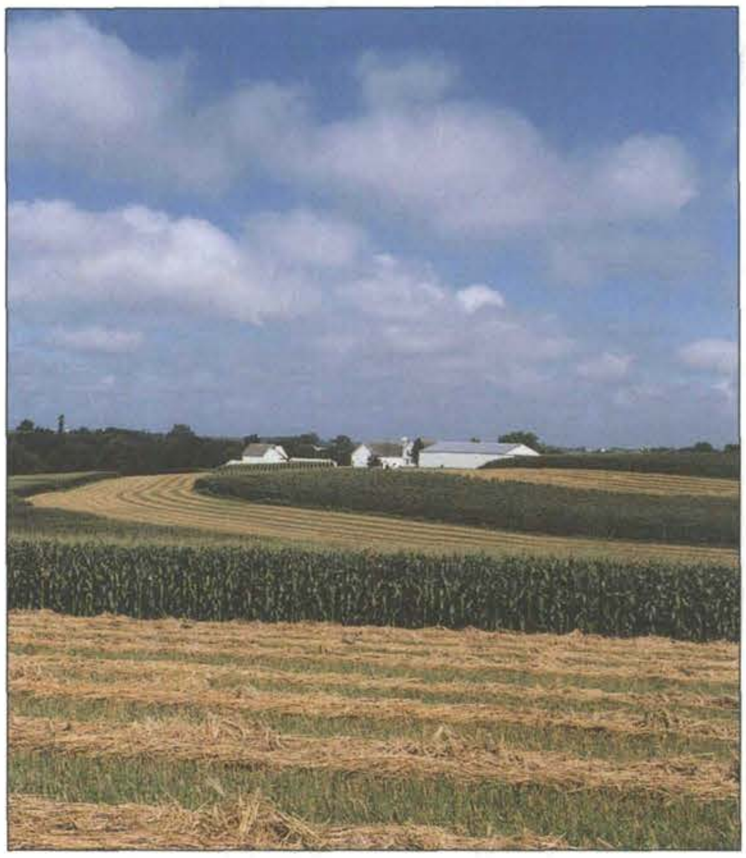


Figure 4.43 Strip cropping (Natural Resources Conservation Service, USDA)

Price support mechanisms were implemented to modulate the boom-or-bust price swings of wheat and other commodities, which had previously driven farmers to try to intensify production. Emergency cattle purchases by the federal government prevented the mass slaughter of animals (Hurt 1981). The Federal Emergency Relief Administration, the Agricultural Adjustment Administration, the Farm Credit Administration, the Farmers' Home Administration and other agencies took a direct role in improving the financial status of farm families. However, not all such efforts were welcomed. An attempt to implement a national land use planning programme through the acquisition of submarginal lands and relocation of farm families was cancelled after it aroused suspicion and resentment throughout the Dust Bowl (Hurt 1981, Lewis 1989). The relatively small amount of land that was purchased was restored and became the National Grasslands, a series of remnant prairie ecosystems that are scattered through the Great Plains.

Some of the most important improvements were made by private initiative, while much of the recovery was due to the general advancement of the national economy (Kassas 1987). Roads and railways were extended further into semiarid agricultural areas, allowing cattle to be moved from summer to winter ranges and to markets more efficiently. Ranchers began sectioning their land and rotating pastures to allow the range to recover. Boreholes were sunk to extend the amount of irrigated agriculture in the Great Plains, though while this insulated farmers from drought it also eventually created a new set of environmental problems associated with soil salinization and water-table lowering.

In 1937, the area of land in the Dust Bowl experiencing serious erosion was 65–70% less compared to the previous year (Hurt 1981). Good rains fell in 1938, allowing farmers to plant soil-holding cover crops. Drought returned in 1939 but soil protection measures implemented in the previous year limited the problems of wind erosion. Normal rainfall returned in 1940 and was average or above average for a decade.

Agricultural boom in the 1940s

By the end of the 1930s, farmers in the Great Plains had developed the technical skills and institutional supports needed to survive a future drought. However, when high wheat prices and normal rains returned in the 1940s, many farmers ignored the lessons they had learned, and began to undo the protections built into their farming systems. When drought returned in the 1950s, unsustainable land-use practices once again magnified the damage (Lockeretz 1978, Opie 1993).

Just as in the 1920s, the 1940s wheat boom was triggered by the effect of a world war on market prices. Between 1940 and 1947 the price of wheat increased from US$27.50 to US$80.70 per tonne, surpassing the previous peak of US$79.20 per tonne in 1919. The resultant economic viability of production led both resident and absentee land owners to increase the area under production. By 1946, 1.6 million ha of retired land was reploughed on the central and southern Great Plains, 75% of which had been labelled unfit for cultivation by the Soil Conservation Service (Opie 1993). On the margins of the area affected by dust bowl conditions in the 1930s, in eastern Colorado, Texas and New Mexico, new land was brought under cultivation. The demand for even marginal lands was such that their value increased from US$1–2 per ha in the 1930s to US$20–30 by 1950.

The wheat boom of the 1940s was supported both by federal agencies and a feeling that scientific know-how had eliminated the risk of a further dust bowl. The United States Department of Agriculture encouraged fence-to-fence planting and emphasised high yields. Slope terracing, shelterbelt and soil conservation district rules were relaxed or eliminated. Wheat yields in 1942 were double those of 1939, with further increases in the next 2 years. Record production levels were attributed to more machinery, better moisture management and better knowledge provided by agricultural scientists. Production was also fuelled by federal aid; wheat production in the Texas Panhandle rose US$38 million in value from 1935 to 1942, but at a cost of US$43 million in taxpayer-supported aid (Worster 1979). Warnings that drought could follow favourable weather and return the region to a dust bowl were ignored by most farmers (Opie 1993).

Drought and dust storms return to the Great Plains in the 1950s

In 1950, rains failed over much of the Great Plains (Hecht 1983, Easterling *et al.* 1992, Figure 4.44). Dust storms returned (Finnell 1954) and US$275 million of wheat crop was lost (Hurt 1981). Through the early 1950s the drought spread from Kansas and Colorado to Texas, Oklahoma and further south. By 1956, region-wide dust storms were fed by 8.4 million ha of damaged land. Aeolian movement of soil in some fields was on a similar scale to the 1930s, with the development of dunes up to 10 m high. The area of degraded land in 1954–57 was double that of 1934–37 (Opie 1993). Lee *et al.* (1993) note that the most severe dust storms recorded to date in Texas and New Mexico occurred during the late 1940s and 1950s (Table 4.19), though records did not start until the 1940s.

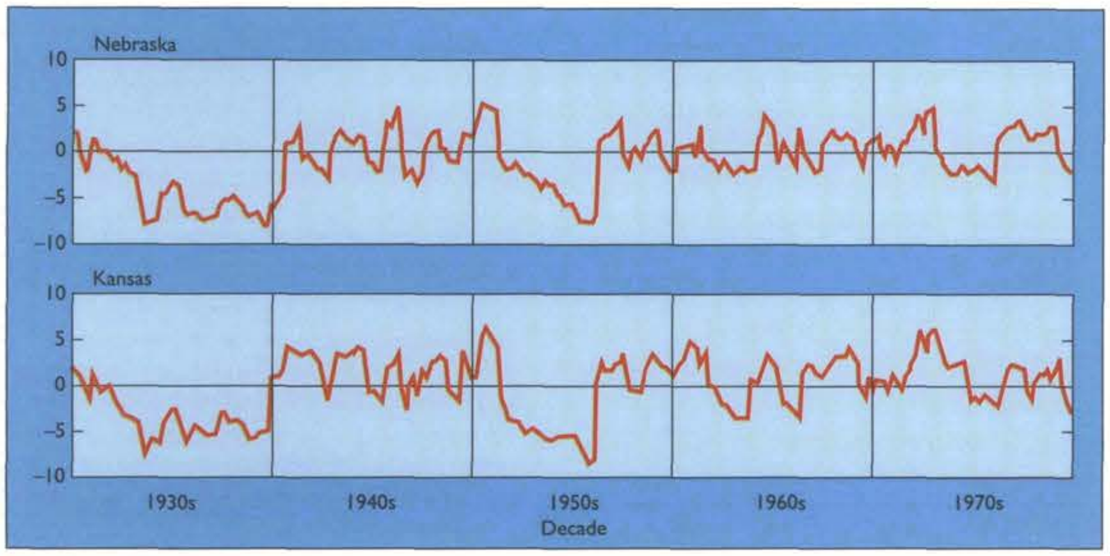


Figure 4.44 Drought severity measured by the Palmer Drought Index for two Dust Bowl states

Table 4.19 Highest Magnitude dust storms at Lubbock, Texas, 1947–94. After Lee and Tchakerian (1995)

Date of storm	*Magnitude, expressed by $E_{l.7}$ index of blowing dust transport*	*Dust storm duration*
29–30 January 1947	53.6	19 hrs 9 mins
11–13 March 1954	40.5	55 hrs
30 March 1948	35.3	13 hrs
16–17 December 1977	27.7	18 hrs 5 mins
4–5 December 1948	27.2	21 hrs 22 mins
9 February 1960	26.8	11 hrs 20 mins
4–5 May 1950	23.5	10 hrs 48 mins
2 March 1951	22.9	9 hrs 23 mins
3 March 1966	22.7	13 hrs 10 mins
8–9 April 1956	20.7	9 hrs 5 mins

Interestingly, the highest magnitude dust storm ever recorded at Lubbock, Texas, was in late January 1947, a year that did not record severe drought conditions. The explanation for this is that post-harvest soils were inadequately protected during the winter making then highly susceptible to deflation. This well illustrates how the combination of poor agricultural practices plus drought can create the worst, prolonged, scenarios, but that bad land management alone can lead to desertification – that one storm accounted for 4% of all dust moved in a 47-year period in the region (Lee and Tchakerian 1995).

Response to drought and desertification in the 1950s

The response to drought in the 1950s was more rapid than in the 1930s. Farmers in many areas undertook conservation ploughing without waiting for government aid. The United States Department of Agriculture supported an emergency tillage programme with US$25 million. The government also provided crop insurance, rice supports and feed loans to keep cattle alive. World crop prices remained high and the general economy was healthy. The result was that most farmers remained solvent and on the land through the 1950s, and the drought did not have nearly the same economic and social impact as that of two decades earlier.

In 1956 the Agricultural Act established the Soil Bank Program, the only direct conservation strategy introduced during the 1950s drought period. This programme aimed to reduce the production of surplus crops but also aimed to conserve soils not needed for production (Ringquist *et al.* 1995). In return for taking designated cropland out of production and for instigating soil conservation practices, farmers received back from the state up to 80% of costs incurred. Enrolment in the programme in the Great Plains peaked just 2 years after its implementation (Ervin and Lee 1994).

It can be asked whether 1940s and 50s farmers in the Great Plains achieved the right balance between economic and environmental considerations. In one respect they had fallen into the same trap as the 1920s farmers, by expanding production into marginal land in response to years of good rains and high wheat prices. However, they responded much more quickly and surely when drought returned, implementing many of the technical and support measures developed in the 1930s. Local initiatives were sufficiently strong that when federal funds to support emergency tillage were made available, many farmers did not qualify for aid as they had already implemented restorative measures themselves.

The movement away from rainfed agriculture in the 1960s and 70s

Unlike the 1930s, at the end of the 1950s drought, resettlement out of marginal areas and conversion of farms to grassland became unthinkable. Even with the payments available under the Soil Bank Program, enrolment in the Great Plains dropped significantly after the drought finished, and dwindled significantly through the 1960s, before the programme ceased between 1970 and 1976 (Figure 4.45). The major reason for the continuation, even expansion, of cultivation was the development of irrigated agriculture in the region, which tapped the extensive Ogallala aquifer. The use of groundwater effectively removed the susceptibility of rainfed agriculture to drought. Through the 1960s and 1970s, centre-pivot irrigation became a feature of Great Plains cultivation.

Severe drought returned to the region in the 1970s. The reliance of arable farmers on irrigation water removed production from the worst effects of the drought. Indeed, during the 1970s high wheat prices, particularly linked to supplying a demanding export market to the USSR (Thomas and Middleton 1994), once again favoured intensive cultivation. In the USA as a whole, including the Great Plains states, 80% of Soil Bank Program land was placed back in production (Ringquist *et al.* 1995). The use of centre pivot irrigation may have reduced the susceptibility of crops to drought, but it had other less advantageous outcomes. To facilitate the rotating irrigation booms, many wind breaks planted since the

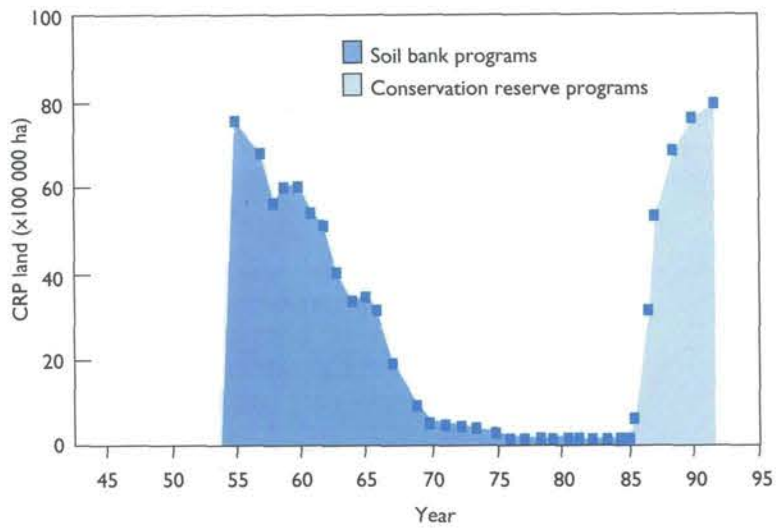


Figure 4.45 Land in the Great Plain states in the Soil Bank and Conservation Reserve Programs (after Ervin and Lee 1994)

1930s were removed (McCauley *et al.* 1981). Wind erosion and dust storms again became a feature of the landscape, on a scale comparable to the 1930s (Lockeretz 1978). One single dust storm originating in the Portales Valley area of New Mexico in February 1977 produced a dust plume covering 400 000 km^2 (Purvis 1977), and in December of the same year the fourth biggest dust storm recorded at Lubbock occurred (Table 4.19). The dominance of economic over environmental concerns in this decade was magnified by a Federal Wheat Disaster Assistance Program that was instigated to compensate farmers for their production losses resulting from wind erosion (Thomas and Middleton 1994). This provided an economic incentive to keep marginal, highly erodible lands in production during the drought.

During the 1980s the balance between conservation and production was somewhat restored by the 1985 Conservation Rehabilitation Program. This had marked similarities to the Soil Bank Program of the 1950s, and aimed to take large areas of highly erodible cropland out of production. Uptake in the Great Plains has been rapid (Figure 4.45) and wind erosion has markedly decreased (Lee and Tchakerian 1995), demonstrating the strong linkage between economic and social factors and the occurrence of blowing dust. Through the 1970s and 80s, however, the region has become susceptible to another form of desertifcation – groundwater depletion.

The Ogallala Aquifer and the Future of Great Plains Farming

Farmers have been aware of vast water deposits under the Great Plains since the 1800s but the technology to exploit them for large scale irrigation has only recently been available. The large-scale conversion of Great Plains farmland to irrigation began in the 1950s, as centrifugal pumps and gasoline engines made decentralised irrigation feasible (Opie 1993). At the peak of the irrigation boom, in 1978, the Great Plains had 170 000 wells pumping continuously, extracting 25.2 million megalitres (1 megalitre = 1 million litres) of water per year to irrigate 6 million ha of crops (Kromm and White 1992).

This water has transformed the Great Plains. It is now the heart of the US beef industry, with cattle-fattening operations utilising the grains and forages produced on the region's farms, 40% of which are irrigated. Wheat only accounts for 15% of the harvest; corn (50%), sorghum (15%) and forage for animals are the main crops (Kromm and White 1992). The Great Plains accounts for 30% of the total irrigated agriculture in the USA and 20% of agricultural output. Unfortunately, the future of this land use system is uncertain, as the rate of groundwater extraction is unsustainable.

It was once thought that the water in the Ogallala aquifer flowed underground from the Arctic as a giant underground river. This myth of an inexhaustible water supply under the Great Plains persisted into the 1950s (Opie 1993). Only when water levels in irrigation wells began to decline in the 1960s did farmers accept the reality that the Ogallala aquifer was indeed exhaustible. This did not lead immediately to conservation, however, but to more rapid exploitation, since farmers who reduced extraction experienced declining water-tables as others continued to irrigate. The 'use-it-or-lose-it' approach to water development was reminiscent of the exploitation of the open range during the days of the Cattle Kingdom (Opie 1993). A particularly damaging act was the conversion of fragile grazing and hay land in the Nebraska Sandhills to grain production with the installation of 15 000 centre pivot irrigators from 1973–1976.

The Ogallala aquifer contains 4.6 billion megalitres of stored water, but recharge over most of the Great Plains is negligible (Kromm and White 1992). About 60% of that water can be economically extracted for irrigation using existing equipment. By 1990, about a third of the available resource had already been extracted (Opie 1993). However, the water is not evenly distributed among the seven states that lie over the aquifer. Most of the water is pumped from the southern part of the aquifer, where regional rainfall is lowest and the aquifer is thinnest. As a result, projections are for 'extreme consequences' for farmers in the south and central parts of the aquifer by 2020, whereas other areas can probably expect to have water for many decades to come. Over the next 30 years, it is possible that half the land irrigated today may need to be withdrawn due to water depletion (Opie 1993). This trend may be accelerated by greenhouse warming, if that results in less rain and more evapotranspiration from crops.

Attitudes of the Great Plains farmers

In many areas of the Great Plains, farmers are now organised into local water conservation districts, and implement a variety of water-saving technologies. In a 1985 poll, 90% of farmers thought ground water depletion was a major issue (Kromm and White 1992). However, it ranked third among their priority concerns, behind crop and energy prices. Less than half wanted water use regulated by local, state or federal governments. When asked their view of the future, 46% thought they would be better off in 5 years than today, 40% thought their condition would stay the same and only 15% thought they would be worse off. A major problem with the use of the Ogallala aquifer is that it is being used as a substitute for rainfall, rather than a supplement. Crops, such as corn, which require substantial water inputs, are being grown instead of wheat which is more tolerant of drought and does not require high levels of irrigation. Furthermore, a single centre-pivot irrigation system costs, at 1996 prices, US$50 000 to install, so that a high return is needed to repay investments. Great Plains farmers have proved resilient and adaptive in the face of repeated challenges to their land use systems, but they continue to rely on extractive, non-sustainable use of natural resources. There is reason to conclude that the vulnerability of the land-use system to periodic drought which characterises this semiarid environment will be as high in the future as it was in the 1930s.

Original text by D.S.G. Thomas, V. Squires and E. Glenn.

Poverty and Degradation

Introduction

Poverty has been described as both a cause and an effect of environmental degradation. In some circumstances poor people overexploit the environment in their struggle to survive, while in other situations environmental degradation leads to falling crop productivity or increasing poor health that in turn create impoverishment. However, while the extent of poverty and the state of the environment may be closely linked this does not imply simple, clear lines of causation. Separating the environmental effects of poverty, population growth, inappropriate property rights and other factors is difficult. Some authors think it may be more appropriate to view poverty as the mechanism through which other factors lead to degradation (e.g. Pearce and Warford 1993).

Moreover, it is clear that poor people often rely directly on natural resources, or 'natural capital', for their living and very survival. Soil, for example, can provide a flow of food or income in the same way that a machine can produce a flow of manufactured goods. Both are forms of capital, one provided by the earth the other man-made. Poor people usually have very small amounts of man-made capital and this means they have virtually no opportunities to generate income by producing manufactured goods. Poor people also have their own labour as a resource but employment possibilities are usually limited.

Poor people generally rely upon a very limited stock of natural capital, such as a small plot of land or access to a small communal common. Even those people who neither own nor rent land, and who rely on employment for income, often supplement this income in an important way by access to some natural capital. Natural capital that can be accessed without a rental or ownership contract is called a 'common property resource' (CPR). Examples of CPRs are woodlands, grazing areas and rivers that can be used by members of the community. A study of rural villages in India found CPRs to account for 14-23% of average household income (Jodha 1992). It is this characteristic of heavy reliance upon natural, capital-based sources of income that typifies many poverty-stricken peoples.

Poverty, natural capital and investment

Natural capital can be degraded by the actions of its users. Soil fertility can be reduced by growing inappropriate crops, for example, and erosion can result from excessive grazing pressure. The maintenance of the stock of natural capital requires sustainable management. In particular, current resources must be invested to ensure that the capital is productive in the future. As an example, the fertilizing of soil to ensure that it retains its productivity involves not using resources for immediate benefit (e.g. the animal dung used as fertilizer could have been used as fuel) and investing them for returns to be received in the future. Irrigation schemes, tree planting and decisions on how much livestock to keep are all examples of investment decisions: planning today to ensure future production levels.

In making any investment decision, people need some way of comparing future benefits (e.g. improved soil fertility and crop yields) to current costs (e.g. the cost of fertilizer). Each person will have a time preference that will determine whether such an investment is worth undertaking. Economists use discount rates to indicate such time preferences. As the discount rate increases, the level of total investment will fall since fewer investment projects will be able to provide a sufficient return. Higher discount rates also mean that short-term investments are favoured over long-term investments.

Poor people often have relatively high discount rates. Studies in India have shown that the rate of return required by poor farmers is 30–40% per annum (World Bank 1992). High discount rates arise from the uncertainty that poor people face about their future. Poor health, diet and living conditions mean that people are uncertain about their future survival and work capacity. In addition, the uncertainty caused by possible drought or flooding may mean investments, especially long-term investments, are not undertaken. Efforts to introduce soil conservation techniques in Burkina Faso, for example, showed that adoption of new techniques was highest when returns occurred within two or three years (World Bank 1992). Another key factor in the investment decision is that poor people may view their property entitlement as uncertain and increase their discount rate accordingly. Future tenancy agreement changes and policy changes may move poor farmers from their land so that they will not be there to reap the benefits of previous investments.

Poverty means, therefore, that discount rates of individuals are high and the planning horizon is relatively short. But many investments in natural capital have relatively low rates of return that continue far into the future (Newcombe 1989). Planting trees, for example, yields benefits in terms of fuelwood and prevention of erosion but these only occur after 5 and more years. A poor community may, therefore, invest only a small amount in its natural capital. This lack of investment may lead to degradation, which in turn implies that future productivity will fall (Venator *et al.* 1992).

It is important to note, however, that poverty does not always lead to degradation. There may be strong social and cultural rules for controlling the use of natural capital. Such rules, which can override individual preferences, may have been built up over long periods of time to ensure the survival of the community. Only when such long-standing rules break down, for example by migration to a new area or by changes in tenurial rights, may degradation become a problem. This is especially the case with the management of CPRs. Traditionally CPRs are governed by social rules established over time but the joint effects of population growth, poverty and policy changes may break down these rules (Jodha 1992). The CPRs then become 'open access regimes' (OARs), areas where people can extract as many resources as they are able. These high extraction rates occur because individuals have insufficient incentive to preserve a resource that is open to all. In essence, the distinction between a CPR and an OAR is that individuals producing under an OAR act as though the discount rates were infinitely high, due to the low probability of appropriating the benefits of foregone harvests. Under an OAR the incentive to invest in the natural resources is effectively eliminated.

Mining the future

Poor people may be able to live in harmony with the environment using traditional methods under normal conditions. However, when subject to 'shocks', whether natural (e.g. floods or droughts) or human-induced (e.g. land tenure changes), poor people either migrate from the affected area or stay and try to survive.

Those who stay in the affected area need to extract sufficient resources to survive. Their poverty means they have a very limited range of resources – only their natural capital stock and their labour. The usefulness of 'human capital' under these circumstances may be limited. A shock may also reduce employment opportunities which means the poor will only have their natural resources for survival. People may be forced to overexploit these resources: land may be grazed too intensively, crops may be planted on marginal soil, or additional fuelwood may be collected from woodlands for sale. This type of resource exploitation is known as 'mining', which means that the stock of natural capital is being reduced for current consumption at the expense of future production. Mining ensures short-term survival but at the expense of environmental degradation and future adverse impacts.

Whether degradation occurs depends on local circumstances. Environments can accommodate a certain level of exploitation and still regenerate themselves to their original state. However, when environments are pushed beyond certain threshold levels, a future decline in productivity may result. For example, land may be able to sustain some periods of heavy grazing pressure, but if the grazing is too intense the mix of species may be altered, after which water and wind erosion may remove soil and prevent plant regeneration (Perrings and Walker 1992).

It should be stressed that not all shocks affecting a community necessarily lead to degradation. Whether or not degradation occurs depends on the resources available and the social rules governing the community. One study in Nigeria, for example, found that the pressure of famine did not affect smallholders' tree conservation practices (Mortimer 1989). Further, Jagannathan (1989) stresses that if additional employment can be obtained in the event of a shock then poor people may restore their income level through work rather than mining the environment. Mining is one possible response to an environmental shock but it is by no means a necessary consequence.

Poverty, migration and degradation

Another possible response open to poor people faced with increasing pressure on resources is to migrate to another region. The pressure on resources could arise from a 'shock' or from steadily worsening conditions. Historically the process of development has led to movements of people from rural to urban areas, fuelling the rapid growth of cities in many developing countries. Table 4.20 shows details of migration trends in selected countries, illustrating that there has also been substantial rural to rural area migration in developing countries over the recent past. Such migration has environmental effects in both the regions of origin and destination. Lower population in the area being vacated may reduce pressure on natural resources and hence reduce degradation.

Migration is not simply a response to 'push' factors in the region of origin (e.g. poverty, natural disasters, changes in land tenure) but is also dependent upon 'pull' factors from the destination region. Such factors may include the offer of free land (and hence the land's resources) or subsidies paid by governments. The movement of people to forest areas and the subsequent deforestation caused by land clearing for agriculture has been a major factor in the loss of forests. Leonard (1989) states that about two-thirds of tropical deforestation in developing countries occurs for agricultural reasons, with about 80% of this attributable to slash-and-burn agriculture being practised by poor immigrants.

New arrivals often clear land rapidly in order to make a legal claim. Indeed, in some countries, including Ecuador and the Sudan, formal property rights are only given when the land has been cleared (Southgate 1990, 1991). Deforested land is usually subject to soil erosion, by runoff or deflation, and accelerated leaching. Some estimates suggest that 50% of a soil's fertility can be lost within 3 years by these processes (Leonard 1989). Such losses of fertility may cause migrants to clear more land locally or to move on to other areas. Although natural environmental factors are often involved in the movements of people to new areas, much of the impact of migration is actually the consequence of a wide range of governmental policies on such issues as land tenure, subsidies and infrastructure.

Poverty as a disabling factor

The conditions of poverty also act to disable people from taking actions that benefit their environment. Efficient and sustainable management of natural resources often requires a range of other resources: human, natural, legal and informational. Poverty implies a lack of breadth as well as depth in such resource assets. The absence of any one of these assets may in itself lead to environmental degradation.

One disabling factor is the lack of credit available to poor people. Even if such people want to invest in their natural capital, for example by irrigating or fertilizing land, borrowing facilities may be limited and interest rates high. Limited credit and high interest rates reflect several factors: the isolation of poor areas, high levels of uncertainty, and poor people's lack of collateral. Poor people may also be dissuaded from investing in the environment because they lack any legal entitlement to it. For example, women in sub-Saharan Africa often have no right of tenure to land despite the fact that they provide 50–80% of the labour (World Bank 1992). Consequently the women have limited access to credit and may also have low incentives to invest due to uncertainty over their rights in the future.

Illiteracy and low levels of education among the poor means that it may be difficult to obtain information about the environmental implications of certain actions. A new pesticide may cause degradation if used improperly, for example, but illiteracy may prevent this knowledge being known. Insufficient knowledge on how, when and how much to apply can lead to soil and water pollution and to the destruction of wildlife.

Environmental problems of this sort are most likely to occur when traditional methods have been replaced by new methods, or when people have migrated to new agricultural areas where soils are different and hence there is no historical experience to rely upon. When this is the case and information is costly, environmental degradation may be the result.

Conclusion

Poverty and degradation have particularly close links, most obviously because the poor people of the world tend to live in ecologically marginal areas. Viewing the environment as a form of natural capital used by poor people highlights a number of reasons why degradation might occur. First, the discount rate used by poor people may be high, with the result that investment in natural capital is often low and biased towards short-term projects. Second, poverty means people have no surplus resources and this implies that any shocks may result in the mining of the environment. Poverty also acts as a disabling factor: poor health, poor education, illiteracy and lack of legal rights may all act to reduce the ability and incentive to prevent degradation. The fact that degradation may lead to more poverty, for example falling crop yields as soils are eroded, means that a vicious circle can develop with disastrous consequences.

Despite the close links between poverty and degradation the two are not always connected. Population pressure, land tenure arrangements and government policies act in conjunction with poverty to cause degradation. Even in conditions of poverty the existence of traditional methods and forms of co-operation may prevent degradation if there is an absence of other malign factors.

Original text by M. Rogers.

Table 4.20 Movements of migrants by origin and destination in selected dryland countries

	Proportion of total annual migrations (%)			
Country (year)	*Rural–rural*	*Urban–urban*	*Rural–urban*	*Urban–rural*
Botswana (1985)*	60.0	8.0	29.0	3.0
Ivory Coast (1986)	14.8	44.2	20.3	20.7
Ecuador (1982)	16.0	46.0	18.0	21.0
Egypt (1976)	26.0	55.2	12.0	6.8
Ghana (1988)	4.6	25.6	9.5	37.3
India (1981)*	16.7	11.9	65.4	6.1
Pakistan (1973)	17.2	38.7	33.0	11.1
Peru (1986)	11.6	51.6	13.6	23.2

Note: data refer to previous place of residence except countries with * where data refer to place of birth.
Source: Bilsborrow (1992)

Desertification and Migration in Mexico

Introduction

The Republic of Mexico contains some of the world's most diverse and unique natural environments. Its climatic zones range from arid desert to tropical rainforest and nearly half of the country's native flora are endemic. Despite the diversity of its climate, drylands predominate in Mexico, and while exact measurements remain uncertain, current data indicate that more than 60% of the country's territory is severely affected by degradation processes (Comisión Nacional de las Zonas Aridas 1993) and more than 260 000 hectares of grazing and arable land are taken out of production annually (Medellin-Leal 1978). This situation has had profound social and economic impacts for the nearly 30 million people living in Mexico's rural areas. This section explores the desertification phenomenon in Mexico and some of its socio-economic impacts.

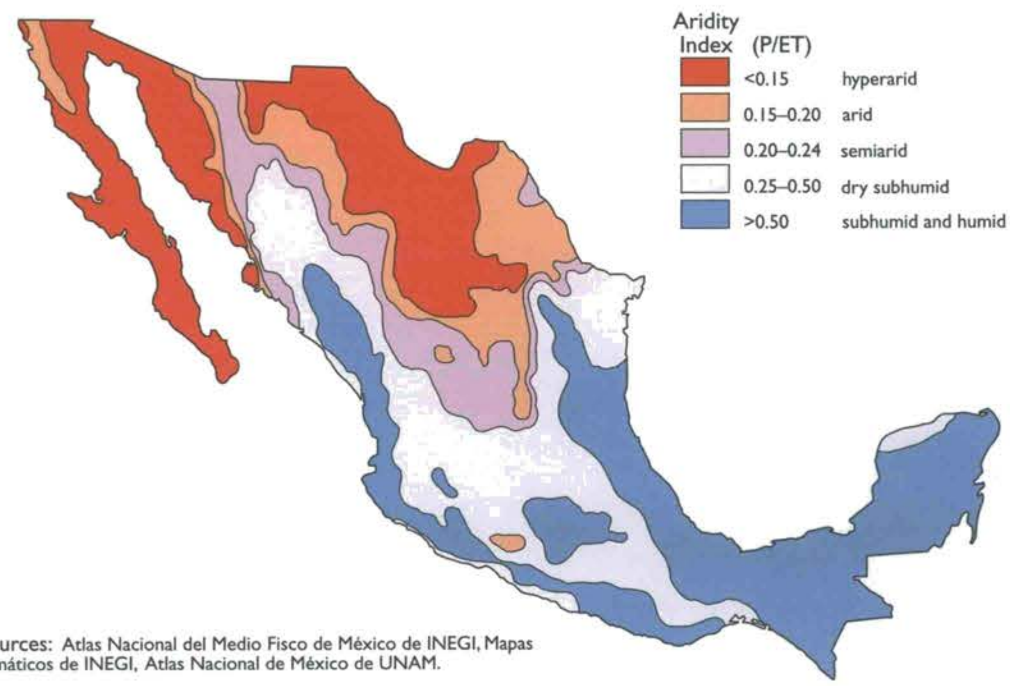
Population

Mexico's current population of 92 million people continues to increase by approximately 1.9 million people per year, mainly in urban areas (CONAPO 1995). Mexico City, the capital, is one of the most populated cities in the world, and is estimated to reach a population of 22 million by the year 2000 (INEGI 1990). Two-thirds of Mexico's poor are farmers or farm workers dependent upon the low and extremely variable annual rainfall for the success of their subsistence crops (Martin 1993). A unique feature of Mexican agricultural management is its communal land or 'ejido' system. These communal farms were created after the Mexican revolution when the government redistributed land from large landowners to landless peasants. Ejido members obtain land as a group from the government, although they typically farm the land individually. The ejido farming sector is particularly important in influencing local land use practices in Mexico. More than 70% of the country's farmers are ejido members, and the sector controls 52% of Mexico's arable land and 50% of its irrigated area, along with most of the degraded forest and rangelands (Martin 1990).

The causes and consequences of desertification

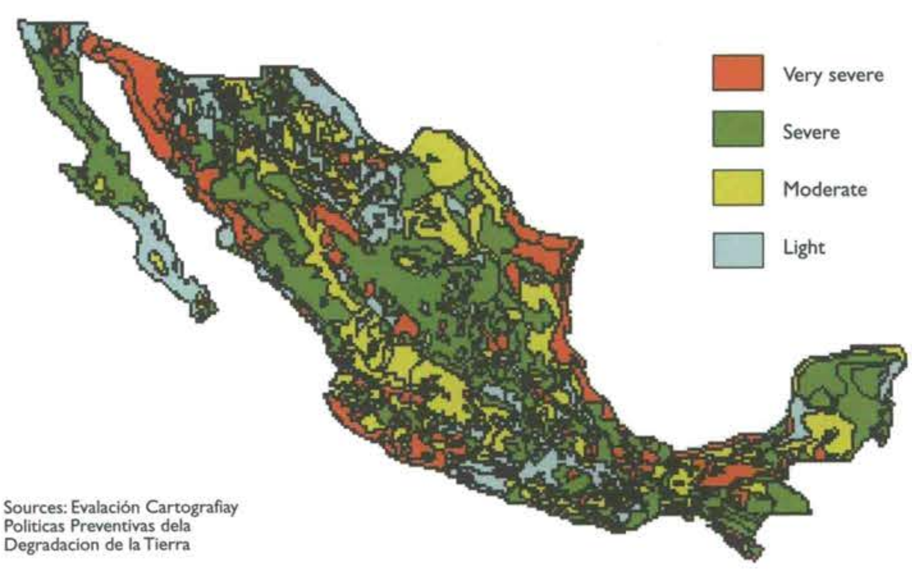
The aridity zones used in this study, derived from P/ET ratios, are shown in Map 4.36. According to this scheme, the susceptible drylands (arid, semiarid and dry subhumid zones) make up 46.8% of the national land area, with 23.6% in the hyperarid zone and 29.6% in the humid zone.

Map 4.36 Aridity zones



Sources: Atlas Nacional del Medio Fisco de México de INEGI, Mapas temáticos de INEGI, Atlas Nacional de México de UNAM.

Map 4.37 Soil degradation severity



Sources: Evalación Cartografiay Politicas Preventivas dela Degradacion de la Tierra

A national assessment of soil degradation has identified the main degradation processes in Mexico to be the loss of topsoil through wind and water erosion, the loss of soil microorganisms (biological degradation), nutrient loss, salinization and sodification. These processes are estimated to affect up to 85% of the national land area (Comisión Nacional de las Zonas Aridas 1993). The overall state of soil degradation in the country using a methodology developed in conjunction with FAO (FAO/UNEP 1984) is shown in Map 4.37, although the data have not been categorised by climate zone. Nevertheless, many of the worst-affected states are located wholly or substantially in the susceptible drylands (See Table 4.21 and Map 4.38), particularly with respect to water and wind erosion, the two most significant types of soil degradation in Mexico.

Human activities have greatly exacerbated the phenomenon of desertification in Mexico. Overcultivation, excessive grazing, deforestation, and overpumping of aquifers are the primary causal factors (Schwartz and Notini 1995). For example, 20% of Mexico's cultivated land is irrigated (Liverman and O'Brien 1991), but salinization is a serious problem in many of these areas due to applications of poor-quality water and improper drainage. Approximately 30% of Mexico's irrigated land is adversely affected by salinization.

Deforestation is a particularly serious cause of land degradation throughout the country.

Table 4.21 Worst-affected Mexican states by process of soil degradation

Soil degradation process	*States with substantial areas in susceptible drylands*	*Other states*
Water erosion (>45% of state area affected)	Aguascalientes, Guanajuato, Coahuila, Michoacan, Zacatecas, Jalisco, Nuevo Leon, San Luis Potosi	None
Wind erosion (>60% state area affected)	San Luis Potosi, Coahuila, Hidalgo, Nuevo Leon, Queretaro, Zacatecas	Baja California, Chihuahua, Morelos
Salinization (>2% state area affected, and >10% irrigated area)	Tamaulipas, Sonora, Coahuila	Baja California, Chihuahua, Colima
Sodication (13-40% state area affected)	Sonora	Campeche, Quintana Roo, Morelos, Yucatan, Tabasco, Mexico
Biological degradation (>90% state area affected)	Jalisco, Michoacan, Sinaloa	Colima, Morelos, Tabasco, Chiapas, Veracruz, Nayarit, Yucatan

Source: Comisión Nacional de las Zonas Aridas (1993)

Map 4.38 Mexican states

Currently, Mexico has only 130 000 square kilometres of forest left. Each year about 1% of temperate forest and almost 2.5% of tropical forest are lost (Mas and Vega 1996). Deforestation is an increasing problem particularly among the poor ejido sector where approximately 75% of Mexico's forests are located and much of the farmland is communal. Between 1980 and 1990, the rate of deforestation in Mexican ejido communities ranged from 24% to 31%, with those communities in the lowest income levels demonstrating the highest rate of deforestation (de Janvry *et al.* 1997, see Map 4.39). Forests are common property among the ejidatarios, and in many areas a lack of management and co-operation have led to the overexploitation and permanent loss of these forest lands.

Deforestation in Mexico is caused by several different factors, but primarily clearance for crops or grazing, and felling for timber, some of which is illegal. These causes are exacerbated by Mexican policies on land reform and rural development (Ballin-Cortes 1990). Despite recent efforts to decentralise environmental regulations, Mexico's tradition of strong central government still causes many key decisions about forest management to be made without full consideration of their impact on local forest-dependent communities. In some areas, Mexico's forestry laws are unenforceable because basic implementation investments such as survey lines have never been made, and because many forest-dependent communities simply choose not to abide by these laws.

The degradation of water resources is another serious desertification issue in a country with less than a third of its area in the humid zone. Only about 12% of the nation's water is on the central plateau where 60% of the population live and 51% of the cropland is located (Liverman 1992). Due to the lack of surface water, Mexico relies on groundwater sources to provide about one-third of its water supply (Gonzalez-Villareal and Garduño 1994). This has resulted in extreme overpumping of aquifers, draining renewable water supplies by 43% each year. In some aquifers, groundwater levels are dropping at rates of 1 to 3 metres per year (Gonzalez-Villareal and Garduño 1994, NHI 1996). In Mexico City, 72% of the city's water supply comes from the Mexico City Aquifer (Joint Academics Committee on the Mexico City Water Supply 1995). The city's falling groundwater levels have led to subsidence in downtown Mexico City of 7.5 metres. This evidence suggests that many of Mexico's existing aquifers will not maintain their current levels of pumping, and water scarcity will almost certainly increase in certain regions.

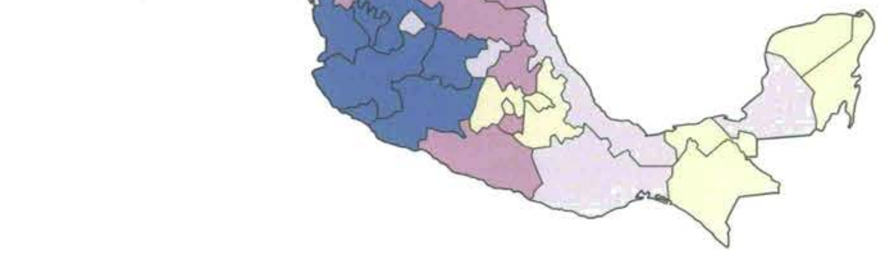
There is also evidence linking desertification to climate change in Mexico suggesting that the two elements are reciprocal contributory factors (Liverman and O'Brien 1991, O'Brien 1995). Projected drying and warming trends in Mexico could reduce crop yields by up to one-third, making life even more difficult for the millions of rural Mexicans dependent on agriculture (O'Brien 1995). A number of studies suggest that drylands at the higher latitudes may become significantly warmer due to global warming, and more arid as a consequence (Williams and Balling 1996). These degraded drylands may themselves perpetuate the greenhouse effect, as they are important stores of carbon (see pages 140–143). Models indicate that, with Mexican customs of burning wood for fuel and 'slash and burn' agriculture, there may be a doubling of CO_2 emissions in Mexico by the year 2025, and an increase in overall temperature by 2 to 5°C (Liverman and O'Brien 1991).

Social and economic dimensions

The physical impacts of desertification in Mexico have had profound social and economic implications. Because rural communities depend on local land and water resources to subsist, soil erosion and decreased productivity lead directly to declines in rural incomes. Poverty, in conjunction with a lack of education, remains highly correlated with population growth in rural areas, particularly among the ejido communities (de Janvry *et al.*

Map 4.39 Deforestation by state, 1980–90

Map 4.40 Migration by state



1997). Land parcels are often subdivided with each generation, leading to more intense cropping patterns and the cultivation of marginal lands. Some researchers have also suggested that the recent withdrawal of many government subsidies to the agricultural sector, particularly credit, have had a major impact on small farmers, dramatically altering their farming practices (de Janvry *et al.* 1995). Without credit, farmers are unable to buy inputs for farming, to rotate croplands, or to withstand the recurrent droughts in Mexico. For example, the Mexican government restructured parastatals, privatising much of the agricultural and agro-business industries. As these inputs became privatised, farmers experienced a further reduction in agricultural subsidies: in a span of 2 to 3 years, 75% of those involved in farm credit programmes were denied credit (Myhre 1995). In turn, these pressures contribute to greater degradation and desertification, fostering vicious cycles of response; both the positive and negative changes tend to be self-reinforcing.

Many of the Mexican government's recent economic reforms were undertaken in preparation for joining the North American Free Trade Agreement (NAFTA). NAFTA aims to shift the labour emphasis from low-productivity farming to better labour-intensive crops or non-farm employment. Ideally, shifting the focus to decentralised industrialisation will move capital to Mexico and create more employment opportunities and less migration, but some observers predict that NAFTA is also likely to have negative short-term effects, such as migration (Martin 1996). Capital-intensive farming may lead to job losses, and the concentration of land ownership may displace peasant households (de Janvry *et al.* 1997). Some researchers have predicted that as many as 15 million rural farmers may be displaced, increasing migration both within Mexico and to the USA (Calva 1991).

Migration between the two countries already takes place at considerable levels. The US/Mexican border is some 3200 km long and many of the Mexicans who enter the USA do so illegally. Mexico, currently the world's largest emigration country, contributes nearly half of total immigration into the USA (Cross and Sandos 1996), which receives more immigrants than any other country.

Research co-ordinated by the Natural Heritage Institute indicates that desertification is highly correlated to migration out of the drylands (See Maps 4.37, 4.39 and 4.40). In 1978, researchers documented that 600 000 people were leaving Mexico's drylands annually, while more recent studies suggest a figure of 900 000 each year (Comisión Nacional de las Zonas Aridas 1993). Most of the agricultural migration to the USA is seasonal, or temporary, rather than permanent, with migrants returning home to tend their lands (Martin 1996).

Mexican migration to the USA historically has been rooted in economic trends on both sides of the border. The USA offers much higher wages relative to Mexico, thus attracting many migrants unable to earn sufficient income at home. US government policies established to provide cheap labour for the domestic agricultural sector, like the Bracero Program, have acted as additional catalysts for migration. Though these programmes have been reformed, there is still much cross-border agricultural migration. A recent survey of 1500 ejido households, a representative sample of the ejido sector, indicates that 10.7% of the individuals surveyed had migrated to the USA at least once and 9.4% had migrated within Mexico.

Among the sample of ejidatarios who have migrated to the USA, there are strong geographical concentrations of both places of origin and destination. The most rural and arid regions of Mexico, the centre, north Pacific, and north, contribute 75% of the migration to the USA, although the fastest accelerating region of migration is the south Pacific (the states of Guerrero and Oaxaca) which now account for 10.3% of total migration. Regions of destination in the US are even more concentrated, with 56% of all migrants going to California and 23% going to Texas (de Janvry *et al.* 1997). These findings indicate that points of origin are becoming more broadly distributed geographically, and that the peasant economy emerging in the ejido sector is a major factor in the process of international migration.

In Mexico, poverty in rural dryland areas is a major determinant of migration. Desertification continually reduces the workable surface areas of the land through erosion of minerals and nutrients, reducing the fertility of the soil in the drylands and their ability to sustain crops or vegetation. The inability to farm or subsist on the land often results in rural unemployment and general poverty, leading directly to migration (de Janvry *et al.* 1997). Although poverty is strongly correlated with migration, the most impoverished cannot afford to migrate and must remain where they are. Education and literacy are also closely linked to migration among ejidatarios. It appears that international migration is most difficult for the least educated ejidatarios, and is least desirable for those with the highest

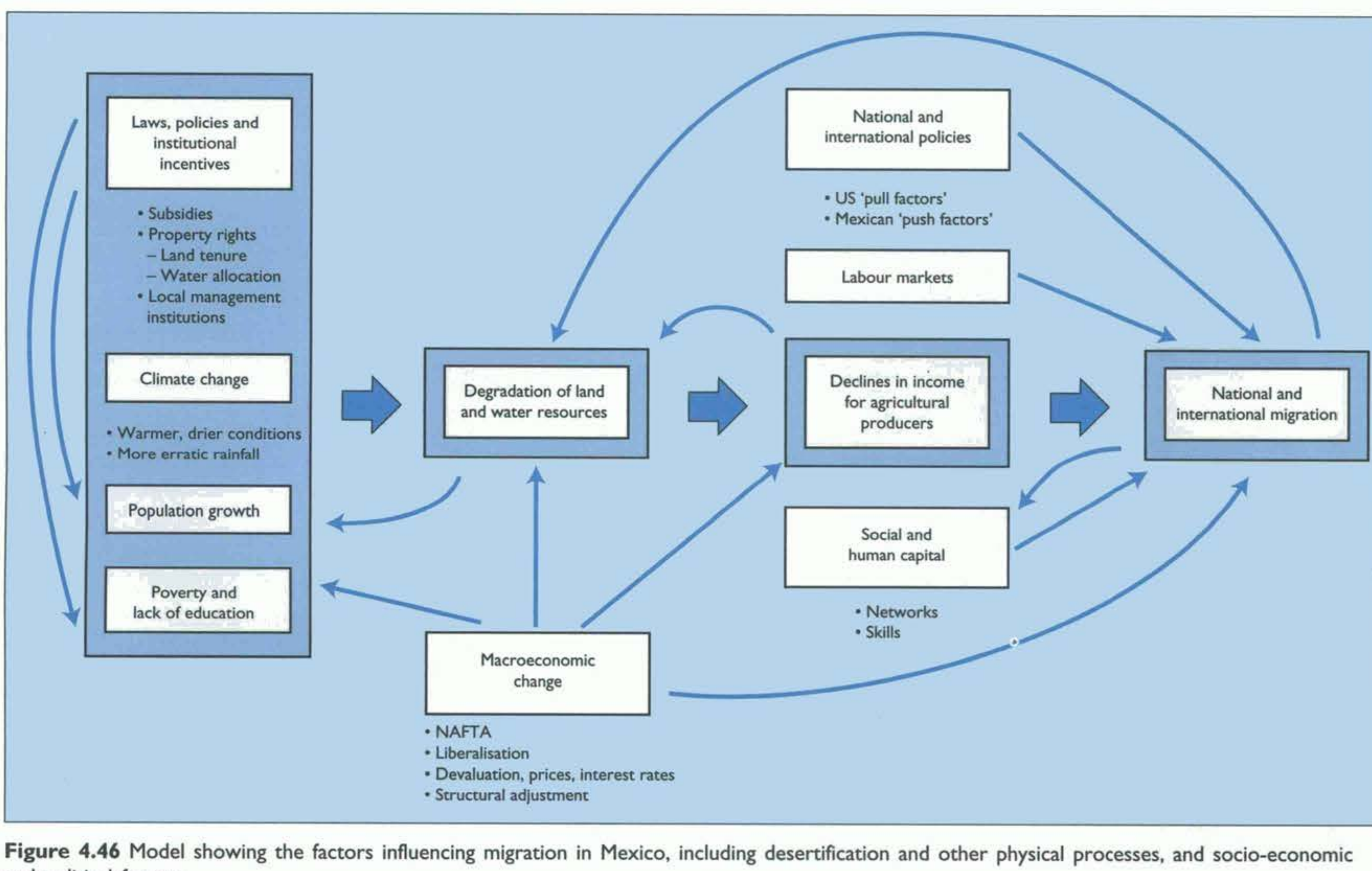


Figure 4.46 Model showing the factors influencing migration in Mexico, including desertification and other physical processes, and socio-economic and political factors

educational levels. In the USA, it is difficult for Mexican migrants to find employment that matches their level of education, thus causing a disincentive to migrate, particularly among those with a mid-level education. Those who have migrated to the USA have an average of 3.7 years of education while those who do not migrate have an average of 5 years of education. However, those who do migrate to the USA have a greater ability to read and write; among those individuals who migrated for work, 88% could read and write compared to 86% who did not migrate for work. Individuals with 3 to 6 years of instruction who can read and write migrate more often to the USA (de Janvry *et al.* 1997).

Improved access to land, particularly irrigated land, is one way to potentially overcome poverty in Mexico. Poverty may also be eased via an increase in the education levels of dryland inhabitants. To achieve this, some suggest that there must be an increase in the profitability of investment in labour-intensive agricultural activities, particularly fruit and vegetable growing. This entails public investment in infrastructure (irrigation and roads), as well as organisational and institutional development so farmers can successfully invest in this area of agriculture. In addition, financial institutions on both sides of the US/Mexican border could be developed to provide services so that migrants can channel their wages back to their areas of origin, and to facilitate lending among community members.

Research also indicates a strong relationship between increasing population pressures on land and water resources and migration in Mexico. Regions of traditionally high emigration report consistently higher birthrates than the national average: 3.7 children per woman in such areas versus 3.3 (as of 1990). Among the country's poorer communities, birth rates are nearly double the national average in certain areas (UN 1989). These higher rates, when combined with the overall decrease in mortality rates in recent years, effectively increase population pressure on available resources such as farm land and food production. As arable lands have become scarcer, there has been a decline in the number of Mexicans involved in food production: from 8.5% in 1983–87 to 7.4% in 1992–93, a trend that threatens Mexico's ability to feed itself (CONAPO 1996). Analysis comparing projections of population growth and production of staple foods indicates that by the year 2030, production will have to increase by over 42% in order to produce enough food to adequately feed the population (CONAPO 1996). Such population pressure will also force agriculturalists to exploit ever more marginal croplands (Figure 4.47) where the likelihood of drought failures and degradation are increased.

Conclusion

Desertification is not only an important physical environmental phenomenon in Mexico, but also a socio-economic one. Because many rural communities depend on local land and water resources for their own subsistence, soil degradation contributes significantly to declines in rural incomes. This decline in income, combined with factors such as government economic reforms, population trends, lack of education and training, and access to labour markets, can stimulate migration (Figure 4.46). This has led to conflict in certain southern regions of Mexico and to heightened controversy over immigration policy in the USA where recent legislation has been decidedly anti-immigration in tone. Addressing the root desertification causes of migration can alleviate some of the pressure on the border region and decrease poverty in Mexico's drylands.

Original text by Michelle Leighton Schwartz.

Figure 4.47 Growing population pressure is likely to force Mexican farmers to cultivate more marginal areas, as here in central Mexico where maize is being grown in the lee of semi-permanent sand dunes (N Middleton)

An Integrated Approach to Dryland Farming: A Success Story in South-western Australia

Introduction

Farming in the Mediterranean climate of south-western Australia (Map 4.41) characteristically involves mixed crop and livestock production, particularly sheep and wheat. More recently a range of more diverse products, including lupins (for oil), canola, oats and lucerne, have been grown. Most farms date only from the early twentieth century, but many experience problems of erosion, waterlogging and salinization that result from clearance of the natural vegetation and practising agriculture in a region of strong seasonal climatic contrasts and relatively poor soils (Figure 4.48). By taking an integrated approach to farming and water management it is, however, possible to overcome problems caused by degradation and create a more sustainable system (UNEP 1994b, UNEP 1996). The practices described here have been developed on a 552 ha farm near the small town of Frankland. An important aspect of the new management system is that it not only combats desertification, but also helps restore biodiversity in an area that saw significant clearance of indigenous forest ecosystems between 1900 and 1950. The integrated farming system also succeeds on small farm units in a region where consolidation and expansion have previously been seen as the only route to economically viable agriculture.

Figure 4.48 The clearance of natural forest vegetation in the twentieth century in south-west Australia has created a landscape of large fields. Problems of waterlogging, salinization, erosion and loss of biodiversity have ensued

Figure 4.49 Waterlogging in lower areas of the landscape has resulted from excess soilwater seepage and has led, as in this photograph, to salinization problems

Map 4.41 Western Australia

Environmental background

'Pyneham', the farm on which the new practices have been developed, is located in a dry subhumid area with a mean annual rainfall of 580 mm. Under the Mediterranean climatic conditions rainfall occurs predominantly during the cool winter, whereas summers are hot and dry, with very high potential evapotranspiration rates (Smith 1951). The farm occupies an area where soils are podsolic and lateritic (Schofield *et al.* 1988). Both soil types have low hydraulic conductivities, which can lead to the development of perched aquifers and waterlogging, especially during the winter and spring. Since farming developed in SW Australia, waterlogging has been exacerbated by the reduced draw on groundwater that has resulted from the clearance of natural forests (Figure 4.48). Waterlogging also contributes to salinization and sodication problems (Malcolm 1983) (Figure 4.49). The severity of these inter-related degradation problems differs according to position within the overall hydrological components of the main catchment (Table 4.22). Some problems of wind and water erosion and nutrient depletion also occur within the farming community (McFarlane 1991, George and Conacher 1993).

While waterlogging and its associated water quality problems are major issues of concern for agricultural production, they also directly affect livestock and humans (Yeomans 1968). On many farms salinization has for 40 years been affecting water held in check dams and used for drinking by people and livestock. A short-term solution to this water quality problem has been to construct new dams higher up the landscape and away from zones of waterlogged soils, but as the area affected by waterlogging has expanded, so these newer dams have suffered declining water quality.

Desertification control and rehabilitation

The key desertification problem is too much water in the wrong place at the wrong time, which in turn reduces soil quality. Rather than

Table 4.22 Areas of hydrological systems within alienated land in the Upper Frankland-Gordon Catchment and their salinity, waterlogging and sodicity ratings

Hydrological system	*Approximate mean annual rainfall (mm)*	*Area (ha)*	*Area (%)*	*Severity*		
				Salinity	*Waterlogging*	*Sodicity*
Mountains and hills	350–700	963	0.2	1	1	1
Dissected areas and their	700–1100	47 770	11.9	2	3	2
undulating upland rises	350–700	203 608	50.8	2	2	2
Landform patterns on	700–1100	3145	0.8	1	3	1
catchment divides	500–700	16 518	4.1	2	3	2
	350–500	5 093	1.3	2	2	2
Very low relief landform	700–1100	4061	1.0	2	4	2
patterns with swampy floors	500–700	35 708	8.7	3	3	3
	350–500	32 207	8.0	3	2	3
Swampy terrains	500–700	38 619	9.6	4	5	4
	350–500	13 440	3.3	4	4	4
Swampy terrains – inland playa lakes	350–700	641	0.2	5	5	5

1 = little or no problem expected
2 = small problem at present but it will increase in the medium-term
3 = moderate problem that needs attention now
4 = the problem is so large that it is expensive to treat
5 = extreme problem

carrying out piecemeal actions to tackle these waterlogging and salinization problems in individual fields, a wholesale catchment approach has been implemented on the farm under consideration (Land Management Society 1990, 1991). This approach, called *integrated whole farm–whole landscape planning,* aims to achieve total control of water movement and use. The higher areas of the landscape are the principal water source areas for the perched aquifers that eventually create the waterlogging and salinization problems. The farm owner believes that for the approach to work effectively it is necessary to carry out water management activities at the catchment scale, not just within the boundaries of his particular property. Therefore each small catchment has to be managed co-operatively and for maximum effectiveness this requires co-ordination across property boundaries and between adjacent farmers.

The key elements of the management scheme are a series of drains to control the nature and rate of water movement after rainfall events, and tree planting that not only acts as shelter belts but provides a way of utilising deep moisture (Figures 4.50 and 4.51). Interceptor drains have been dug in the slopes of the upper and middle parts of the catchment.

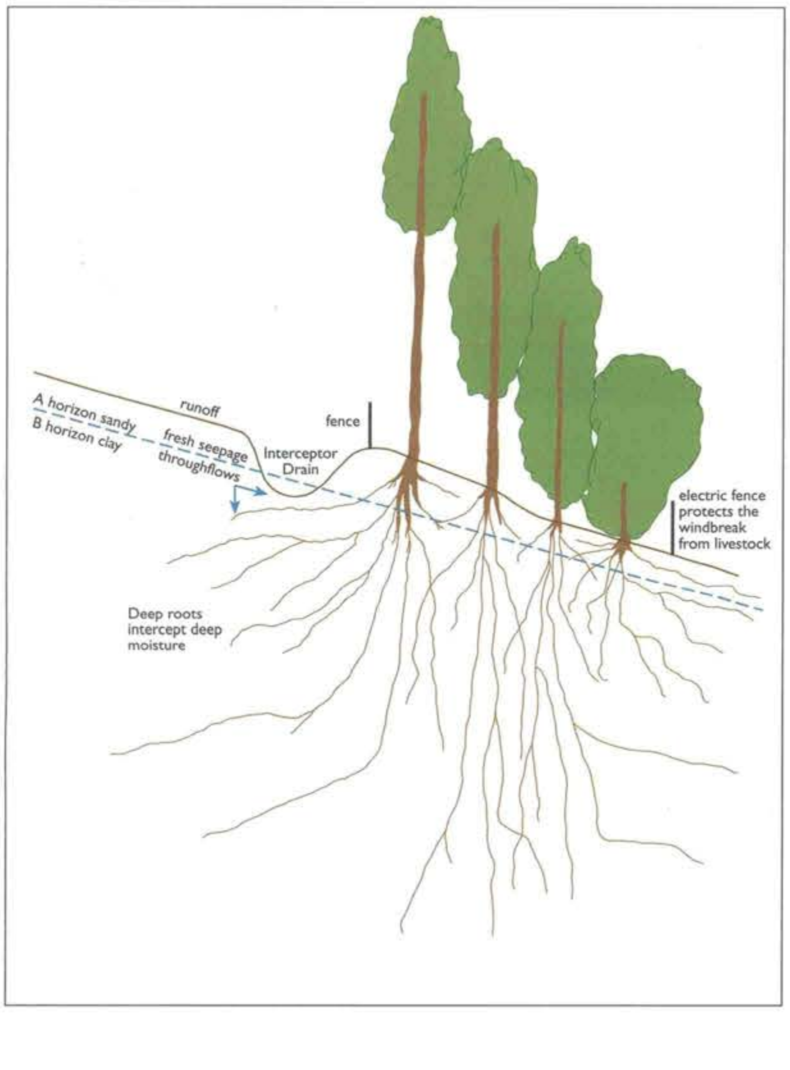


Figure 4.50 Schematic diagram of the main elements of the integrated whole farm – whole landscape planning system. Contour drains intercept runoff and seepage from upper slopes and inhibit waterlogging in lower areas. Enhanced seepage of soil water is created as the clay zone of soil B horizons is reached. Four-row plantings of trees utilise deeper groundwater, act as windbreaks and provide wildlife habitats and livestock fodder

Figure 4.51 A landscape of contour drains, windbreaks and more trees is an outcome of the management system

Their purpose is to capture surface runoff and seepage from rainfall events that would otherwise drain rapidly to the lower catchment areas, causing waterlogging. The interceptor drains are designed to capture water that seeps within the upper soil A horizon and which does not otherwise penetrate the clay zone or hardpan in the lower B horizon of the soils. The principal drains run across the slopes, normally at a gradient of 1:400 (0.25%), and follow the contours of the impervious B horizon. The drains, however, are cut through the clay horizon so that while they redirect surface flow and A horizon seepage flow, they also allow water to percolate to greater depths below the clay zone, providing recharge below the upper perched aquifer. The water from the drains is stored in dams for domestic, stock and irrigation purposes.

Figure 4.52 A newly dug interceptor drain. On the left is the bank formed of the excavated soil, on which the first plantings for the windbreak can be seen

The soil dug from a drain, by bulldozer, grader or by hand depending on the depth of the B horizon, is banked up on the downslope side. The top of the bank is flattened and forms an excellent medium for tree planting (Figure 4.52). The trees are planted in a series of four rows on each bank, and serve several purposes. First, they act as windbreaks, and since they follow the contour-hugging drains they protect crops and livestock against winds and harsh weather from every direction. Second, the tree roots penetrate to significant depths, utlising soil water and therefore helping to tackle the waterlogging problem. Third, they contribute to the restoration of natural biodiversity in the region. Attention has been given to preserving and regenerating native hillside and riparian vegetation, fencing it off and integrating it with the windbreaks to improve the native fauna and flora and allow wildlife corridors throughout the property. The windbreaks and residual natural forests reduce the effect of large farms being 'wildlife deserts', and attracting birds which are important for pest control (the farm where this system has been developed operates an organic policy and does not therefore use chemical pesticides). Fourth, the windbreaks protect the drains from livestock trampling. Finally, the outer row of trees in the windbreaks is planted with tagasaste or tree lucerne, which acts as a fodder for livestock during drought periods.

Figure 4.53 The interceptor drains lead into check dams that provide water for humans, livestock and irrigation

Soil management together with improved management of crops, pastures and livestock, is part of the land management system. Stubble mulching has been practised on the farm for 15 years. Soil acidity problems are being corrected with lime (dolomite) and sodicity with gypsum. Less reliance is placed on water soluble fertilizers, with slow release fertilizers being used for long-term nutrition. Organic fertilizers, organic matter residue and chisel ploughing are used to reduce nutrient mobility and encourage earthworm activity. Dung beetles have been released and microbial ploughs are being encouraged.

Benefits

The integrated whole farm–whole landscape-planning system has improved the environment, restored degraded lands and, by being coupled to a more diversified approach to agriculture, has enhanced the economic viability of the farm (Land Management Society 1990). Rather than continuing to make economic gains from a decreasing environmental resource, the system is maintaining the economic gains while building up the health of the environment. The long-term benefits of this strategy will be the greater financial security of the farming enterprise and a healthier environment for both humans and animals (UNEP 1996).

Agricultural benefits

By intercepting and redirecting water, the primary degradation issue has been tackled. By controlling where water goes on the farm, water quality has improved too (Figure 4.53). The windbreaks have contributed to ecological and agricultural diversity and the trees

Figure 4.54 Biodiversity is enhanced by the windbreaks which mainly comprise native tree species. The fields of canola are testimony to the agricultural productivity that has been achieved

Figure 4.55 Good regeneration of natural vegetation in an area where livestock are fenced out

themselves utilise excess soil water. When mature, the tallest windbreak tree species, the Spotted Gum (*Eucalyptus maculata*), will eventually be harvested for sawn timber, pulpwood, fence posts and firewood. Constructing the drains and windbreaks has led to many hectares of the farm being fenced off. Nevertheless livestock carrying capacity has increased by an estimated 10% and a greater area is available for cropping (Figure 4.54). An economic analysis of the farm has found that gross margins for crops are more than double the local average and for sheep almost four times the average. Other farmers adopting the system have also shown it to be economical, with considerable benefits apparent on previously waterlogged soils within the next cropping season. One Frankland farmer recorded a 25% increase in gross income within 12 months, following implementation of the management system.

Environmental benefits

Biodiversity has been increased by the planting of 38 tree species throughout the farm and the natural regeneration of many native species. Of the 38 tree species used in the treebelts the most prominent have been Spotted gum (*Eucalyptus maculata*), Wandoo (*Eucalyptus wandoo*), Golden wreath wattle (*Acacia saligna)* and Tagasaste, also known as tree lucerne. Wandoo and Golden wreath wattles are planted in the middle rows of the windbreaks to provide nectar for birds and insects, and to create a more diverse wildlife habitat. Cold burns in autumn have been successful in removing previously introduced non-indigenous grasses and encouraging natural regeneration, with the reappearance of native orchids being particularly rewarding. The increased habitat created by the treebelts and the regeneration of remnant vegetation (Figure 4.55) and waterways, has already had a noticeable effect on the bird population.

Replication of the system

The land management system has to date been adopted by 20 other farmers in Western Australia, both in the immediate vicinity of Frankland and further afield. The benefits of the system are being recognised more widely and its adoption/replication rate is accelerating. None the less, the rate of adoption is in part hampered by the perceived cost of implementation. Several interested farmers claim that cost has deterred them from implementing the system. It seems, however, that they overestimated the true costs and did not realise that the system could be implemented in stages over an extended period of time. For waterlogged cropping land the payback period was likely to be only one cropping season.

This land management system is a catchment-based design and to achieve the best results it needs to be implemented on a community basis rather than on single farms. As with any community-based concept the difficulty is to secure agreement from all the people of the community rather than with the proposal itself. The success this system is achieving in south-west Australia shows just how significant the accrued benefits of co-operation can be, and how desertification, biodiversity and productivity issues can be addressed simultaneously.

Original draft by E. Migongo-Bake.

Afforestation and Salinity Control with Tamarix: A Success Story in North-western China

Introduction

Settlements on the southern margins of the Taklimakan Desert, in the south-west of China's Xinjiang Uygur Autonomous Region, are traditionally based on farming. Cultivation and the herding of livestock is only possible on the desert's edge because the Taklimakan itself is very largely made up of shifting sand dunes (Chinese Academy of Sciences 1993). During the long history of human occupation of the region, these dunes have periodically inundated settlements, forcing them to relocate (Fan Zili 1993), but in more recent times human population growth and agricultural mismanagement have caused widespread desertification problems. The main causes of degradation in the region have been the overuse of natural Tamarix sand dune forests for fuelwood, declining groundwater levels due to agricultural expansion and soil salinization on irrigated cropland. This case study documents the re-establishment of Tamarix forests in four counties: Cele, Yutian and Mingfeng in Hotan Prefecture, and Jiashi in the Kashi Prefecture (XIBPDR 1993, see Map 4.42). The new Tamarix trees have provided a sustainable crop of fuelwood and fodder, and the successful reclamation of salinized cropland (UNEP 1994a).

Map 4.42 Location of the Xinjiang Tamarix project counties

Desertification problems

The sand sea, or erg, of the Taklimakan Desert is situated in the Tarim Basin, surrounded by the Tianshan Mountains to the north and the Kunlun Mountains to the south. Between these mountain ranges and the desert lies a narrow belt of alluvial hills and plains where agriculture is possible. The high precipitation levels of the mountain areas feed more than 100 rivers and streams that flow into the Tarim Basin providing surface and groundwater that is used for irrigation in the small oasis settlements around the perimeter of the desert. The importance of the mountainous water sources to these oases is underlined by the fact that average annual rainfall at the desert margin varies from 31 mm to 46 mm and potential evaporation exceeds 1600 mm a year. The area is also subject to great extremes of temperature and very strong winds. The precarious survival of the people who live in these oases depends on their ability to manage their limited and variable water resources in order to meet their irrigation and domestic requirements. Agriculture is the main source of livelihood. Important crops include wheat, cotton, maize and fruit. Fodder and pasture are also cultivated, for sheep, goats and cattle. The average livestock holding is 12 head per household (XIBPDR 1993).

Increasing population is an important driving force behind the acceleration of desertification in this dryland region of north-western China. Between 1949 and 1983 the population approximately doubled to 1.2 million. This increase in demographic pressure has been accompanied by widespread deforestation for fuelwood, and the overuse of scarce water resources for irrigated food and fodder crops in Cele, Yutian and Mingfeng. The result has been a drastic reduction in the area of natural forests (predominantly *Tamarix* spp. and *Populus euphratica*), agricultural expansion into marginal lands and a reduction in groundwater recharge in the lower reaches of rivers, with consequent effects on the sparse natural desert vegetation.

In Jiashi County the most serious desertification problem is one of salinization on irrigated cropland and surrounding rangelands. Jiashi is located in the middle of the Kashgar River basin, and cultivation depends on diverting irrigation water from this river. The water-table is high (1 to 3 m below the surface) with a high salt content (1 to 10 g l^{-1}). Summer floodwater accumulates on the extensive flat and poorly drained areas causing waterlogging. The accumulation of salts is exacerbated by the clearance of natural vegetation prior to cultivation, since forest clearance has allowed the water-table to rise. The combination of the destruction of the natural vegetative cover, the high water-table and the high evaporation rate has resulted in extensive salinization. It is estimated that more than 60% of the agricultural land in this county suffers from serious salinity problems, and most forests and grasslands are also badly affected.

Socio-political context

Within the four counties are networks of villages organised according to their size: large (*Xiang*), medium (*Cun*) and small (*Zheng*), each with representatives for the various natural resource and community aspects of development.

Each village is communally responsible for the maintenance of irrigation channels, planting and watering trees, maintaining rural roads and the management of other common property resources within their village. The management of larger works covering several villages is planned by the respective *Cun* or *Zheng* and the work is shared by all the households.

The Tamarix project

Tamarix is an indigenous species in the project area and one that is valued by local people as a fuelwood and for tool and basket making. Tamarix survives under conditions of sand inundation, and grows on both waterlogged and saline soils, making it an ideal species to reverse the environmental deterioration of degraded dune forests and heavily salinized areas. Once established, Tamarix offers long-term soil protection since individual trees can live for 50 to 100 years (Yu-Hua Liu 1993).

Under natural conditions, *Tamarix* spp. propagates by seed carried and distributed by summer floods, and this natural dispersal mechanism has been employed to regenerate large areas by controlling and directing surplus summer floods on to areas to be rehabilitated. Two main methods have been employed to divert the floodwaters. The first is to build an earthen embankment around the area to be treated and then to inundate it with diverted summer floods. The second method is to construct small parallel channels, about 3 m apart, with a large mould-board plough attached to a bulldozer (Figure 4.56). The floodwaters are released into these areas along

Figure 4.56 Constructing summer flood diversion channels

the channels. The latter method has proven to be more effective as is possible to complete the channels across an area at the rate of 1 hectare an hour and to cover 2–3000 ha each year. The flood water requirement is between 750 and 1500 $m^3 ha^{-1}$. Only one inundation is usually required to achieve good Tamarix re-establishment. However, this method can only be used in relatively flat areas.

Following the flooding of an area, the re-established seedlings are totally protected for 3 years by which time new Tamarix seedlings can reach a height of 2 to 3 m. At this stage, a controlled system of exploitation is introduced where fuelwood is cut from a different third of the area each year (i.e. on a 3-year rotation management system).

Protection during the first 3 years is carried out by one of three ways. In some cases, a forest guard is employed to protect the seedlings. Small salaries for these guards are paid partly by the government and partly covered by the local community out of fuelwood income generated from more established plots. Guards are also allowed to continue some farming and livestock rearing to supplement their income. In other areas, volunteers are appointed from the village to protect the area. These volunteers are paid a small honorarium from the proceeds of fuelwood sales. Alternatively, local leaders and villagers share the management activities. Protection is backed by a system of fines against those who violate the local forestry laws (XIBPDR 1993).

Using these methods, more than 15 Tamarix species have been re-established in project areas, achieving a vegetative cover of up to 60% within a period of 4 years. This includes 6600 ha each in Cele and Yutian Counties, 13 300 ha in Mingfeng County, and more than 40 000 ha in Jiashi County. In Cele, Yutian and Mingfeng Counties, the re-established Tamarix have been successful in combating sand dune encroachment and providing a sustainable source of wood. Of the total area treated in Jiashi by 1994, 5300 ha has subsequently been returned to agricultural production. The lines of Tamarix trees act as a 'biological pump' to keep the water-table well below the surface, and crops are grown in the strips between the Tamarix. As in the other counties the trees are also harvested to provide fuelwood and materials for cottage industries. It is planned that up to 50% of the Jiashi County areas that have been treated to date will eventually be used under this system of forest-cropping.

Project benefits

Fuelwood: Under this system of management it has been possible to achieve an annual sustainable fuelwood production of about 5 t ha^{-1} (Figure 4.57).

Fodder: The cultivation of Tamarix has also resulted in an improved supply of fodder for animals, with a consequent increase in the number of head per capita. In Jiashi County, for example, the average number of animals has increased from 1.7 per person in 1985 to 2.7 in 1993. Many villagers have now adopted a cut-and-carry feeding system, so that uncontrolled grazing of forest areas on oasis margins has been dramatically reduced.

Cropping: The rehabilitation of degraded agricultural land and its return to productive use has contributed to an overall improvement in agricultural productivity and household incomes. The average annual household income in Jiashi County has risen from RMB 2179 in 1985 to RMB 3374 in 1992. Table 4.23 details the improvement in agricultural productivity and the increase in livestock numbers over the life of the Tamarix project.

Cottage industry: The marketing of products manufactured from Tamarix, such as baskets, earth carriers and trolleys, can generate a net profit of about RMB 6000 per year per household. About 33% of the households are involved in these cottage industries.

Factors contributing to the sustainability of the project

The success of the Tamarix project has been based on a number of interrelated factors. The most important of these are as follows.

- The problems caused by saline/alkaline lands and dune encroachment are being solved through a combination of factors which include: i) The availability of a large volume of flood water; ii) the participation of local people and the involvement of local organisational structures in the management of these resources; and iii) the socio-political system in China which encourages people to participate voluntarily in work which has communal benefit.
- The project has made a major contribution in developing a simple technique for re-establishing ecological stability under extremely challenging environmental conditions, with considerable social and economic benefits to the local people.
- The project has influenced the budgetary allocations for land management activities, and all four counties now have an annual allocation for Tamarix cultivation. The county governments now have an effective programme for protecting natural forests.
- Scientists from the Xinjiang Institute of Biology, Pedology and Desert Research (XIBPDR) have also played a critical role in identifying and promoting this simple approach, and in strongly supporting the county governments during project implementation.
- There is a very high level of enthusiasm about the project, and people are actively participating in the management of the Tamarix areas. They also continue to contribute towards the maintenance of the plantations and irrigation structures.

Figure 4.57 Fuelwood harvest from an project area rehabilitated with Tamarix

Table 4.23 Selected agricultural indicators for Jiashi, 1985 and 1992

Indicator	*1985*	*1992*
Per capita grain production (Kg)	325	600
Total cotton production (t)	3000	18 000
Livestock population	370 000	670 000*

*1993 data
Source: Yu-Hua Liu (1993)

Replication of the techniques

Although the project period itself has been completed, this method of forest rehabilitation has been adopted as a regular annual development activity in all four counties. The approach is also being adopted in 50 other counties throughout Xinjiang, and in two counties of neighbouring Gansu Province.

Original draft by E. Migongo-Bake.

Environmental Protection and Restoration: A Success Story in Northern Senegal

Map 4.43 Location of the Louga region, Senegal

Introduction

The Louga region, in the North Sahelian zone of Senegal (Map 4.43), suffered extensive desertification during the early 1970s largely as a result of drought, demographic changes and modifications of land-use practices. The local population mainly comprises subsistence farmers and herders from two major ethnic groups, the Wolof and the Peulh, who have used indigenous agro-forestry techniques for centuries to produce abundant food supplies from sandy dryland soils. Their way of life was severely affected by severe and prolonged drought that began in 1973, resulting in loss of livestock, enhanced soil erosion by wind, and an increase in male migration to urban centres in search of alternative work. This case study outlines a community-based project to rehabilitate the area's ecology and economy (UNEP 1994c).

The effects of drought

Annual precipitation in the region is low and irregular, and the annual average total of 600–800 mm prior to the drought of 1974 has since been sharply reduced. In the period after 1974, rainfall has averaged 200–300 mm a year. Water supply has always been a problem in this dryland area, but the drought made shortages even more acute.

The initial drought impact was the loss of livestock to dehydration and starvation which, in turn, threatened the long-term food-security system of the pastoralist/nomadic population. Farmers lost food, fertilizers from animal dung and a significant source of income. Decreasing rainfall also forced a change in land use. Yields from traditional *Tokeur* plots, small areas of cropland protected by local trees and shrubs, declined and many were replaced by monoculture cropping of peanuts and millet. These crops gave poor yields, however, resulting in a reduction in fallow and rotation periods in an effort to boost output. Trees throughout the region were cleared to make way for additional farmland and to meet firewood needs. This led to enhanced wind erosion, which, combined with the decline in fallow periods, resulted in accelerated land degradation.

The onset of drought also had a major impact on the demography of the Louga region. Much of the economically active male population left the area in search of work opportunities in the cities or abroad. This migration resulted in an increase in the number of households being headed by single women. At the height of the drought, nearly 60% of the women left behind with children had to assume duties as temporary household heads.

Project background

The environmental restoration and protection project for the Louga region was initiated in 1985 by the non-governmental organisation World Vision International (WVI). The overall objective was the sustainable improvement of living conditions in this degraded sylvi-agropastoral environment through improved water supplies, access to back-up services like education, and increased agricultural production through better land use and soil conservation. The principle underlying this approach was that a regular supply of basic needs such as water and income-earning opportunities is the foundation for household food security, and this basic security is the necessary precursor to any attempts to address environmental degradation.

Using the Participatory Rural Appraisal method (Guèye 1995), WVI staff held discussions with more than 17 villages that served as pilots for the project's development. The project adopted a self-centred development approach which aims to help people recognise resources within themselves and their communities. It is deliberately 'bottom-up', aiming to stimulate community involvement and support, as well as accountability within the community. It emphasises the following:

- a grassroots approach, revitalising and building on existing traditional knowledge;
- respect for the social context of any intervention, group and individual endeavour;
- social mobilisation and an increase in individual awareness of sustainability;
- adaptation of innovations to the needs of the population;
- a partnership relationship within communities;
- eventual withdrawal of outside advisors, as a means to achieve self-sustainability.

The design of the WVI project is closely in line with Senegalese policies on desertification, environmental protection and conservation, and a close relationship has been developed with relevant ministries during its implementation. Within the framework of the Senegal's 'Plan de Développement Economique et Social' (PDES), the government has launched two important development policy documents: Une Nouvelle Politique Agricole (New Agricultural Policy Document), 1993, and the Forestry Action Plan Document, 1994. Both documents advocate an integrated approach towards agricultural and rural development with emphasis on:

- improvement of the institutional framework;
- sustainable use and management of forestry and other natural resources;
- restoration and conservation of soil fertility, through the promotion of agro-forestry and sylvi-agropastoral farming systems;
- training programmes on protection and conservation of the environment;
- promotion of participatory approaches with beneficiaries using their own know-how;
- training for improvement of the living conditions of certain groups (e.g. women and youth) through income-generating activities.

Project innovations

Water availability: Initial studies showed that the shortage of water was one of the most basic problems in the Louga region villages. In collaboration with the Ministère des Eaux et Forêts, Direction de l'Hydraulique, a total of 458 boreholes have been drilled since 1987 and supplied with manual or wind-driven pumps (Figure 4.58). Wells have been confined to settlements with more than 250

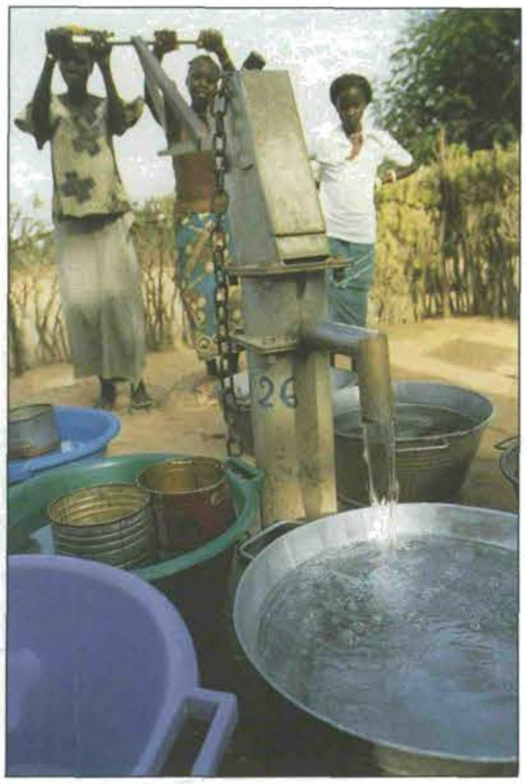


Figure 4.58 Drawing water from a new community-managed well

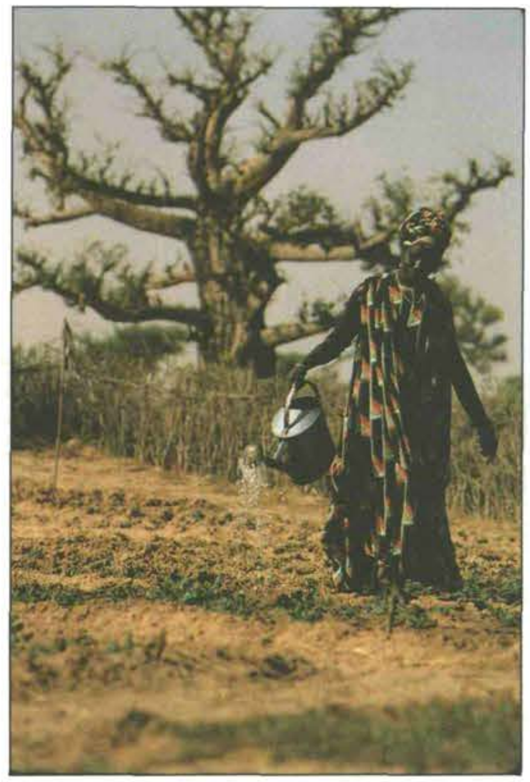


Figure 4.59 Watering vegetables in a communal *Tokeur* women's garden near the village of Par Cissé

people. Village water committees, consisting of both men and women, were first established to raise the 150 000 CFA (US$300) necessary for construction. Monitoring of the water-table in the region indicates that the new wells are utilising groundwater at a sustainable rate.

Afforestation and natural generation of species: Villagers throughout the Louga region project area have successfully revived the old system of *Tokeur*, the planting of living fences of Euphorbiaceae (known locally as *Salans*) to provide grazing exclosures of about 15 m^2 in which crops are cultivated. The *Salans* both protect crops from straying animals and against wind erosion. Planting within the *Tokeurs* is carefully planned to rehabilitate the soil. A couple of seasons of manioc, a basic food crop with a low phosphate requirement, are followed by potatoes and cowpeas. As the soil quality improves, crops such as millet and tomatoes are planted (Figure 4.59). This relatively intensive cropping reduces the need for tree clearance on surrounding lands for agricultural extension. Fodder crops are also grown in the *Tokeurs*, reducing grazing pressure on surrounding pastures.

A vital part of the strategy for soil conservation was the introduction of Kad trees (*Faidherbia albida*) and leguminous crops like cowpeas, as well as the revitalisation of traditional methods like the euphorbia fencing. As a result of the project activities, several species have been re-established for the first time in 10 years: Kel (*Grewia bicolor*), Baobab (*Adansonia digitata*), Ngigis Mborin (*Philostigma reticulatum*), Mbep (*Sterculia setigera*), and Bér (*Sclerocarya birrea*). Tree planting and nurseries are managed by women and children and in some cases by school classes. These activities are labour-intensive and do not yield high incomes, but villages now enjoy the benefits of many shade trees.

Table 4.24 The success of *Tokeurs* in villages in the Louga region

Villages	*Plots*	*Total area (ha)*	*Kad trees*	*Salans fencing length (m)*	*Fruit trees*	*Manure production (tonnes)*	*Potato production (tonnes)*	*Vegetable production (tonnes)*
Par Cissé plus 5 surrounding villages	51	50	1217	19 625	796	12.45	1000	3.2
Keur Sidi Maica Fall	82	62.5	1082	21 255	1624	17.5	1150	8
Total	133	112.5	2299	40 880	2420	29.95	2150	11.2

Source: WVI Senegal (1993)

Throughout the Louga region, the project has led to the establishment of 10 village horticultural nurseries, 5 nurseries for fruit trees, and 133 agro-forestry nurseries. The outcome of the sylvi-agropastoralism and soil conservation activities in a selection of villages is summarised in Table 4.24.

Cropping outside the *Tokeurs*: In the fields surrounding the project villages, many different crops are produced – mainly cowpeas, peanuts, cassava and vegetables (potatoes, tomatoes, eggplants) – promoting food security and income generation at the village level. The cultivation of cowpeas has proved to be particularly successful. The crop provides a good ground cover that protects soil against erosion, and high yields have been produced from a newly introduced, improved variety. Cowpea is now processed into couscous, providing an additional basic food to supplement the traditional staple: millet-based couscous. The possibilities of exporting surplus cowpea production to South Africa are also being negotiated with private traders.

Economic empowerment through revolving funds: In 1993, when the above schemes to combat the basic problems of water supply and crop production had been running for 8 years, a new economic element to the Louga region project was initiated. A revolving fund scheme was set up to enable villagers to run their own income-generating projects. Loans over periods of 3 to 6 months are made to groups who pay interest on the money at 3% below the prevailing bank rate. The repayments are used as loans to other groups or individuals.

The revolving fund scheme has proven to be a great success, with repayment rates to date of 100%. Borrowers have used the funds for a variety of schemes, including 'zero-grazing' fattening of livestock using forage grown in the *Tokeurs*, the provision of food-processing equipment for women's groups and the introduction of more-efficient stoves.

Zero-grazing livestock-fattening schemes have been implemented both collectively and by individuals for young bulls, sheep and goats. Women tend to concentrate on sheep and goat rearing, while men have specialised in bulls (Figure 4.60). In one example in the village of Par Cissé, a men's group with 10 bulls made

Figure 4.60 Zero-grazing feeding of cattle

Table 4.25 Economic proceeds from millet mills in two Louga region villages, 1992–94

Village	*Net income (CFA)*	*Deposits made at the bank (CFA)*
Ngueball Fall	5020	100 045
Ndame Mor Fademba	44 770	63 195

Note: 500 CFA = 1 US$
Source: UNEP (1994c)

a profit of 150 000 CFA (US$300), or 15 000 CFA (US$30) per person after just 4 months. This figure included income generated from the sale of 7.5 tonnes of manure to gardeners and nursery managers.

Millet mills have generated the highest levels of income for groups who have invested in food processing. Table 4.25 shows the economic results in two villages over the period 1992–94.

In another food-processing scheme, a number of women's associations bought an improved model of manual peanut press, produced by local village blacksmiths. Use of these communally owned presses has yielded high returns. The processing costs are 0.5 CFA per litre of oil pressed, while one litre of oil can be sold for 335 CFA and more. The average family unit (11 or more members) produces 1000 kg of peanuts per year. If all the harvest is processed into oil, and the cake and husks are sold or used as animal feed, the net revenue could reach 43 870 CFA. The widespread acceptance of the new peanut oil presses, and high demand among women for further supplies of the machines, indicate the project's success in dissemination of appropriate technology.

The improved fuel-saving stoves are well appreciated by the women, who build them themselves with mud. They claim that they use only 25% of the wood used in their previous stoves. However, the design of the new stoves needs further improvement, since most need some form of repair after 3–5 years, and few women currently bother to carry these out.

Education and training: The project has also focused on other significant areas. Foremost among these are training and literacy programmes. Since 1990, 19 education centres have been established and 1200 children participated in educational courses. The quota of girls participating in school activities is gradually nearing 50%. Of these children, 59% can read and write French and know the basics of mathematics.

Adults have also participated. About 75% of the 750 adults who have attended courses can now read and write Wolof and have a notion of book-keeping. Leadership training is especially important for the management of the mills, which is entirely in the hands of women. Literacy training has been most successful for women, since unlike the men they do not migrate away from the villages in search of employment.

Women and development: Women's needs have been a special focus for the Louga region project. In 1992, for example, WVI opened Women in Development (WID) offices in Mbacke and Thies employing eight women professionals as staff. The objective behind this move was to integrate local women more fully into the project's activities and its institutional set-up, hence both responding to the women's needs, and implementing the long-term strategic needs of making women and girls partners in development. The women are given training in a range of skills, including income generation, institution-building, management and leadership, book-keeping and credit. Mothers and daughters are also provided with education in family planning.

Prospects for replication and sustainability

There is a general acceptance among the population of the Louga region of the expansion of the *Tokeur* plantation system, the natural regeneration of trees, and the planting of multi-purpose trees around the villages, but only after a water supply is assured. The intensive livestock raising in fenced fields contributes to the improvement of soil quality, as manure is used as fertilizer. Social group cohesion is encouraged and the villagers consider themselves an integral part of project activities. In this way, the sustainability of project activities is almost assured. The project has laid a good foundation for income generation through specific revolving funds and training programmes for the beneficiaries. Under the circumstances, the project provides a good example of a high level of awareness in the population on environmental degradation issues and on ways of tackling them with the full involvement of the population concerned.

Sustainability in the pilot village areas is secured through the use of revolving funds. The mechanisms for accountability are established through community structures for agricultural and livestock activities to promote desertification control. These include committees concerned with nurseries, water maintenance, revolving loans, mills, training and many more. The different committees, especially in the pilot villages, have opened bank accounts with the formal Senegalese banking system to assure sustainability. The setting up of WID offices in 1992, with a professional team of eight local women, is another sign of the potential of sustainability, in a setting where female-headed households are in the majority.

This project has initiated positive steps towards combating and controlling desertification in the semiarid zone of Louga. The project has created consciousness and raised awareness in the local community of the fact that desertification control is a long-term process and that ultimately it is only they who can successfully tackle this task.

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