WORLD ATLAS OF DESERTIFICATION

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PREFACE

Desertification is destroying the food-producing capacity of vast tracts of dryland in every continent of the world. Many millions of people living in almost 100 countries, including the United States, the Soviet Union, Africa, Asia, Central and South America and Australia, suffer its effects.

Of the world's drylands used for agriculture, 70% are affected to some degree by various forms of land degradation. One sixth of the world's population is threatened by the effects of desertification. Their numbers are rising alarmingly. In 1977, when the United Nations Conference on Desertification was held in Nairobi, 57 million people were suffering the direct effects of land which had degraded to the extent where it no longer produced enough food to sustain them. By 1984, their numbers had risen to 135 million. And the relentless advance of desertification continues.

Every year, nearly six million hectares of previously productive land in arid, semiarid and dry subhumid areas loses its capacity to produce food. In terms of income lost, this destruction of productive capacity costs the world in 1990 prices some US$42.3 billion each year. By the end of this century, it is estimated that the world will have lost a substantial portion of its arable land if the current advance of desertification is not arrested.

In terms of area, Asia suffers the worst ravages of desertification, with 1312 million hectares of degraded drylands. In terms of severity of degradation, however, North America and Africa are by far the worst off, with 76 and 73% of their drylands degraded. The situation is still more different if only soil degradation is considered: 434 million hectares or 22% of the total area of drylands in Asia and 355 million hectares or 18% of the total area of drylands in Africa are degraded.

Clearly, the situation is serious. With a rapidly expanding global population, the world can ill afford to lose any of its productive land, let alone such large areas. Desertification is a global problem, demanding urgent global action. And this action must involve more than a campaign against the processes of desertification. It must become an essential part of the broad process of development and the provision of basic human needs.

Although desertification is a complex process of land degradation in arid, semiarid and dry subhumid areas resulting mainly from adverse human impact, this atlas is essentially based on soil degradation maps for the global and continental Africa sections. Degradation of vegetation, rangelands and different types of lands are other important aspects of desertification, but there is no adequate global database for assessment of vegetation degradation as well as of overgrazing, land use patterns and population. Data from nations which have mapped these phenomena are included in the more detailed national and continental maps.

There are three major causes of soil degradation – overgrazing, deforestation and unsustainable agricultural practices. Overgrazing and deforestation destroy the protective layer of plants which cover drylands, making it possible for wind and water erosion to strip away the fertile top layers of soil. Unsustainable agricultural practices sap the soil of nutrients, overload it with salts, dry it out, compact or seal its surface and cause waterlogging which removes air from the soil and allows toxic substances to accumulate.

UNEP has long been concerned about this relentless loss of productive land. The United Nations Conference on Desertification, organized in 1977 under UNEP's auspices, drew up a Plan of Action to Combat Desertification (PACD). Since 1978, UNEP's Governing Council has regularly reviewed the implementation of PACD, reporting its findings and decisions to the United Nations General Assembly through the Economic and Social Council.

An external evaluation of the Plan, carried out in 1989, concluded that it should remain a global strategy for desertification control, with slight revisions that should give greater emphasis to socio-economic factors associated with desertification.

Accordingly, when UNEP's Governing Council met in May, 1991, it reaffirmed its conviction that the PACD was an appropriate instrument to assist Governments in developing national programmes for arresting the process of desertification – subject to some revision which followed the findings of the evaluation report.

The main goal of implementing the PACD remains the same as when it was formulated in 1977 by the United Nations Conference on Desertification. The immediate goal is to prevent and arrest the advance of desertification, and where possible to reclaim desertified land for productive use. Ultimately, the objective is to sustain and promote, within ecological limits, the productivity of arid, semiarid and dry subhumid areas which are vulnerable to desertification.

National Plans of Action to Combat Desertification (NPACDs) should be incorporated into broader national development programmes; they should become an internal part of the development matrix of the countries affected. To fully implement the PACD, resources and institutional capabilities will have to be mobilized—nationally, regionally and internationally. Countries should introduce new land use policies which encourage the sustainable development of land and water resources, and improved land use practices. Infrastructures in areas affected by desertification need improvement and strengthening.

Within these broad goals, it is crucial that the emphasis should be on the involvement of the people who use the land, whose activities are currently degrading it. If they do not realize that remedial measures will improve the quality of their lives, and if they are not involved in planning and implementing these measures, no anti-desertification strategy will succeed.

This atlas represents the current stage of our understanding of desertification, its extent and its possible solutions. One of the clearest ways to depict a global problem is to show it in an atlas. If it is true that one picture tells a thousand words, it is probably also true that one map of a global situation tells many more than a thousand words.

The atlas is structured in three parts, dealing with global, continental and national/local situations. Different countries have taken different approaches in assessing the extent of desertification. Their surveys provide greater detail of the problem at a national or local scale, and give illuminating insights into both the scale of desertification, and its various forms. This difference of approach has demanded a thematic approach for the atlas.

The continental section of the atlas deals with Africa. Africa's problems of desertification have been most visible. The famines and mass starvation that have menaced the countries of Africa in the period between 1968 and 1984 have aroused international concern and led to an acceleration of research into the extent of desertification on this continent. Consequently, Africa offers the most detailed available data for any continent.

The atlas represents an important step forward in our understanding of the complex environmental issue. It has been made possible through the sort of global co-operation that will also be needed if we are to arrest and remedy the inexorable progress of desertification of the world's drylands.

The data used are scientifically sound, and allow comparisons between regions, and between varying degrees of soil degradation, both within regions, and between continents. Much more research and monitoring are needed, and I expect this atlas to be used as a reference point for future research. This research should continue to update data, and to extend the coverage of monitoring programmes, both within countries and within regions.

It is my 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, and for a free flow of technology on favourable terms to areas affected by desertification.

Desertification has for too long been the poor relative of environmental issues. It is mainly experienced in rural areas of the world, and in many cases in developing countries. In both cases, it has been less visible to politicians and policy makers than problems such as urban air pollution and the disposal of hazardous wastes. Yet as the world's population expands, desertification will become of increasing concern. Measures to combat its advance have until now been hampered by lack of political commitment, and lack of funds. But as the atlas clearly shows, this is a global problem, and a serious one, well deserving the priority status accorded it in the preparation for the 1992 United Nations Conference on Environment and Development. Desertification is accelerating. The costs of combating it rise with each passing year. And if it is not controlled soon, we can expect a dramatic increase in world food shortages. Any one of these factors is reason to take urgent action. Taken together, they represent an unarguable case for global concern, and global action.

DR MOSTAFA K. TOLBA
EXECUTIVE DIRECTOR
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LIST OF ABBREVIATIONS

ACSAD	Arab Centre for the Studies of Arid Zones and Dry Lands
AI	Aridity Index
AP	animal pressure
asl	above sea level
AVHRR	Advanced Very High Resolution Radiometer
CET	crop evapotranspiration
cm	centimetre
CRU	Climatic Research Unit
DC/PAC	Desertification Control/Programme Activity Centre
DH	desertification hazard
DR	desertification rate
DS	desertification status
dSm^{-1}	decisiemens per metre (formerly milimhos per centimetre)
EC	electrical conductivity
ECOWAS	Economic Community of West African States
ESP	exchangeable sodium percentage
FAO	Food and Agriculture Organization of the United Nations
GEMS	Global Environment Monitoring System
GIS	geographic information systems
GLASOD	Global Assessment of Human-Induced Soil Degradation
GRID	Global Resource Information Database
GVI	Global Vegetation Index
ha	hectare
ICIV	Institut de la Carte Internationale de la Végétation
IGADD	Intergovernmental Authority on Drought and Development
IGN	Institut Géographique National
IR	inherent risk
ISRIC	International Soil Reference and Information Centre
IUCN	International Union for Conservation of Nature and Natural Resources
km	kilometre
mm	millimetre
ms^{-1}	metres per second
MSS	Multi-Spectral Scanner
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
PET	potential evapotranspiration
PP	population pressure
SADCC	Southern African Development Co-ordination Conference
sq	square
TM	Thematic Mapper
UEA	University of East Anglia
UN	United Nations
UNCOD	United Nations Conference on Desertification
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USLE	Universal Soil Loss Equation

INTRODUCTION

Desertification/Land Degradation – The Background

More than 6.1 billion hectares, over one third of the Earth's land area, is dryland. Nearly one billion hectares of this area are naturally hyperarid deserts, with very low biological productivity. The remaining 5.1 billion hectares are made up of arid, semiarid and dry subhumid areas, part of which have become desert since the dawn of civilization while other parts of these areas are still being degraded by human action today.

These lands are the habitat and the source of livelihood for about one quarter of the world's population. They are areas characterized by the persistent natural menace of recurrent drought, a natural hazard accentuated by imbalanced management of natural resources. Particularly acute drought years in the Sahelian region of Africa from 1968 to 1973, and their tragic effects on the peoples of the region, drew worldwide attention to the problems of human survival and development in drylands, particularly on desert margins.

These problems have been addressed by the United Nations (UN) General Assembly, in conformity with the Charter of the United Nations. The UN General Assembly's Resolution 3202 (vi) of 1 May 1974 recommended that the international community undertake concrete and speedy measures to arrest desertification and assist the economic development of affected areas. The Economic and Social Council's Resolution 1878 (LVII) of 16 July 1974 requested all the concerned organizations of the UN system to pursue a broad attack on the drought problem. Decisions of the Governing Councils of the UN Development Programme (UNDP) and the UN Environment Programme (UNEP) emphasized the need for undertaking measures to check the spread of desert conditions. The General Assembly then decided, by Resolution 3337 (xxix) of 17 December 1974, to initiate concerted international action to combat desertification and, in order to provide an impetus to this action, to convene a UN Conference on Desertification (UNCOD), between 29 August and 9 September 1977 in Nairobi, Kenya, which would produce an effective, comprehensive and co-ordinated programme for solving the problem.

For the purposes of this atlas, desertification/land degradation is defined as:

Land degradation in arid, semiarid and dry subhumid areas resulting mainly from adverse human impact.

Sustainable Land Use

The concept of degradation is inseparable from that of sustainability. 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 determines its sustainability under a particular use is its resilience, and it is important to note that the resilience of a resource system will vary according to different land uses and indeed may vary from time to time, depending largely on 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 disturbance the area can recover from, the greater its resilience. In essence, land degradation is the weakening of an area's resilience. One measure of land degradation is the cost of rehabilitation.

Variability in Drylands

One serious 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 used to measure the aridity of drylands and these can be used to delimit dryland areas (see the section on climatic data pages 2–5). 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. It is not unheard of, for example, for the more extreme dryland areas to receive all their "average" annual precipitation in just one rainfall event, and commonly such regions receive their average annual totals in just a few days. The meteorological systems that bring rainfall to dryland regions are typically convective cells, which means that spatially rainfall often falls in small specific zones.

These characteristics of dryland climate, to which indigenous plants and animals have adapted, 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". Again, indigenous plants and animals have adapted to cope with this inherent variability of the dryland ecosystem.

Implications for Desertification Study

The implications of this environmental variability for the study of desertification are manifold. Firstly it has implications for the location of drylands themselves. Although for the purposes of the assessment carried out in the pages of this atlas dryland areas are highlighted and given specific boundaries, it is important to note that these boundaries are simply based upon average conditions and that actual ground conditions vary greatly through variable timescales.

There are also implications for the human inhabitants of dryland regions. 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 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/land degradation 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 fringes of drylands indicate that the natural variability in climate is reflected in a green vegetation dryland boundary that can fluctuate by up to 200 km from a dry year to a following wet year. With such great natural fluctuations in the ground state of drylands, it is clearly necessary to monitor potential areas of desertification/land degradation over a timescale of decades before it is possible to safely 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 such 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. But before these underlying causes can be tackled it is necessary to locate and quantify the nature of the problem.

Unfortunately, accurate and reliable data on the extent 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. Early attempts to assess the extent of desertification on the global scale, such as the world map prepared for UNCOD, represent useful first steps towards the goal of solving the problem. But these first efforts had their problems. Perhaps most importantly was 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. 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 and these regions are referred to as the "susceptible drylands".

There can be grounds for criticizing a global approach to the problem in itself. The complex nature of desertification means that adequate assessment and consequent plans to counteract the problem can only be usefully carried out on the local scale. Nonetheless, it is useful to attain a worldwide appreciation of the phenomenon in order to estimate its magnitude worldwide and to identify more specific problem areas at the national and local scale. For this reason this atlas is organized specifically to start from a global perspective and to zoom in to the local scale. Hence the atlas is divided into three sections – global, continental and case studies – and within each section the general picture is given before more detailed analysis.

A Thematic Approach

The scarcity of data on desertification and the many forms it 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 is to map the many indicators of desertification and the factors that affect those indicators. Global data sets for all these variables are not currently available however, so that the contents of this atlas have been constrained by data availability. 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 by no means exhaustive. Human-induced soil degradation is an important indicator of desertification, but it is certainly not the only one. The degradation of vegetation is another important aspect of desertification. The loss of grassland resource potential due to overgrazing 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 visible impact on the soil resource, or at least not immediately.

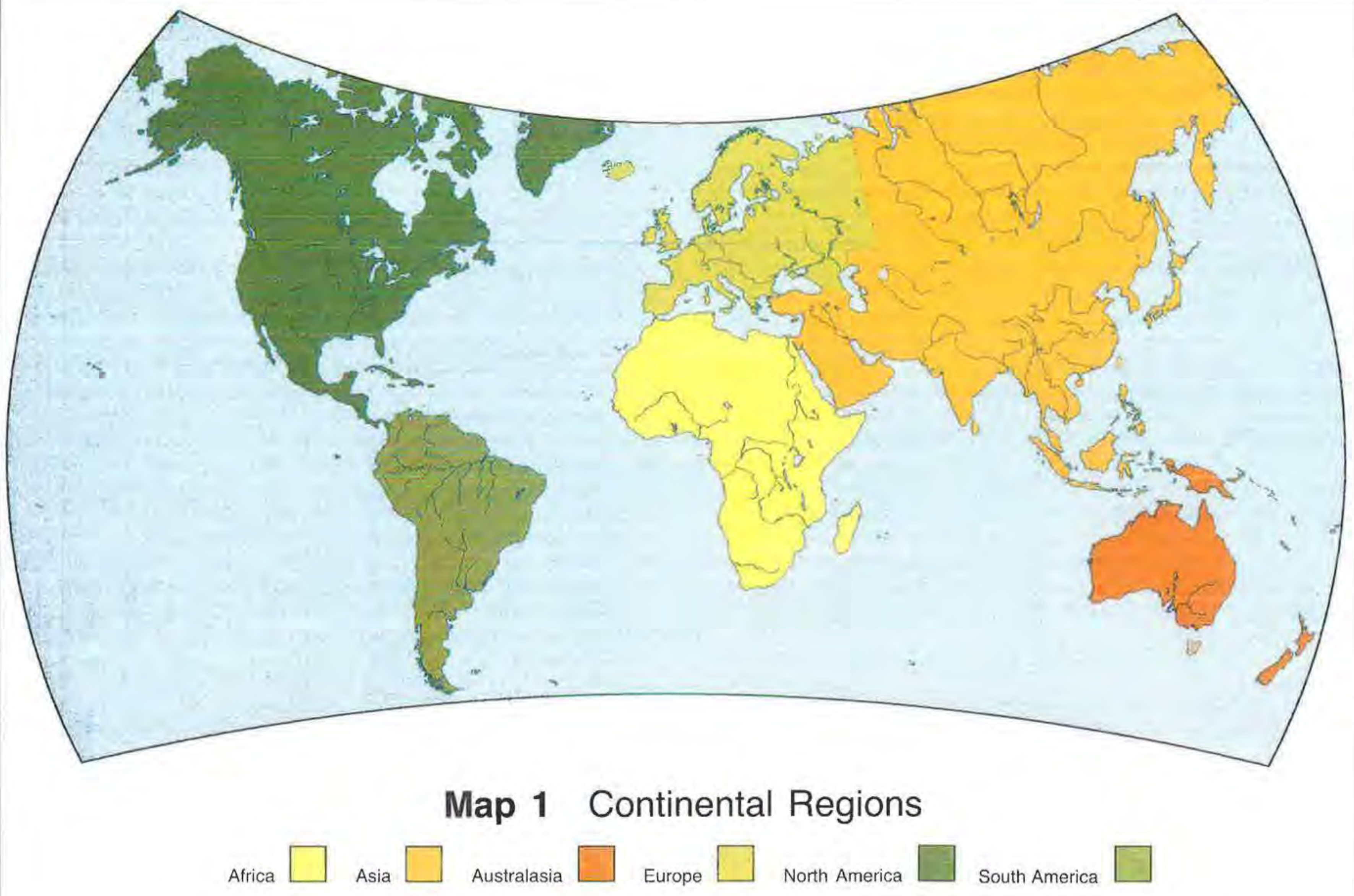
These deficiencies of the atlas are not highlighted in order to denigrate the contents of this volume. On the contrary, this atlas represents a significant step forward in our appreciation of desertification as a phenomenon and in our approach to its resolution. It uses new data and employs a fresh technical approach. The difficulties outlined above simply illustrate some of the problems involved in studying such a complex environmental issue.

Map Projections

All of the maps shown in the global and continental sections of this atlas use the Van der Grinten projection. Whilst at the global scale some projections achieve minimal area distortion and others minimal distortion of the shape of continents, Van der Grinten is amongst those which achieve a good compromise between these two variables. The benefits of this projection, however, decline towards the poles, hence the maps are cut off at 72°N and 57°S. This does not detract from the utility of the atlas since dryland areas susceptible to desertification are largely found within thirty degrees of latitude either side of the Equator. Tables in the text showing data for continents refer to the regions defined by the Times Atlas of The World and shown in the map below. Since the Van der Grinten projection is not a true equal area projection, it could not be used for area calculations. Using the computer, all maps were transformed into Mollweide, an equal area projection, before calculating data on areas. Maps used in the national section use various different projections as appropriate to the representation of areas at a larger scale.

Geographic Information Systems

The data used in the compilation of the maps, tables and diagrams in the global and continental sections of this atlas are stored on computer in the UNEP Global Resources Information Database (GRID). GRID is developing a global network of centres which use computer technology to process environ-



Map 1 Continental Regions

mental data and analyse the interactions of environmental variables, thus forming a bridge between monitoring and assessment, and environmental management.

GRID uses geographic information systems, or GIS, and remote sensing technologies for environmental monitoring and assessment. A GIS stores both spatial or geo-referenced and non-spatial data, and allows the user to manipulate, retrieve and analyse these data to produce information which can be used for environmental assessment and management. Results can be produced as maps, in tabular form, or as statistics. Hence annual rainfall data for a global network of meteorological stations can be spatially referenced, processed by the computer, and then output as a world map showing "surface" rainfall totals. If monthly rainfall totals are available, they can be used to output a series of monthly rainfall distribution maps. When rainfall data for the next year become available, these data can be fed into the GIS and another annual map produced which can be compared to the previous year's distribution for changes in time as well as space analysis.

The system enables the investigator to have almost infinite flexibility to generate maps according to the particular research interest. One map might show annual rainfall distribution by 100 mm classes for example. A different query of the database could be prepared to show all areas that have received less than 250 mm in a year.

A GIS allows the investigator to superimpose or overlay different data sets to produce a new map, enabling the user to visualize, model and quantify the interaction between many different parameters. Hence the annual rainfall map could be superimposed upon a world map of soil degradation in order to identify those areas where water erosion is most prevalent. If the rainfall were combined with a map of population distribution, it would highlight those areas where large human populations are affected. The overlay maps can be produced at global, continental or regional level, depending on the nature and scale of the data provided and the need of the researcher.

For the decision-making process, GISs provide the opportunity of fast updating of databases and speedy data analyses. Therefore, scientists can propose a number of alternative scenarios, analyse results and modify parameters according to the desired objectives. This approach to problem-solving could be much slower, cumbersome and prone to error with conventional manual methodologies.

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 two which are central to the global and continental sections. These are a global soils degradation database and a global climatic database.

The development of climatic data sets to produce a bioclimatic database used to delineate drylands is explained in detail on pages 2–5. The data on soil degradation are taken from the Global Assessment of Soil Degradation (GLASOD). GLASOD is the result of a collaboration between UNEP and the International Soil Reference and Information Centre (ISRIC) in the Netherlands. There are in fact two soil degradation databases prepared by ISRIC, 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. More detailed appraisals of these data sets and their characteristics are given on pages 11 and 29.

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 the phenomena concerned. The GLASOD 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 an A3 page mean that an entire polygon is coloured according to a particular characteristic (red for very high degradation severity on page 10, for example) this does not necessarily mean that all the land within that unit possesses the characteristic. A map unit with an overall very high degradation severity may be characterized as such because moderate degradation processes occur in a very large part of the unit, but alternatively for example because extreme degrees of degradation occur in a smaller part of the unit. Hence the maps often give a somewhat exaggerated impression of the extent of degradation. This exaggerated impression is particularly marked in hyperarid areas where a large map unit is often coloured according to a particular degradation severity while on the ground the actual degradation occurs in highly specific zones around oasis settlements. However, the proportion of land within the unit that is damaged is recorded in the database, and the exact figure has been extracted to compile the tables and figures on the pages facing 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.

SECTION ONE

Global

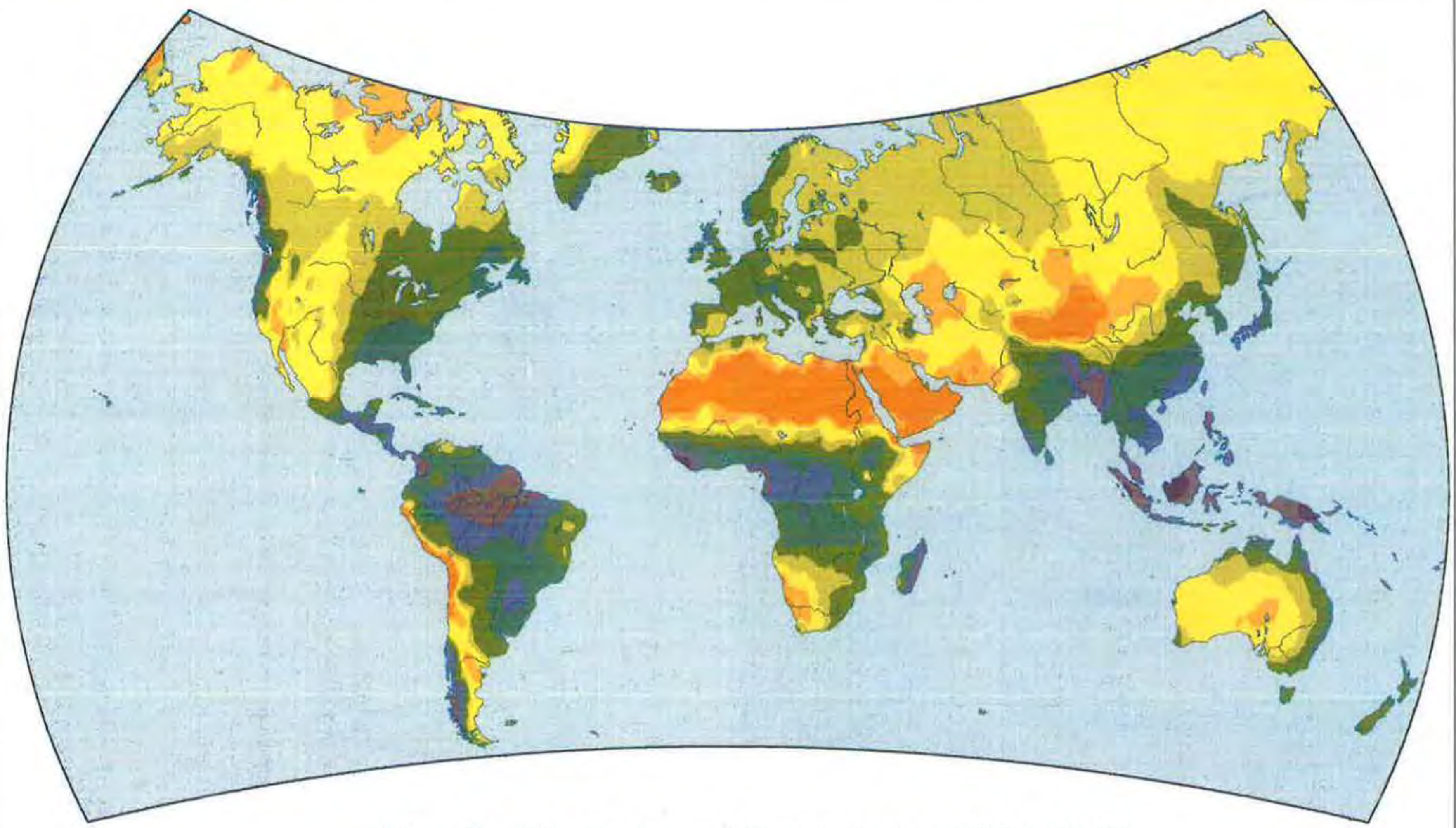
Section one begins by outlining the methodology used to designate the aridity zones in the global and continental Africa sections of this atlas. This is followed by an appraisal of climatic variability in drylands, an important characteristic of drylands which must be taken into account wherever the problems of desertification/land degradation 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 the continental Africa and case studies sections.

CLIMATIC SURFACES AND DESIGNATION OF ARIDITY ZONES

The map of aridity zones demarcates the distribution of global drylands and designates the regions that form the basis of the following maps in this atlas. Aridity zones are based on an evaluation of the relationship between key climatic variables, creating an index of moisture availability, the Aridity Index. There are a number of ways in which this index could be derived from climatic data; it is thus important to understand the basis used here and the ways in which it differs from other methods, for example that used for the 1977 UNESCO map of the world distribution of arid regions.

The Climatic Data Set

The climatic database from which all maps were derived consists of monthly mean precipitation and temperature values derived from worldwide data sets at the Climatic Research Unit (CRU), University of East Anglia, United Kingdom. These data can be interpreted in either a "timeless" manner or in terms of specific timebands. In the former, mean variable values are

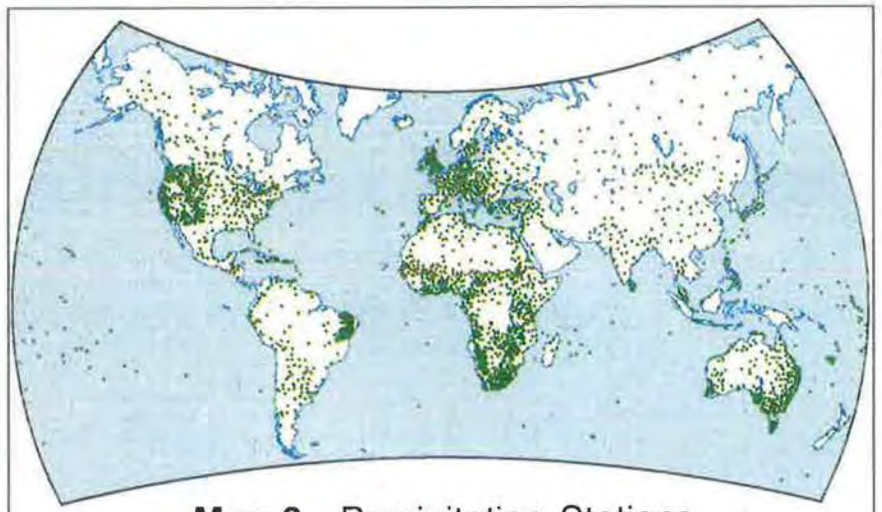


Map 2 Mean Annual Precipitation 1951–1980

0 100 200 400 600 1000 1500 2000 3000 (mm)

Source: CRU/UEA, UNEP/GRID

Approximate equatorial scale 1:175 million



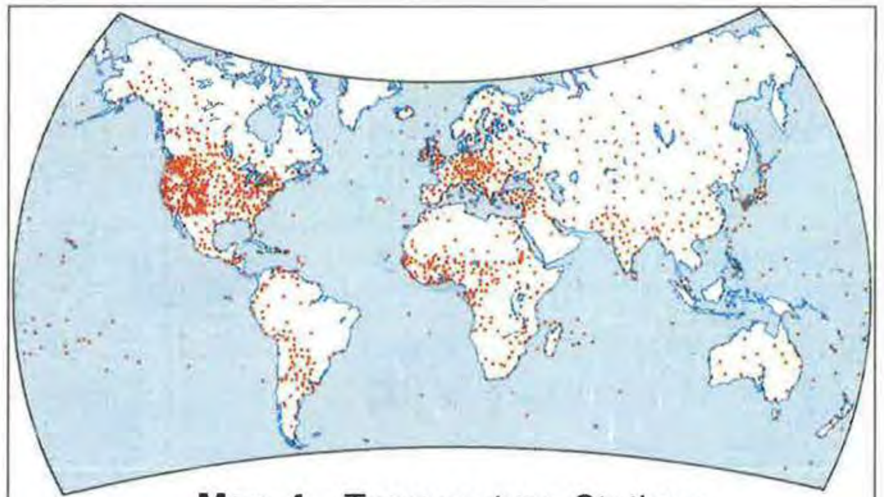
Map 3 Precipitation Stations

Number of stations: 3758

1951–1980

Source: CRU/UEA

Approximate equatorial scale 1:350 million



Map 4 Temperature Stations

Number of stations: 1834

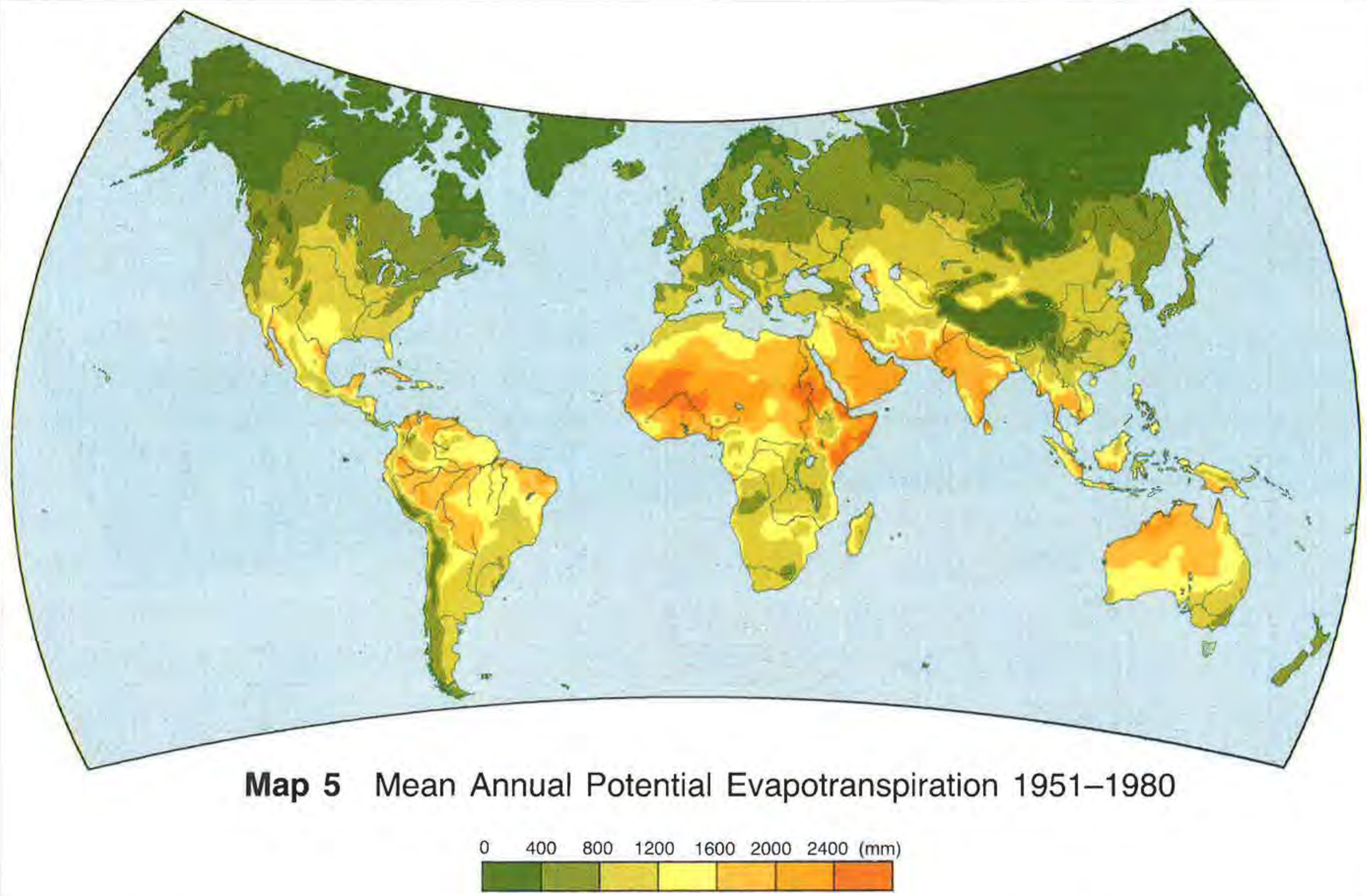
1951–1980

Source: CRU/UEA

Approximate equatorial scale 1:350 million

calculated for individual stations regardless of the length of time for which data exist. This permits the best spatial coverage to be achieved as data from all contributing weather stations can be incorporated, but considerable problems can arise when comparisons are made between data from stations with different length records. This approach can lead to too much confidence being placed in values derived from data runs of only a few years and may unwittingly contain data reflecting exceptionally wet or dry years.

The timeband approach has several advantages over the above method and was employed in this study. First, it allows greater confidence to be placed in the compatibility of data from different locations. Second, it creates the possibility of producing maps of aridity zones for different time periods, permitting changes in the location and extent of zones to be identified between different timebands (see pages 8–9). In this study, stations with data for the period 1951–1980 were used to produce mean monthly global temperature (T) and annual precipitation (P) surfaces as inputs to the calculation of the Aridity Index. The thirty-year period is regarded by climatologists to be representative of long term climate. Initially, 1834 station means were used for T and 2769 for P. Because of the lack of robustness of P data for extrapolating point data to area coverage, a further 989 stations were added for areas where data were sparse, involving some relaxation in selection criteria. This enabled a global grid of 0.5° cells to be generated for the production of the climatic surfaces.



Map 5 Mean Annual Potential Evapotranspiration 1951–1980

Source: CRU/UEA, UNEP/GRID

Approximate equatorial scale 1:175 million

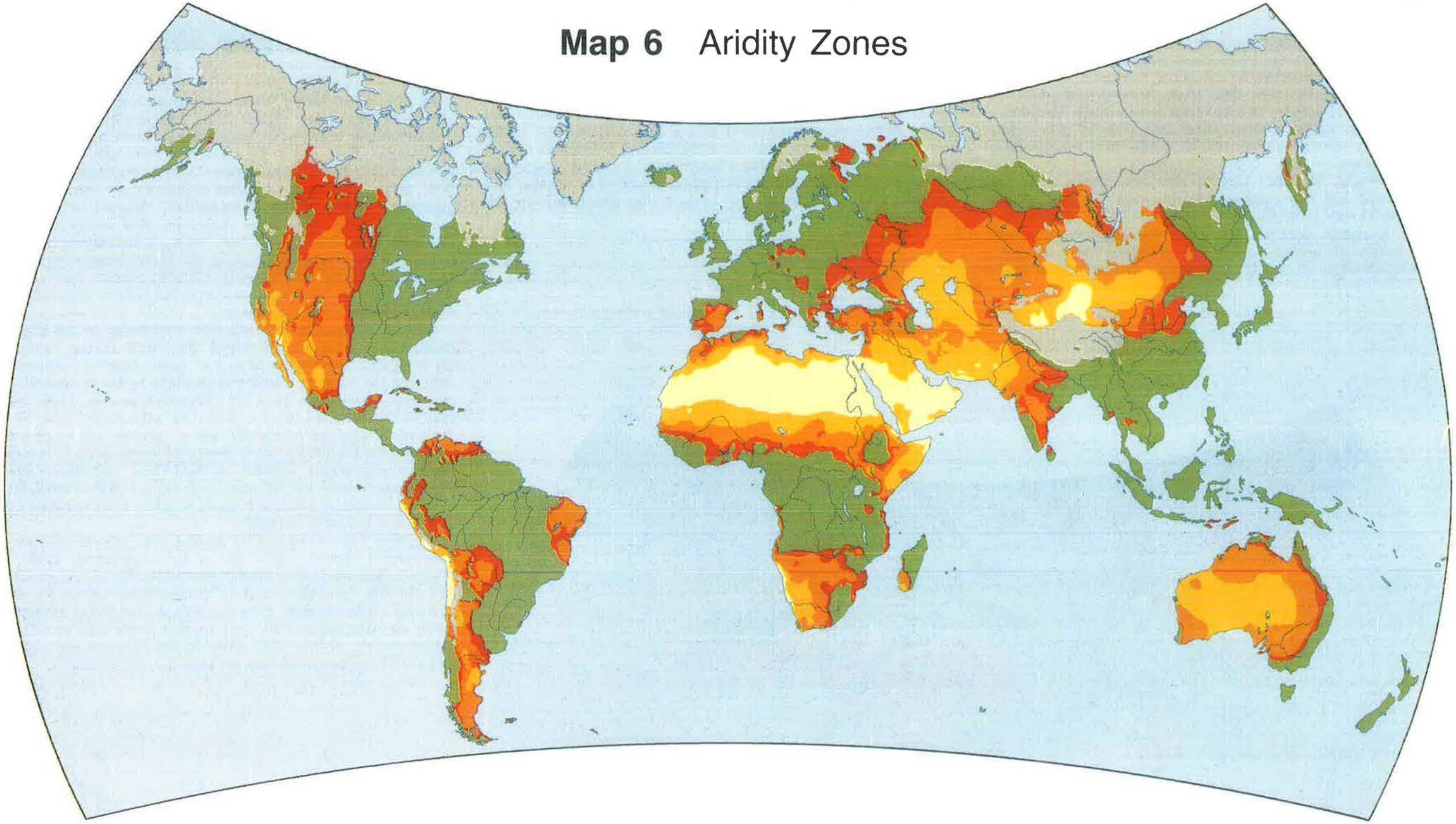
Calculation of Evapotranspiration Values

Potential evapotranspiration (PET) values needed to be derived from the interpolated mean monthly temperature surfaces before Aridity Index values could be calculated. PET can be determined in three ways, each having its own limitations and advantages. First, it can be calculated from actual evaporation determined by direct measurement using lysimeters or evaporation pans, but the available database is small and the equipment used is not standardized. Second, PET can be calculated using theoretical formulae. The method of H.L. Penman, proposed in the late 1940s, is commonly used but 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 useful approach relies on knowledge of the empirical relationship between measured PET and certain variables, allowing PET calculation from just mean monthly temperature data and the average number of daylight hours by month. This method, established by C.W. Thornthwaite in 1948, has a practicality relevant to the scale of this study and to the drylands where environmental data are scarce, and was used by P. Meigs for his 1953 UNESCO map of world aridity. Though a more sophisticated related method that calculates evapotranspiration rates for different crop types (CET) is available, it was not used here because it again requires a further data input that is not generally 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 moist and cold environments. Consequently an empirical adjustment factor was derived by CRU and applied to the data to bring the values closely in line with those of the Penman method. The global PET surface is shown on Map 5.

Map 6 Aridity Zones



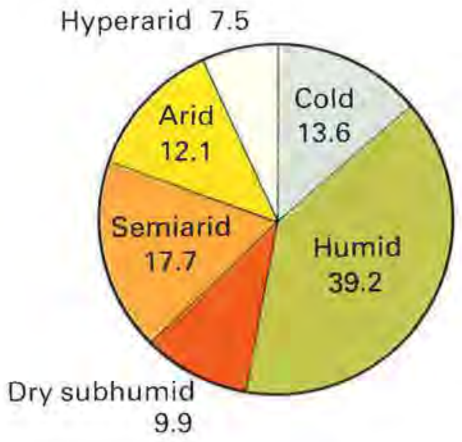
Source: CRU/UEA, UNEP/GRID

Approximate equatorial scale 1:115 million

Aridity Index

The Aridity Index (AI), calculated as the ratio P/PET, was derived from the climatic surface maps. Values were averaged to provide a map of mean annual potential moisture availability for the period 1951–1980 and a global climatic classification based on potential moisture availability, with AI values of <1.0 indicating an annual moisture deficit. The zonation of the classification is shown in the legend on Map 6.

The P/PET boundary between arid and hyperarid zones was increased from the 0.03 used in the 1977 UNESCO map of the world distribution of arid regions to 0.05, to compensate for the Thornthwaite method underestimation of PET in very dry environments. The boundary between the dry subhumid and humid zones was introduced in order to exclude moister areas from consideration in this study. The separate designation of cold mountain and tundra climates based on a temperature criterion was introduced because while these areas may suffer from an annual moisture deficit, such cold environments present a different range of problems than those in warm dryland environments. As such these areas are excluded from further consideration in this desertification study.



Global land area by aridity zone (%)

Table 1 Aridity zones by region (millions of hectares)

Zone	Region						Total
	Africa	Asia	Australasia	Europe	North America	South America	
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	13012.7

Dryland Types

Drylands may be defined in several ways but most simply aridity represents a lack of moisture in average climatic conditions, caused by one of four climatic situations which may interact in the case of individual dryland areas: continentality, topography, anticyclonic subsidence and oceanic cold currents. The nomenclature for aridity zones used here are those commonly employed in scientific literature. Although at the global scale each zone inevitably embraces a range of environmental conditions, the following general criteria can be used to characterize them:

Hyperarid environments (P/PET < 0.05): cover 7.5% of the global land surface and have very limited and highly variable rainfall amounts 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 offer very limited opportunities for human activity.

Arid areas (0.05 ≤ P/PET < 0.20): mean annual precipitation values up to about 200 mm in winter rainfall areas and 300 mm in summer rainfall areas but more importantly interannual variability in the 50–100% range. Pastoralism is possible but without mobility or the use of groundwater resources is highly susceptible to climatic variability.

Semiarid areas (0.20 ≤ P/PET < 0.50): highly seasonal rainfall regimes and mean annual values up to about 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 other sedentary agricultural activities are susceptible to seasonal and interannual moisture deficiency.

Dry subhumid areas (0.50 ≤ P/PET < 0.65): less than 25% interannual rainfall variability and rain-fed agriculture is widely practised.

Problems of Delineating Dryland Boundaries

Dryland boundaries are neither static nor abrupt. 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 boundaries on the ground or define them in terms of features such as natural vegetation are likely to fail. 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.

It should also be recognized that individual aridity zones do not represent homogeneous climates. Specific P/PET ratios can be derived from a wide range of values for individual meteorological parameters. The zones therefore represent one way of characterizing climate, a way that has particular relevance to desertification studies.

Comparison with the 1977 UNESCO Map of Aridity

It is important to identify how the map of world aridity zones differs from the widely used 1977 UNESCO map. Objective direct comparisons between the two cannot be made since specific information on the construction of the UNESCO map, including time period, length of time period for individual stations, or station network, is not available and hence the UNESCO methodology could not be replicated. Furthermore, where spatial coverage by 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 method, requiring a wider range of meteorological data inputs. Although the Thornthwaite values calculated for this atlas were empirically adjusted to better fit Penman values, there may still be statistical divergence in areas of the Aridity Index values.

Overall, the use of timebound climatological data will more easily permit future reliable comparisons with maps for other designated time periods. 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 utilizes less meteorological data and therefore reduces errors inherited from primary data collection.

CLIMATIC VARIABILITY IN DRYLANDS

Introduction

The study of desertification is hampered by the normal variability of dryland areas, as outlined briefly in the Introduction. Accurate indentification of the causes of desertification, and thus suitable strategies for its treatment, can only be made by paying close attention both to the human use and possible mismanagement of resources and also to the way in which dryland ecosystems and their resources respond to climatic variations. While this atlas concentrates on human-induced soil degradation, it is important to note the dynamic nature of some of the natural environmental elements in the dryland equation.

The inherent variability of dryland environments is very largely governed by the variations in climatic parameters that characterize such regions. Chief among these climatic parameters is precipitation, the input of moisture into the desert ecosytem. While many dryland areas receive important inputs of moisture from dew, and some others from fog, rainfall is the key source of moisture in most of the world's dryland regions. However, the "effectiveness" of rainfall, that is the amount available for plant growth or other uses, is also dependent upon the main output from the ecosystem, evapotranspiration, which is governed by parameters such as vegetation cover and type, wind speeds, and perhaps most importantly temperature. Hence in this section a closer look will be made at the variability of rainfall and temperature in the world's drylands as a contextual background to the preceding pages on dryland degradation. The graphs and maps shown on these pages are supplied by the CRU.

Rainfall

Figures 1 to 3 show time series graphs of annual rainfall for three dryland regions: the Sahel from the Atlantic coast to 35°E; the northeastern region of Brazil from 44°W to the Atlantic coast and from the Equator to 10°S, and North China from 100°E to the China Sea coast and from the borders with Mongolia and Russia to 35°N.

The graphs for each area have been derived as follows: the annual rainfall series for each station in the area is normalized by taking away the long-term mean from each value and the difference is then divided by the long-term standard deviation. The long-term period on which the mean and standard deviation are based in each area is 1951–1980, the period of the climate surfaces used for the annual Aridity index which has given the dryland area boundaries throughout the global and continental Africa sections of this atlas.

Normalizing gives a set of data series that are more readily comparable as each series will then have a mean close to zero and a standard deviation close to one. The spatial mean rainfall anomalies are then found by averaging the values for all stations in the area with data. Although the number of stations with

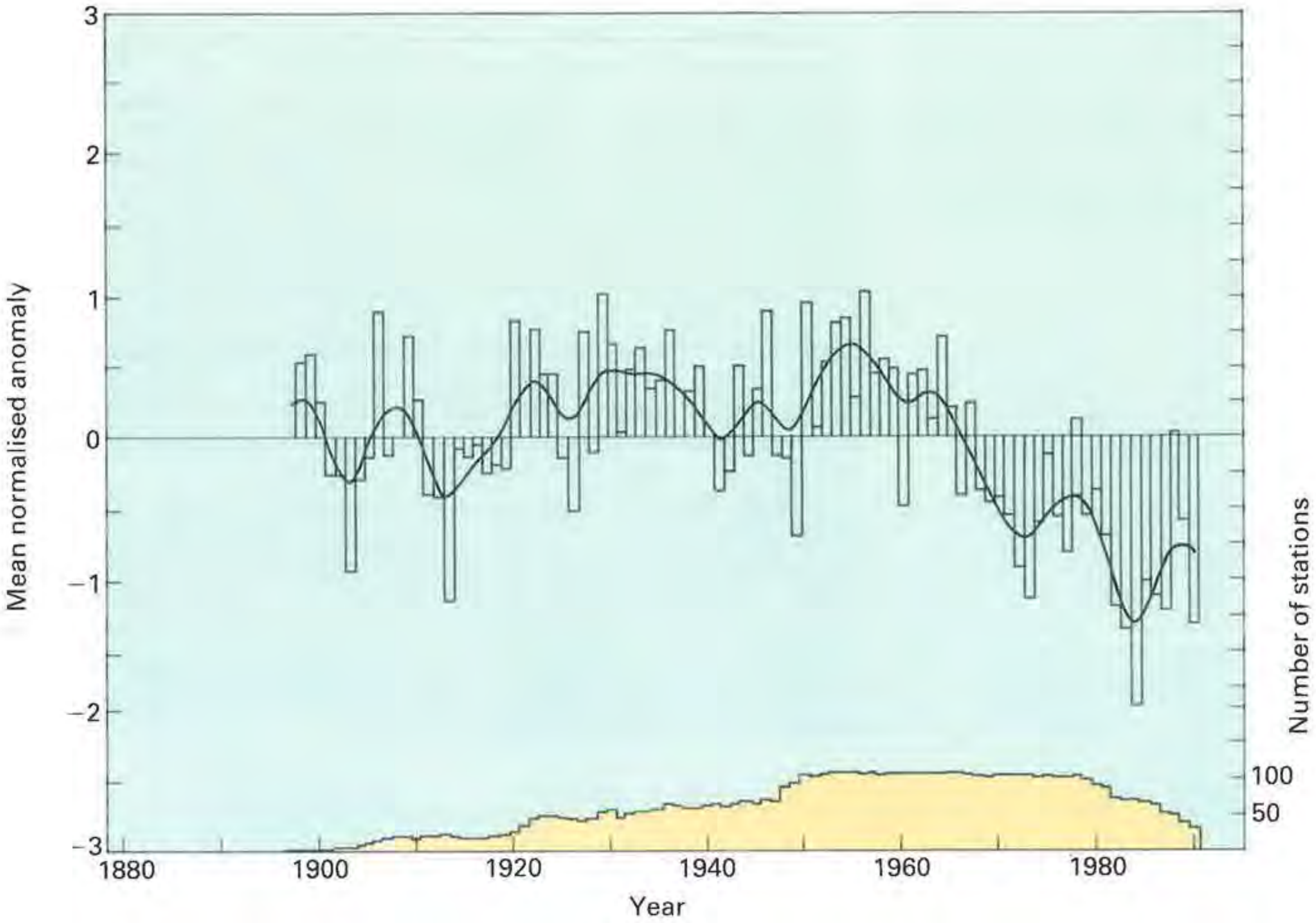


Figure 1 Time series of annual rainfall – The Sahel (1897–1990)

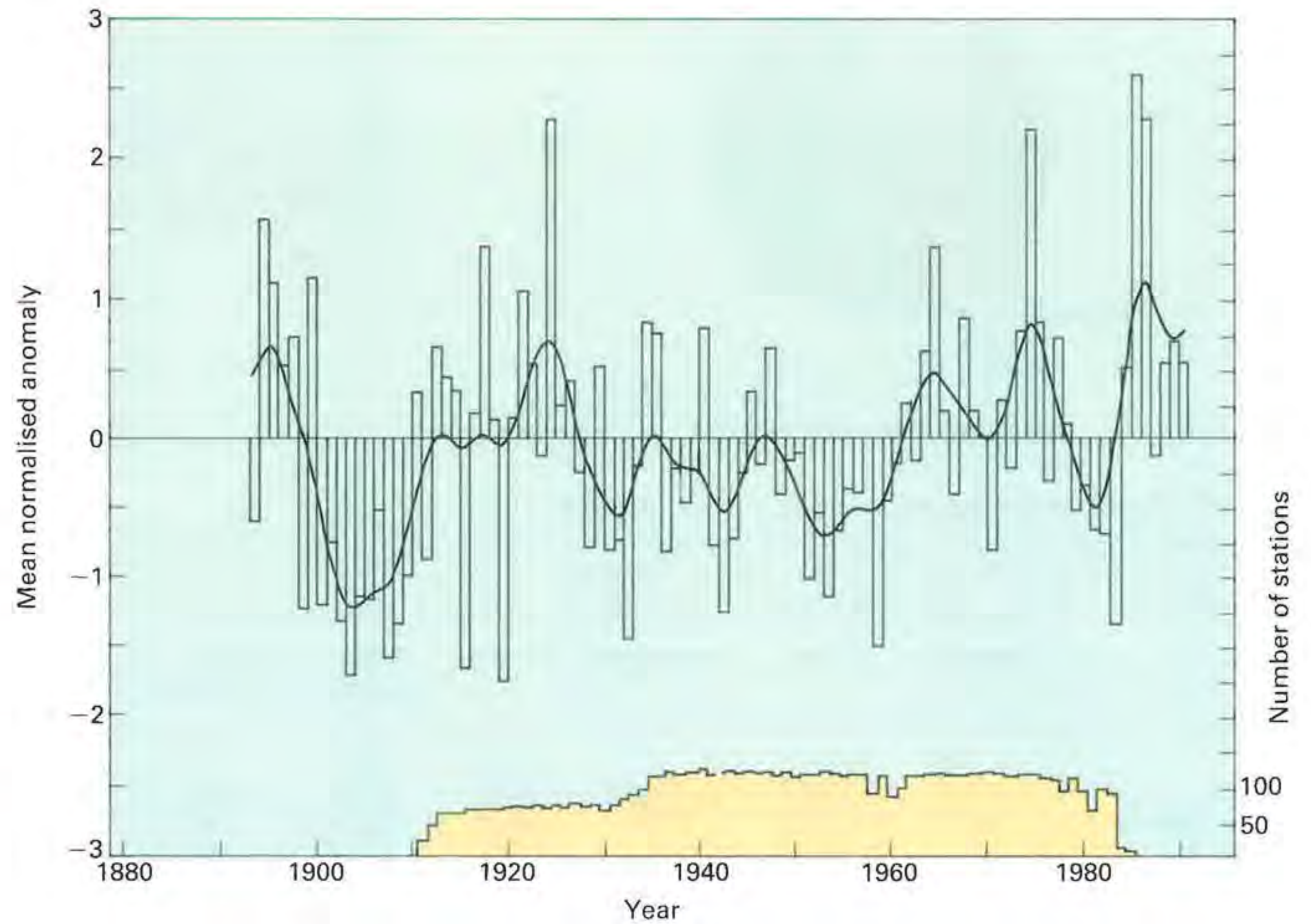


Figure 2 Time series of annual rainfall – Northeastern Brazil (1893–1990)

data throughout each period in each of the three areas is not constant, the time series are the best available, and since they represent a spatial average for each area they reliably reflect the annual rainfall anomalies in the regions in question.

The smooth curves on each time series are ten-year Gaussian filters which suppress variations of less than ten years. They therefore give a reliable indication of trends in rainfall anomalies.

All three graphs clearly illustrate that dryland regions experience prolonged periods of above and below average rainfall, as well as dramatic year on year fluctuations. The Sahel graph (Figure 1), covering the period 1897–1990, indicates that 1903 and 1913 were particularly dry years. The 1930s and the 1950s were prolonged periods of above-average rainfall across the region, the latter period particularly was a time of increase for both human and livestock populations. The period dating from the late 1960s has seen extended drought conditions, with only 1978 and 1988 being above normal in a twenty-three year period. During this time, certain years were particularly deficient in rainfall, such as 1972–1973 and 1982–1984. This most recent two decades of rainfall deficiency has tempted some scientists to suggest that the Sahel is experiencing a change in its climate. While most climatologists would argue that it is too early to talk of climate change in this region, this prolonged drought certainly puts a question mark over what we perceive to be "normal" rainfall in this region. Although our ability to predict future rainfall totals in this area is not good, many scientiists now believe that it would be wise to treat the rainfall conditions of the last twenty years or so as a basis for future planning for the region.

The rainfall graph for the northeastern region of Brazil (Figure 2) shows more dramatic variations in rainfall anomalies over short periods. Compare for example the extremely dry years of 1915 and 1919 with the very wet year 1917. Similarly, there are prolonged periods of drought such as the first decade of this century and during the 1950s. The 1980s, in contrast to the Sahel, has been a time of steadily improving rainfall conditions, from a drought in the first four years of the decade to high rainfall years since. Although it is beyond the scope of this atlas to examine the causes of drought in drylands, the northeastern Brazil graph shows certain times of extreme rainfall variations from the norm which correspond inversely to those in the Sahel. The drought during the 1950s is an obvious example, while individual extremely wet years occur the year after extremely dry years in the Sahel: 1974 and 1985 for example. The parallels drawn here are not totally coincidental. Several researchers have noted that extremes of rainfall in those two areas are related to anomalous sea surface temperatures over certain parts of the tropical Atlantic Ocean.

The rainfall graph for North China (Figure 3) also shows typically high year on year variations, such as those from 1913 to 1914 and from 1965 to 1966, as well as prolonged periods of above and below average rainfall, notably the drought from 1895 to 1909. In recent years, however, there is no discernible trend in rainfall anomalies, unlike the rainfall patterns in the Sahel and northeastern Brazil.

It is of course the years that are deficient in rainfall that are of particular interest in the study of desertification and dryland development. Figures 1 to 3 illustrate that such years are common, both as individual years and as runs of a number of years. Although the annual meteorological input of moisture through rainfall is important, as outlined above, it is as well to remember that other aspects of rainfall deficiency, such as the timing of rains, may be as important to the inhabitants of drylands. It is also relevant to note that these Figures show meteorological drought, and that particular absolute rainfall deficiencies will affect different land use activities to different degrees. A certain level of rainfall deficiency may mean the critical loss of a sorghum crop for example, but be less deleterious to the yields of millet on a neighbouring field. Hence the severity of impact brought about by a particular lack of rainfall will depend upon the land use in the area affected.

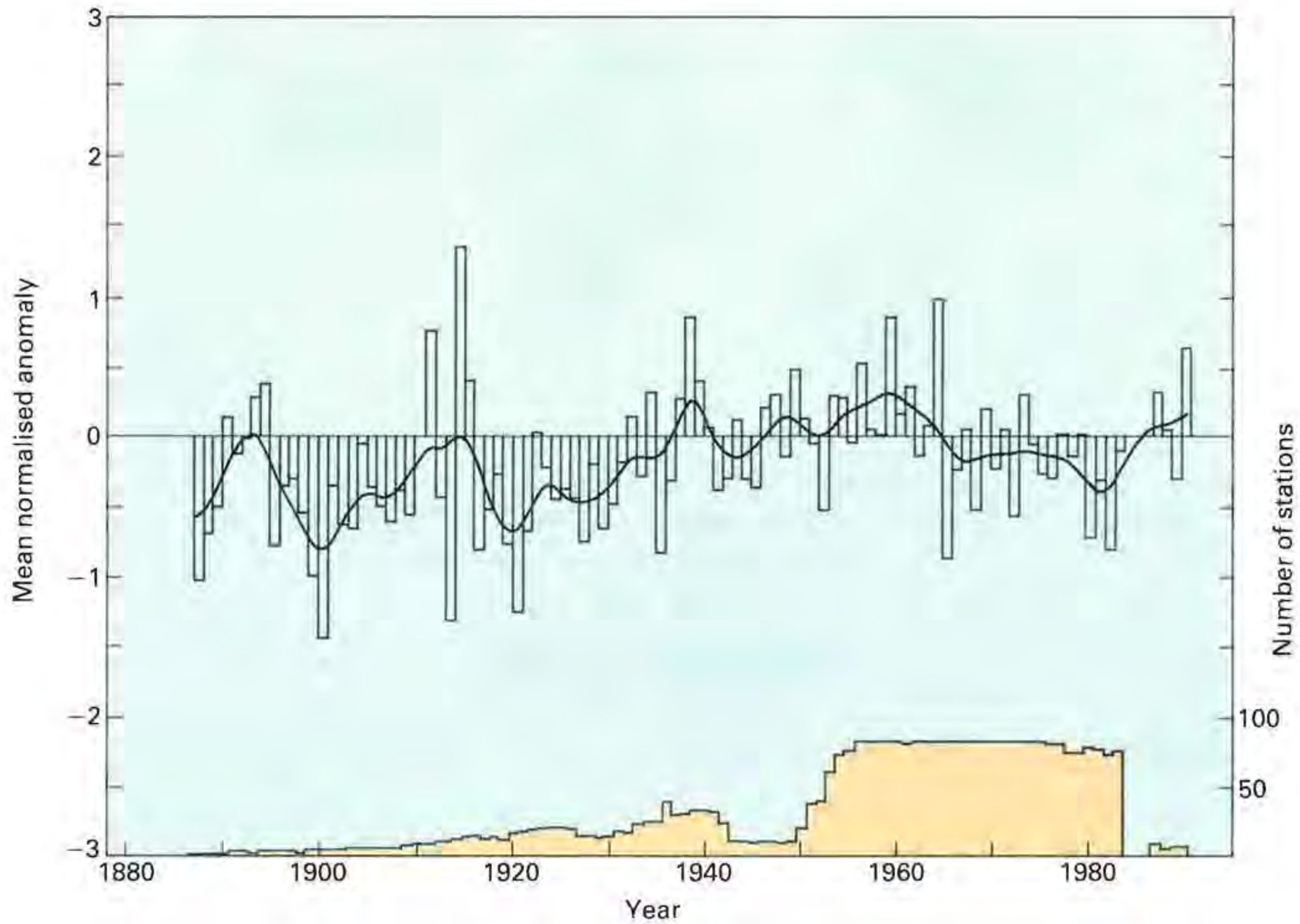


Figure 3 Time series of annual rainfall – North China (1887–1990)

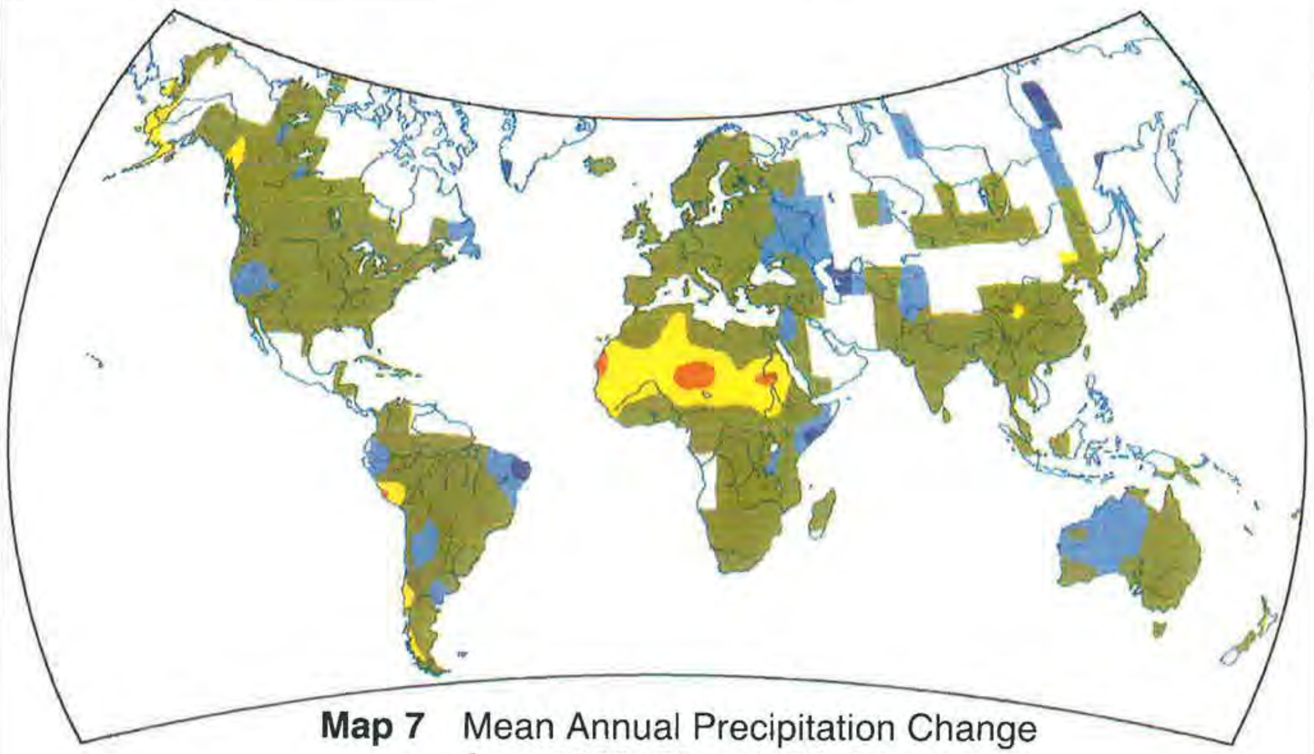
Changes in Climatic Surfaces 1930–1959 to 1960–1989

Maps 7, 8 and 9 give a spatial perspective on the climatic variability of drylands. These maps show change in global climatic surfaces between two thirty-year periods, 1930–1959 and 1960–1989, for precipitation, temperature and the Aridity Index as outlined on page 5.

The rainfall graphs for the Sahel and northeastern Brazil are confirmed in Map 7 which shows that these regions have been drier and wetter respectively during the second, most recent period. Most of the Sahel west of Ethiopia has been considerably drier, with annual precipitation declining by between 10% and 30%. In southern Somalia, by contrast, an area where climate is dictated by a largely separate set of influences, annual precipitation has been greater by more than 30% in recent decades. A similar story is illustrated for northeastern Brazil and for the Middle Asian region of the former USSR east of the Caspian Sea. Much of central and western Australia and parts of the drylands of the American southwest have experienced precipitation between 10% and 30% greater than the first thirty-year period. Other dryland areas in southern Africa and north China received roughly similar annual precipitation totals during the two periods.

Map 8 shows mean annual temperature changes between the two thirty-year periods, and indicates a number of dryland areas where temperatures have been significantly different. The region of northeastern Tibet and the eastern portion of the Kunlun Mountains were between 0.5°C and 1.0°C colder, while much of the Middle Asian Republics of the former USSR were between 0.5°C and 1.0°C warmer. The global mean temperature change between the two periods, derived from the data set used to produce Map 8, is very small: 1960–1989 being 0.07°C warmer than 1930–1959. Figure 4 implies a slightly greater temperature difference between the two periods, but this is due to the larger size of the data set used for Figure 4.

Map 9, which shows changes in Aridity Index values, indicates the composite picture of differences in precipitation and temperature in terms of moisture availability. The most striking area of relative moisture deficiency is the Sahel from Ethiopia westwards and parts of the Maghreb. Southern African drylands are also moisture deficient since although precipitation was little changed, temperatures were slightly greater (see Map 8). Areas such as northern Mexico, by contrast, where precipitation inputs were little changed but temperatures were slightly colder, experienced greater moisture availability, as did northeastern Brazil due to greater precipitation and slightly cooler temperature.



Map 7 Mean Annual Precipitation Change from 1930–59 to 1960–89

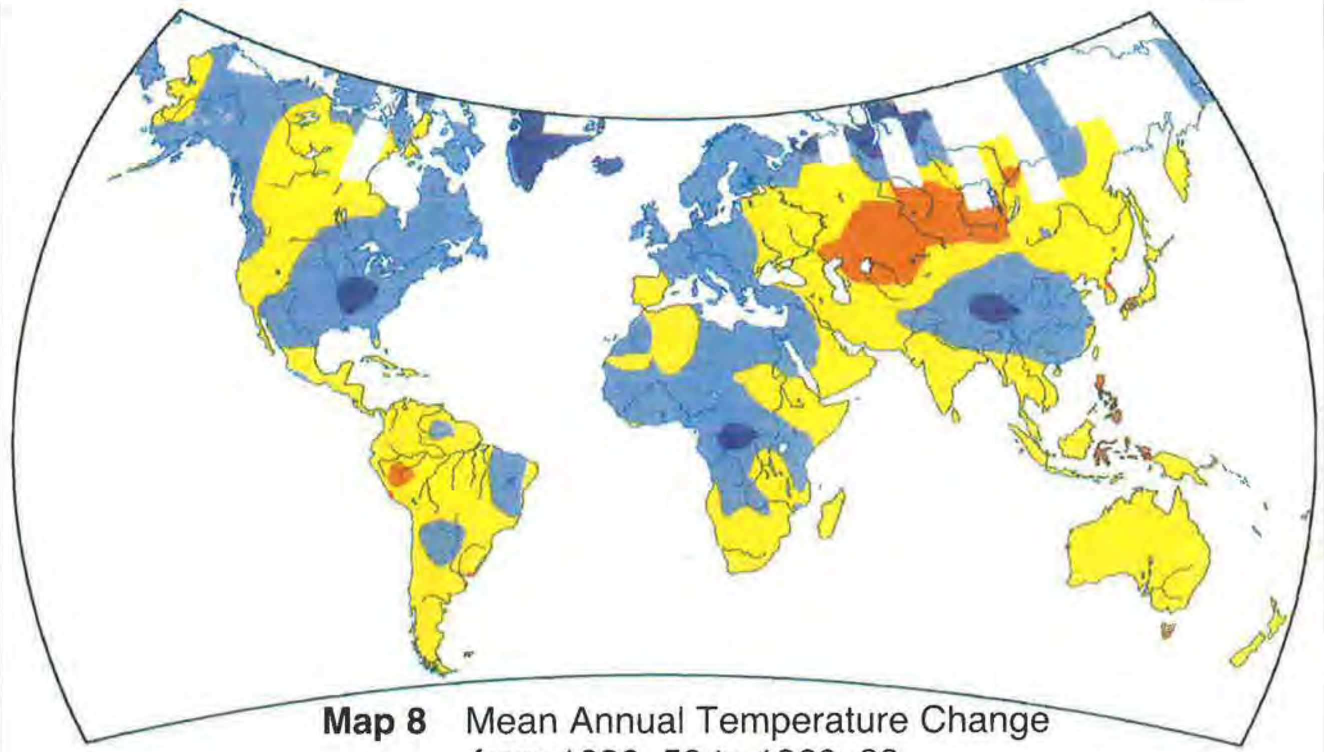
Percent

−30 −10 +10 +30

No data available

Source: CRU/UEA

Approximate equatorial scale 1:235 million



Map 8 Mean Annual Temperature Change from 1930–59 to 1960–89

Degrees Celsius

−1 0.5 0 +0.5 +1.0

No data available

Source: CRU/UEA

Approximate equatorial scale 1:235 million

Our ability to predict what dryland climates will do in the future is at present limited. Meteorological forecasting in the tropics is only possible two to three days in advance, compared to seven to ten days in temperate latitudes. Attempts to forecast regional climates within a year, from season to season, are being worked on with some limited success. On the longer timescale of decades, however, it is not yet possible to produce objective predictions of future regional climates anywhere in the world. In addition to the problems of predicting natural climatic variability, there is the very real possibility that regional climates may be significantly changed as a result of increasing levels of carbon dioxide and other greenhouse gases in the atmosphere. Figure 4 indicates the phenomenon of global warming for the two hemispheres and the whole globe. While not all climatologists are convinced that the warming trends in these graphs can be conclusively attributed to human activities, the implications for dryland climates should this trend continue are great. Computer simulations from Global Circulation Models for Sahelian climate in a "warmer world", for example, disagree, some suggesting a drier climate, others a wetter one.

Whatever the affects of global warming on the regional climates of drylands, many scientists are now arguing that the anthropogenic impact can no longer be ignored as a new input to the global and regional climate systems, the resulting changes of which will also have to be incorporated into future efforts to ameliorate the problems of land degradation/desertification in the world's drylands.

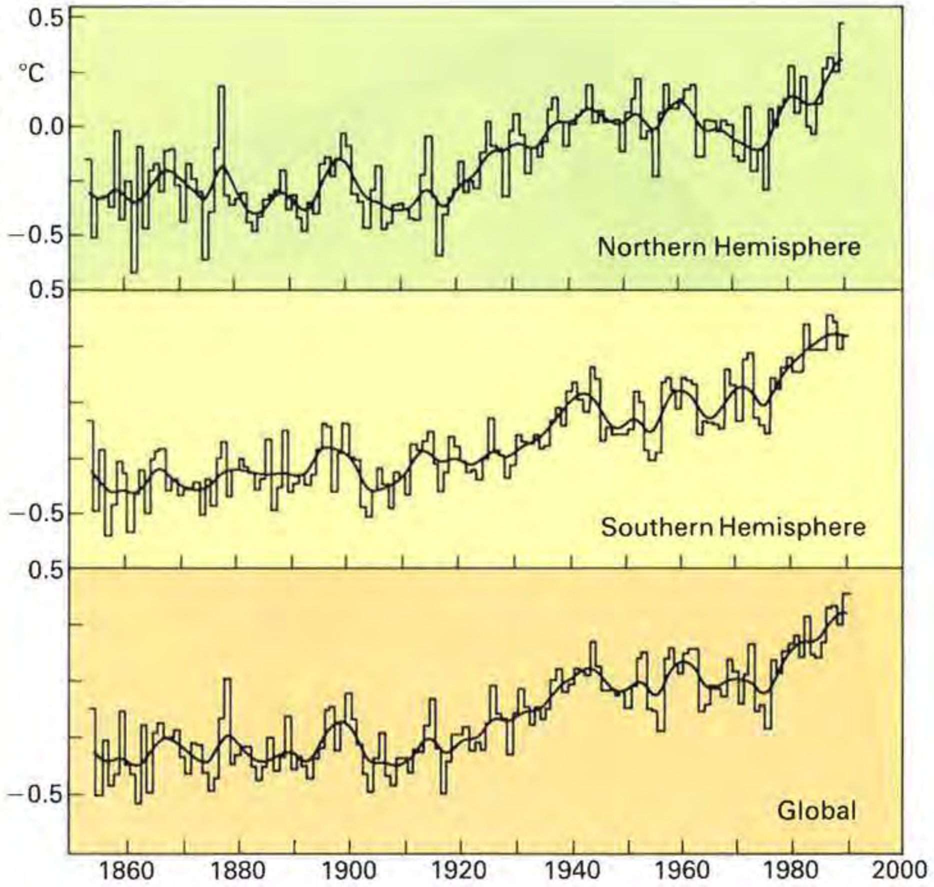
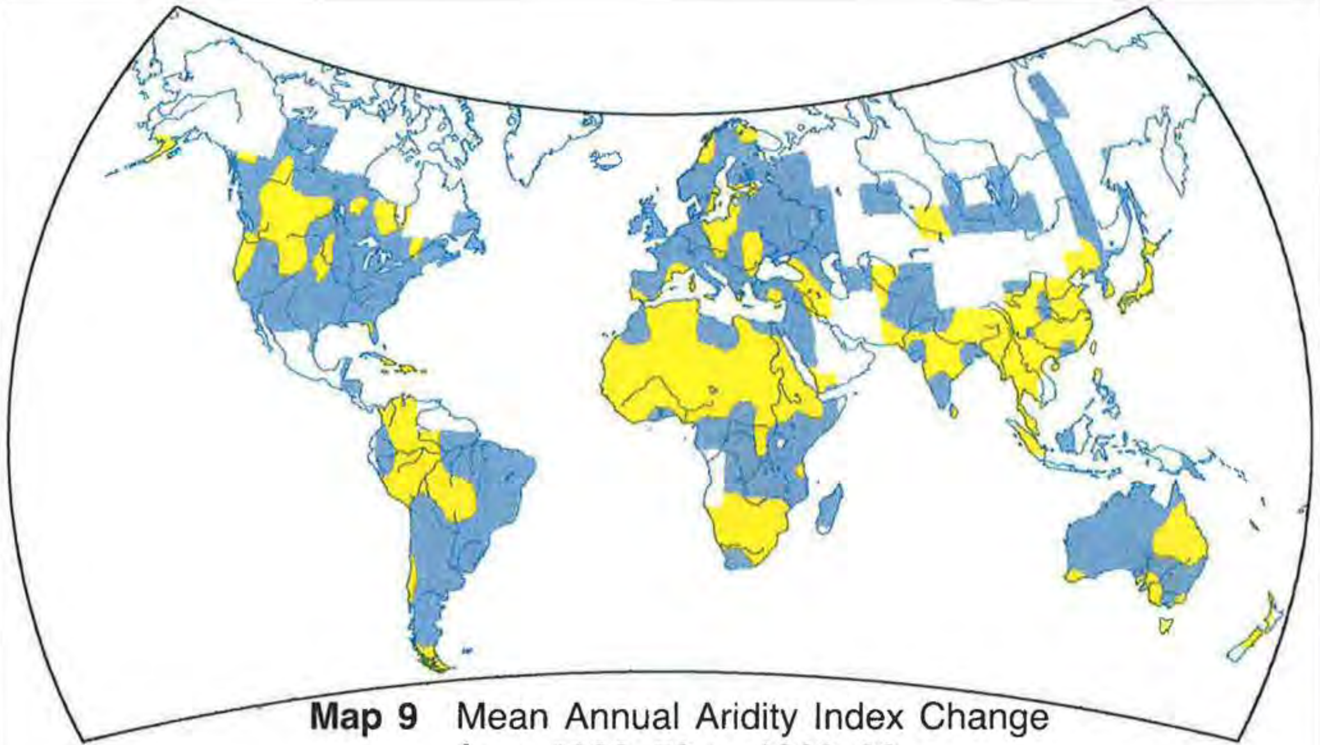


Figure 4 Hemisphere and global warming trends



Map 9 Mean Annual Aridity Index Change from 1930–59 to 1960–89

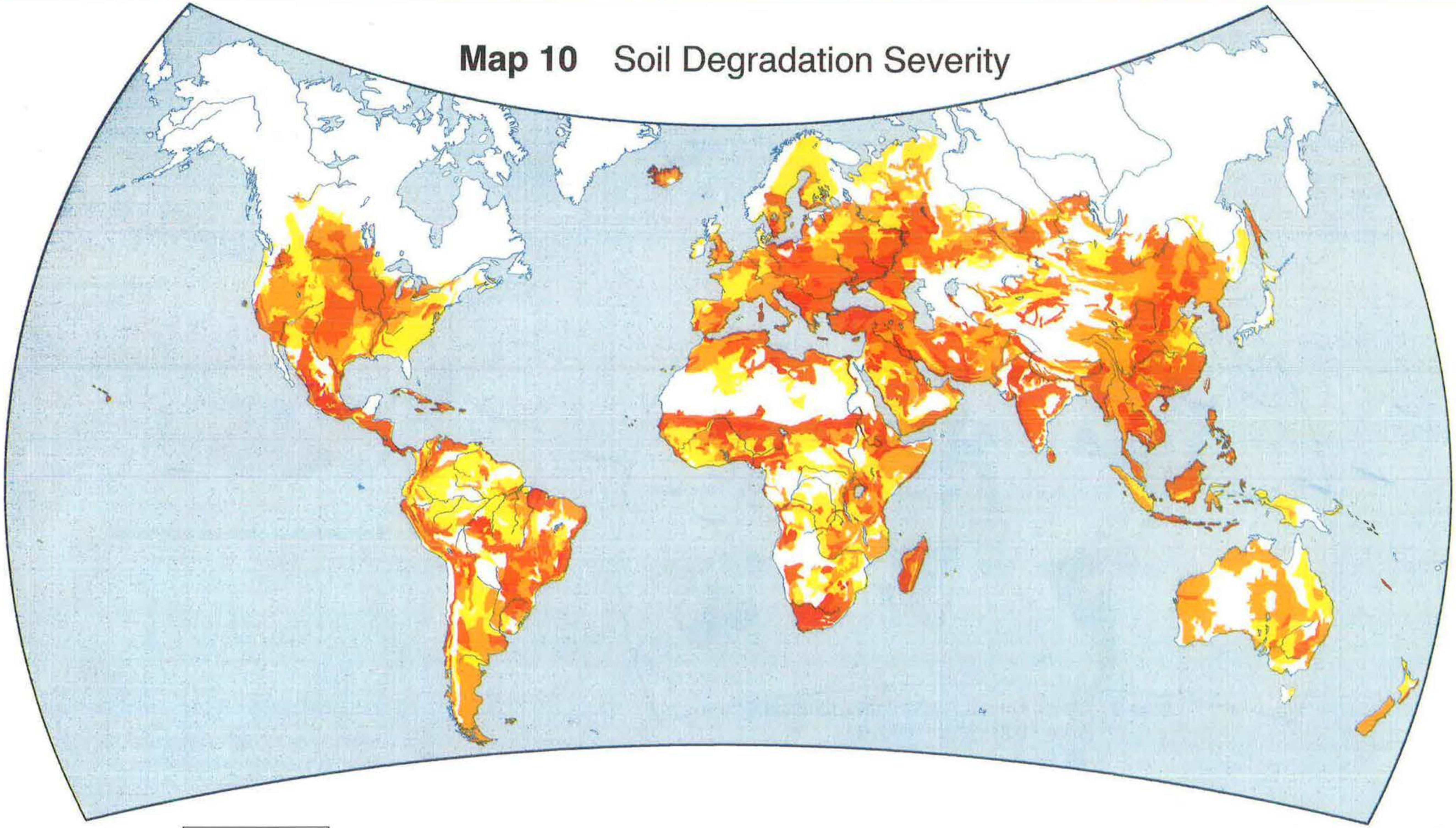
- Increase in moisture availability
- Decrease in moisture availability
- No data available

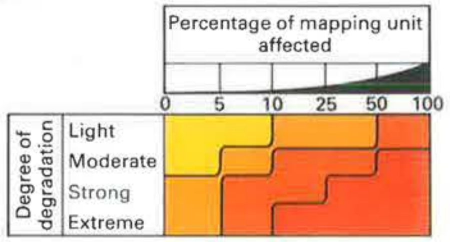
Source: CRU/UEA

Approximate equatorial scale 1:235 million

SOIL DEGRADATION

Map 10 Soil Degradation Severity





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

Source: UNEP/ISRIC

Approximate equatorial scale 1:115 million

Introduction

The map of soil degradation severity (Map 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 categories of human-induced soil degradation processes are recognized. 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. 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.

Map 10 shows the severity of human-induced soil degradation on the global scale. Soil degradation is assessed over the recent past, averaged over the last five or ten years. Although GLASOD specifically deals with human-induced soil degradation by the processes noted above, and not natural degradation by these processes, it is necessary to emphasize the difficulties that may be involved in distinguishing between human- and naturally-induced degradation processes. 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 naturally enhanced soil erosion and that due to human activities will inevitably be subjective to some degree.

Areas that are non-degraded are either "stable" or are being degraded by natural processes, unaffected by human actions. Stable regions may be those where human intervention is minimal due to very low population densities, or regions where soil improvement or protection programmes have been successfully implemented. Some of the areas with very low population densities may be of little value for human use. Many of these zones are in hyperarid areas, such as the central Sahara and parts of Arabia.

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 declined 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 waterlogged 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 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 to 10% of the unit is affected.
Frequent: 11 to 25% of the unit is affected.
Very frequent: 26 to 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, twenty combinations are possible. These combinations have been grouped into four severity classes as illustrated opposite. Each severity class is given a different shading on Map 10.

Interpreting the Maps and Tables

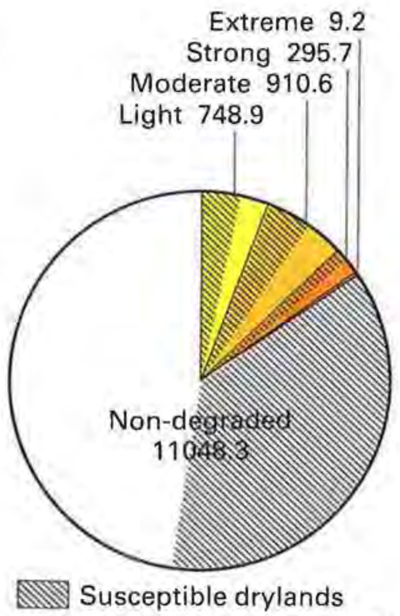
The maps on the following pages indicate the areas in which degradation occurs and the severity of that degradation according to the accompanying key. The tables, however, provide a more detailed indication of the actual areas within units affected. It is important to note that while the maps indicate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

Table 2 shows that just over one billion hectares, or approximately 20%, of the global extent of susceptible dryland soils are currently being degraded by human activity. The pie chart indicates that in the light, moderate and extreme categories more land area in susceptible drylands is being degraded than in non-dryland regions ("Others" in Table 2).

At the continental level a greater proportion of Europe's susceptible dryland soils suffer from degradation (33% of the total area) than in any other continent. These degraded soils occur in Spain, Sicily, Greece and in the former USSR. In North America, by contrast, 11% of susceptible dryland soils are degraded. Africa, with 25% of its susceptible drylands affected by soil degradation, has the highest proportion of its susceptible dryland soils affected by strong and extreme severity, while Australia's 13% affected area is very largely in the light severity category.

Table 2 Soil degradation degree by region: inside the drylands (susceptible) and outside the drylands (others) areas (millions of hectares)

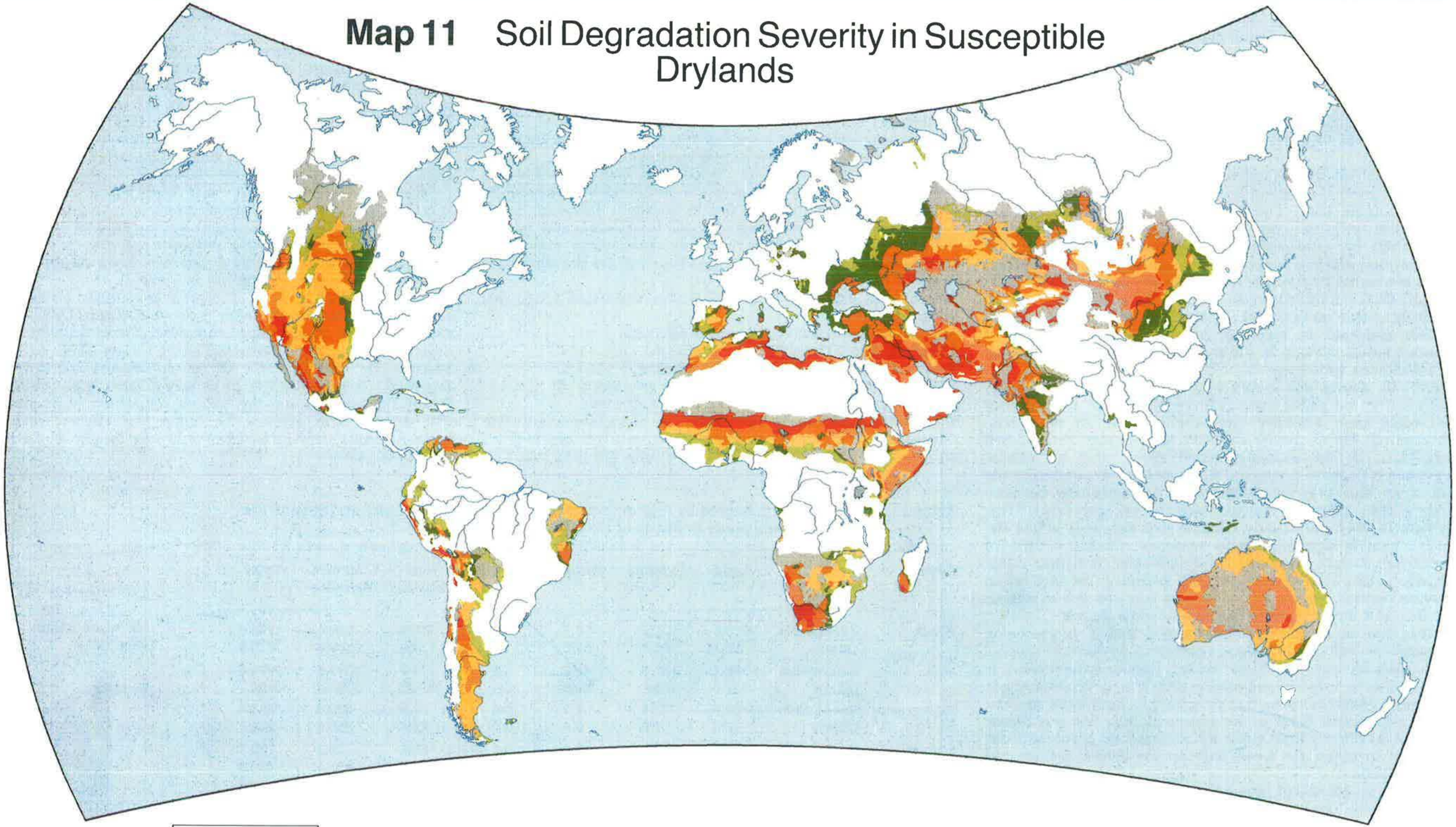
Region		Light	Moderate	Strong	Extreme	Total Degraded	Total Non-Degraded	Total
Africa	Susceptible	118.0	127.2	70.7	3.5	319.4	966.6	1286.0
	Others	55.7	64.6	52.8	1.7	174.8	1504.8	1679.6
Asia	Susceptible	156.7	170.1	43.0	0.5	370.3	1301.5	1671.8
	Others	137.8	174.2	64.6	0.0	376.6	2207.6	2584.2
Australasia	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 America	Susceptible	13.4	58.8	7.3	0.0	79.5	652.9	732.4
	Others	5.5	53.7	19.5	0.0	78.7	1379.8	1458.5
South America	Susceptible	41.8	31.1	6.2	0.0	79.1	436.9	516.0
	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	11048.3	13012.7

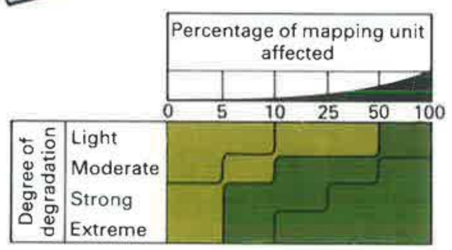


Global land area by degree of soil degradation (millions of hectares)

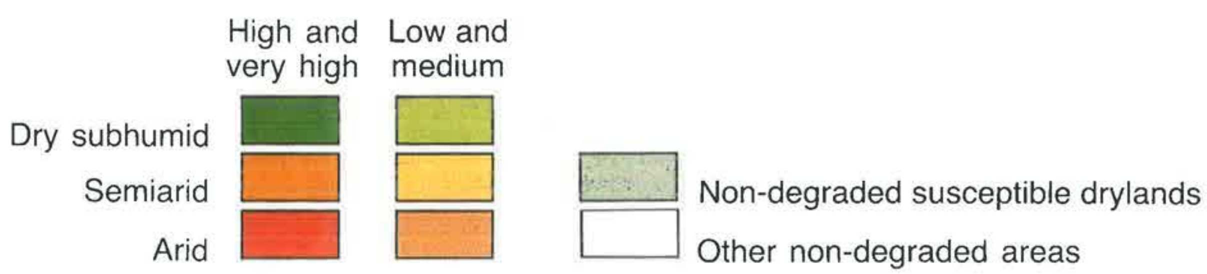
SOIL DEGRADATION IN DRYLANDS

Map 11 Soil Degradation Severity in Susceptible Drylands





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



Approximate equatorial scale 1:115 million

Source: UNEP/ISRIC, CRU/UEA

Introduction

This atlas concentrates on arid, semiarid and dry subhumid areas, of 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; and they offer only limited opportunities for degradation-inducing human land uses. An exception to this, the Nile Valley, is discussed in more detail in the continental Africa section. Map 11 therefore concentrates on areas where natural soil properties are susceptible to degradation and where land use activities may trigger this damage. Such areas are termed the susceptible drylands.

Soil Degradation in Drylands

An important characteristic that makes dryland soils specially 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 at low speeds. Salts, once accumulated, tend to remain *in situ*. The build-up of organic matter, which is usually consumed at high speed under warm conditions, takes a long time, and moisture deficiency discourages recolonization by plants that have been removed or damaged. Hence the ability of soils in dry areas to recover from negative changes in the soil/land surface is 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. Susceptibility to wind erosion, once a 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 resistance to deflation than silty or sandy soils because of particle cohesion. With mixed grain sizes, selective winnowing of the deflatable component can dramatically reduce soil fertility and resilience. In southern Africa, the Sahel belt, central and eastern Asia and Australia, extensive areas of ancient wind-lain sediments in drylands are particularly vulnerable to deflation following damage to the protective vegetation cover.

Topography affects susceptibility to water erosion. High relative relief, for example in the Ethiopian Highlands, 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 usually manifests itself in scattered patches through rilling and gullying. 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. Other characteristics such as salinization occur 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. Overall therefore, susceptibility to degradation, in total or with regard to specific processes, is by no means even throughout the drylands, reflecting a range of natural antecedent conditions.

Spatial Patterns

Some 1035 million hectares of the world's susceptible drylands are affected by soil degradation, of which about 90% are in the light and moderate categories. The distribution by continent and by aridity zone is given in Table 3. 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. When considered in terms of the total dryland area, soil degradation affects some 320 million hectares in Africa out of a total of 1286 million, or about a quarter of the drylands. A similar proportion is affected in Asia but in Europe, some 99 million out of 300 million dryland hectares, or a third, are degraded to some degree. Just over 10% of North American drylands, 15% of those in South America and 13% in Australasia are affected.

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. This is probably a consequence of two main factors. Human populations are generally higher in such areas than in the core of drylands, because of the greater resource base. Additionally, such areas are likely to experience the expansion of agricultural practices from neighbouring humid areas, the nature and intensity of which will increase the vulnerability to degradation. The level of overall severity is consistently lower in Australasia, a probable result of the dominance of low intensity agricultural practices in dryland areas.

Relative Importance of Different Degradation Types

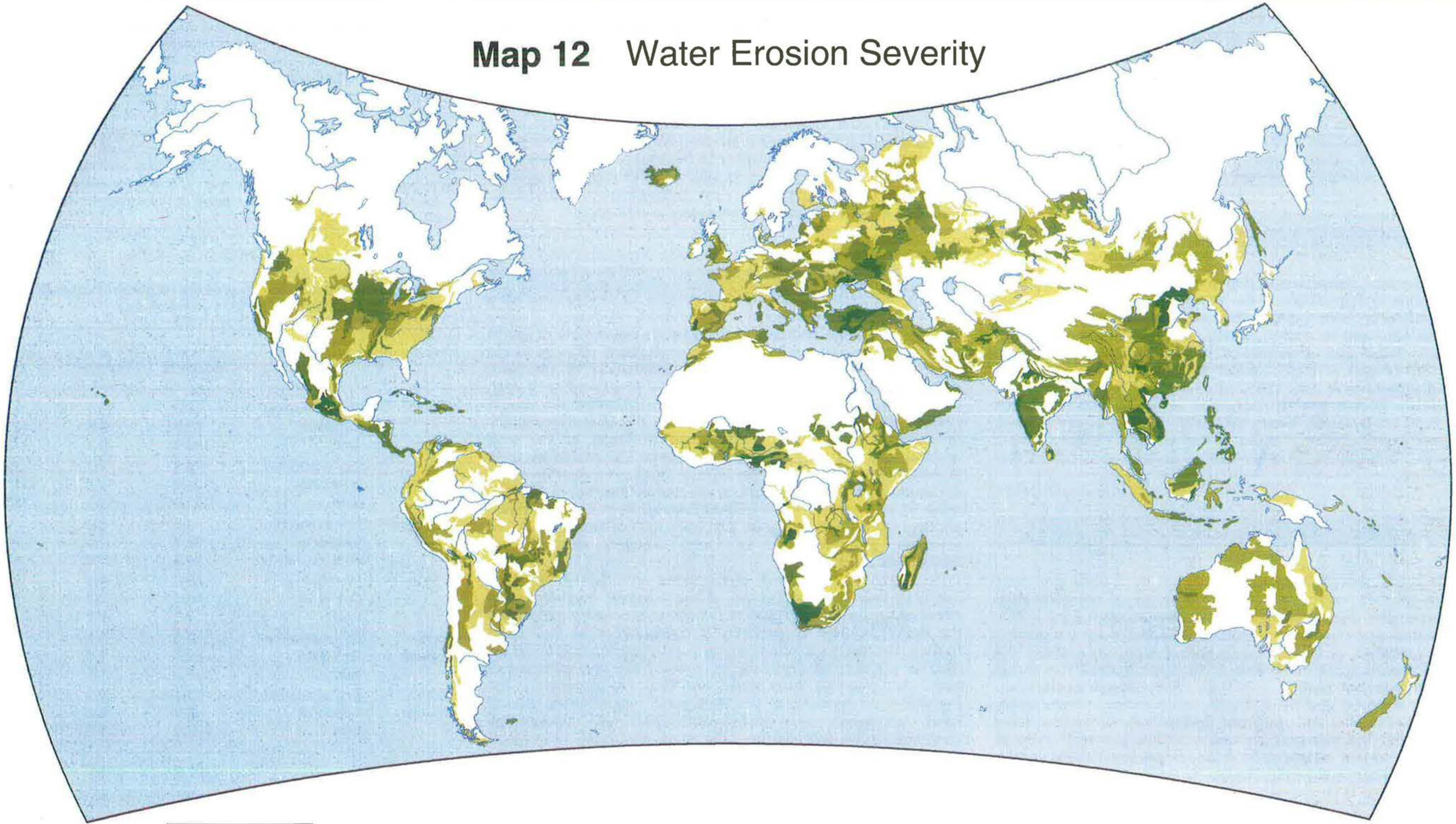
At the world scale, the GLASOD database indicates that dryland degradation is dominated by water (48%) and wind (39%) erosion. Chemical deterioration accounts for 10% and physical deterioration just 4%. This situation however varies according to bioclimatic zone. Given likely variations in vegetation cover, it is not surprising that 60% of soil degradation in arid zones is by wind erosion, 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 more susceptible, accounting for 63% of dry subhumid degradation but 29% of that in arid areas. These and other trends are explored in greater detail in the analyses of different degradation types at the global scale.

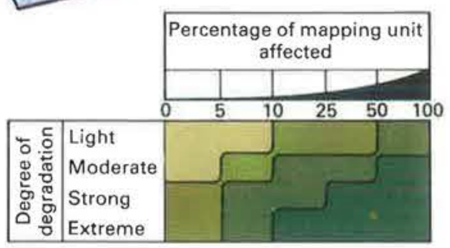
Table 3 Soil degradation degree by region in susceptible dryland areas (millions of hectares)

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	133.7	1035.2

WATER EROSION

Map 12 Water Erosion Severity





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

Source: UNEP/ISRIC
Approximate equatorial scale 1:115 million

Introduction

The spatial and temporal limitations of dryland rainfall events do not discount the significance of erosion by water. In drylands limited natural vegetation covers, relatively thin soils and high rainfall intensities all promote runoff during precipitation events and therefore erosion. By reducing natural plant densities, replacing a perennial plant cover with a seasonal crop, ploughing steep slopes and causing surface compaction by livestock trampling or the use of mechanized farming implements, human actions can readily lead to accelerated water erosion in drylands.

Methodology

The definitions and criteria used by GLASOD for the designation and identification of water erosion are as follows:
Light: for soils with a rooting depth exceeding 50 cm, part of the topsoil 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 topsoil will have been removed from deep soils. Rills may be present, less than 20 m apart. Gully development will have occurred at a spacing of 20–50 m. Thin soils will have lost part of the topsoil and are likely to have rills with a 20–50 m spacing. Perennial/original/optimal vegetation cover in pastoral areas reduced to 30–70%.
Strong: all the topsoil 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 topsoil 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.

The map shows land units in which human-induced water erosion occurs. It 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.

Nature of Dryland Water Erosion

A soil is commonly unable to absorb all the energy and mass provided by raindrops hitting the ground surface. A plant cover will act as an interceptor, reducing direct drop impact on the soil surface and reducing the energy available for erosion. Bare or partially exposed soils are vulnerable to the dislodgement of individual particles by drop impact (splash erosion), and the subsequent generation of overland flow which transports the particles down slope. The ability of a soil to absorb raindrop energy is therefore dependent on antecedent environmental conditions and the nature of the rainfall event.

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. Sandy soils have a relatively large pore space and therefore a greater infiltration capacity than silty soils. Clay rich soils have a tendency to form clods and are also susceptible to surface sealing. Together with their low pore space, this makes them susceptible to rapid overland flow generation. The depth of a soil also influences its ability to absorb and store rainfall, 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 attain higher velocities than in non-dryland areas.

Processes of Water Erosion

Water erosion means not only increased loss of topsoil but also of water and nutrient storage capacity. It has downstream effects of flooding, siltation and eutrophication, but river erosion and sedimentation are not covered here. Apart from river erosion, water erosion takes various forms, designated as follows:
Sheetwash or inter-rill 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 drop impact and normally affects the upper parts of hillslopes. Where sheetwash operates across an entire slope it can lead to the reduction in fertility in upslope locations and a corresponding increase at the slope foot. Plant productivity can mirror this pattern. Sheetwash can be difficult to monitor and therefore may be underestimated.
Rilling: results from the concentration of overland flow. 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. They can however 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.
Gullying: caused by the widening and deepening of rills, or by a change in surface conditions on a slope leading to a sudden increase in runoff. 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 mechanized farming methods.
Piping: is erosion through the development of subsurface tunnels. This can occur naturally, particularly in certain types of susceptible soils, but it is readily enhanced by a reduction in surface vegetation and a loss of internal binding by roots.

Dryland Water Erosion Assessment

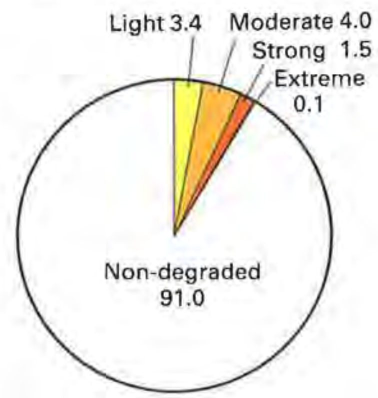
GLASOD data indicate that human-induced water erosion affects about 140 million hectares in dry subhumid areas, 213 million in semiarid areas and 113 million in arid areas. It even affects 11 million hectares in the hyperarid zone. Translated to percentages of the total land area by aridity zones, this 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 and degree of severity (see Table 4).

Only European and African susceptible drylands contain areas that have experienced extreme water erosion, affecting more than 2 million hectares in each case. In Europe, this especially affects Murcia in southeast Spain, where water erosion severity is very high under both traditional vine and almond stands and more intensive land use.

When overall severity is considered, water erosion is a particular degradation problem in parts of Africa's Sahel belt, throughout the drylands of South Africa, in Spain and in China. In many cases, this can be attributed to the inappropriate use and intensification of agricultural practices on steep slopes, as in the Loess Plateau area of China, the northern Ethiopian Highlands, the Adamawa Highlands of Cameroon. 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 what has been described by some experts as irreversible erosion damage.

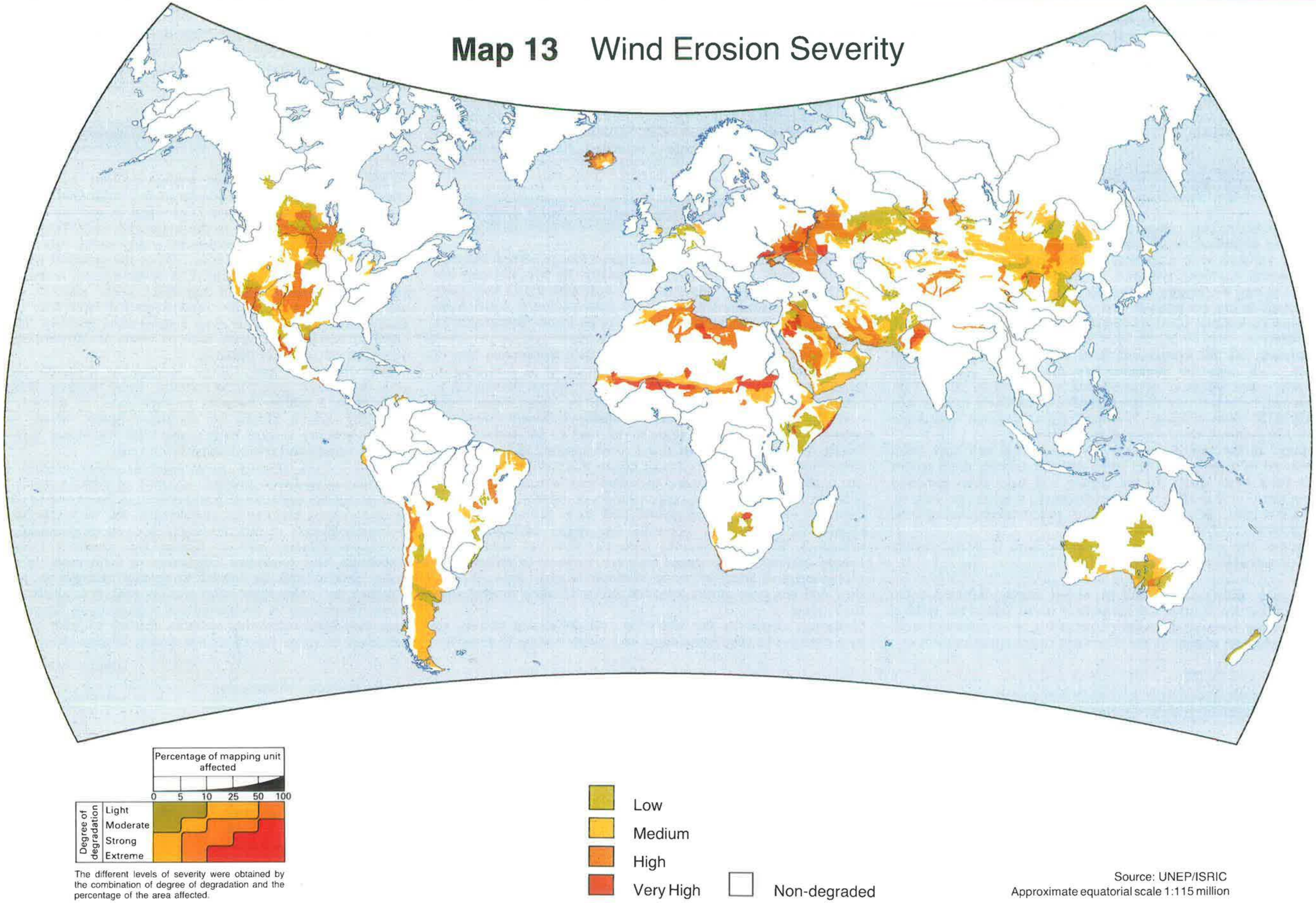
Table 4 Degree of water erosion by region in susceptible dryland areas (millions of hectares)

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



Global susceptible drylands degraded by water erosion (%)

WIND EROSION



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

Source: UNEP/ISRIC
Approximate equatorial scale 1:115 million

Introduction

The movement of soil particles by wind occurs naturally in many environments. It is most pronounced and presents the most serious problems, however, in the world's drylands due to their normally sparse vegetative cover and low erratic rainfall.

Methodology

Wind erosion, one of the two soil degradation processes involving the displacement of soil material covered by GLASOD, has been subdivided into three effects. These are: a 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.

The guidelines followed in the compilation of the GLASOD data describe the following criteria for designating the degree of wind erosion:

Light: in deep soils: topsoil partly removed 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 country: groundcover of perennials of the original/ optimal vegetation from 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. It 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.

Nature of Wind Erosion

When and where wind erosion occurs depends upon the mutual interaction between the ability of the wind to entrain particles, its "erosivity", and the susceptibility of the soil surface to movement, its "erodibility".

A wind's erosivity is determined by such factors as its speed, turbulence, frequency, duration and direction. The erodibility of a soil surface is determined by the properties of the soil itself, such as particle size, cohesive properties, moisture content and organic matter, and the state of variables that protect the soil surface. Important 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.

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, the most important aeolian process in soil degradation, preferentially removes the finest particles. 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, clay and organics has deleterious 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. The fine silt and clay particles also have the maximum concentration of nutrients attached to them, so that their removal therefore 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. Structures such as walls, telegraph poles and fences can also be affected. Large volumes of eroded material in dust clouds present visibility problems to road and air transport, and can adversely affect radio and satellite communications. The inhalation of fine particles, some of which may be disease-carrying pathogens, can create hazards for human and animal health.

Material deposited by wind can bury and kill plants, fill ditches and block roads, runways and pipelines. 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.

Table 5 Degree of wind erosion by region in susceptible dryland areas (millions of hectares)

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

Dryland Wind Erosion Assessment

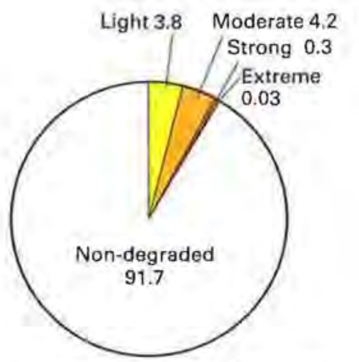
The map opposite clearly indicates that human-induced wind erosion is very largely confined to the world's drylands. Some regions immediately become apparent as suffering from a particularly acute wind erosion problem. These are the Sahel, the Maghreb, a broad belt of land stretching from the northern shores of the Black Sea to the north of the Caspian Sea, Mongolia, China, Mesopotamia and parts of the Levant, and the Thar Desert in India. 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 localized situations.

On the global scale, human-induced wind erosion affects 430 million hectares, or 8% of the susceptible dryland area. In terms of the total degraded area of susceptible drylands, wind erosion is an important degradation process on 42% of the area.

In absolute terms, wind erosion problems are most extensive in Africa and Asia, both showing areas in excess of 150 million hectares affected (see Table 5). The 16 million hectares affected in Australia are located in three zones, in Western Australia, South Australia and Northern Territory. In South America the 27 million hectares affected are largely to be found in the Argentinian regions of the Pampas and Patagonia.

The human activities most commonly responsible for inducing wind erosion are those that change or remove vegetation cover and those that destabilize 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 manoeuvres.

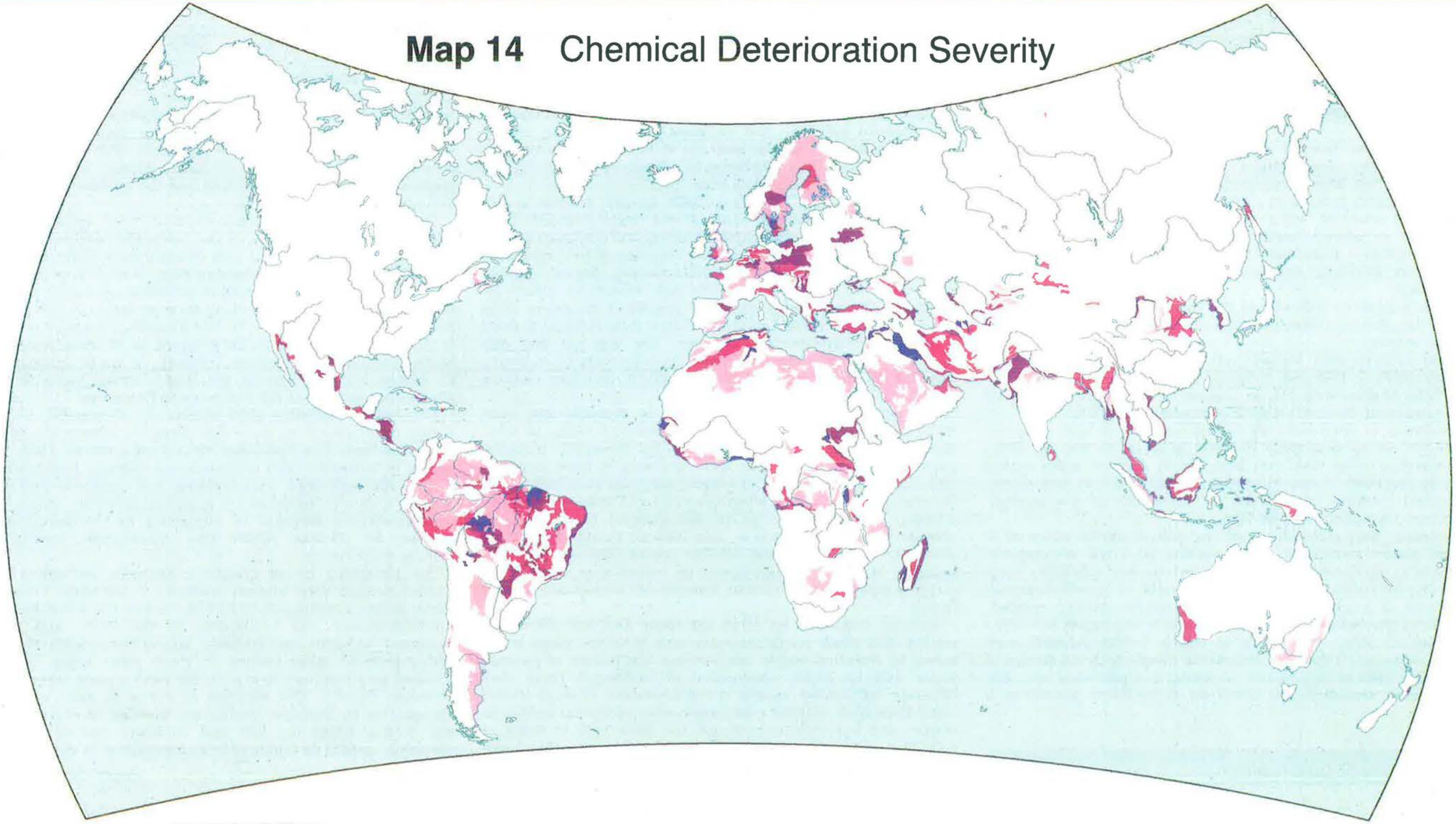
The ploughing up of grassland for grain cultivation has created massive wind erosion problems in the Great Plains of North America, notably in the 1930s, and in the wheat belts of southern Russia and Kazakhstan in the 1950s, and these continued activities are probably largely responsible for the human-induced wind erosion in these areas today. Similar activities go a long way to explain the wind erosion areas of the Canadian Prairies. The situation in Africa is more complex. Overgrazing by livestock, excessive cultivation of dryland soils and cutting wood for fuel and extensive use of fire are commonly quoted as causes of land degradation in the Sahel for example.

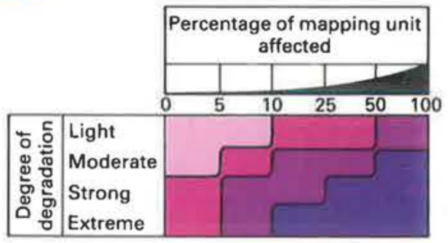


Global susceptible drylands degraded by wind erosion (%)

CHEMICAL DETERIORATION

Map 14 Chemical Deterioration Severity





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

Source: UNEP/ISRIC

Approximate equatorial scale 1:115 million

Introduction

The potential for chemical deterioration is likely to increase in situations where land use methods become more intensive and in some cases reliant on the addition of artificial fertilizers and particularly irrigation water. It is thus a problem that is unlikely to be of major significance throughout the drylands but rather one that can hit specific localities particularly hard. Such localities may also be in hyperarid regions, such as in desert oases and in the Nile Valley.

GLASOD methodology recognizes several processes in the chemical deterioration category: salinization, nutrient and organic matter loss, acidification and pollution. The explanation below concentrates on those mechanisms particularly important in drylands, although the map opposite makes no distinction according to process.

Nutrient Depletion

Soil nutrient depletion is a further component of chemical degradation relevant to some dryland locations. It can occur through over-cultivation and the inadequate application of replacement nutrients. This can also occur with natural vegetation clearance, burning in savanna areas of poor soils, where much of the nutrient store is held in natural vegetation rather than the soil. It also occurs 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 water erosion, where increased runoff removes nutrients in solution or to wind erosion.

Salinization

High evaporation rates 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 due to excessive salt concentration, causing an inability to take up the moisture necessary for their growth. The salinization problem also embraces alkalization, the excess accumulation of sodium, which rises in association with the dissolved salt load of irrigation water.

Though there are extensive areas of natural salt-affected soils, salinization is a problem when human activities cause soil salinity to rise significantly. 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 about 8 million hectares in 1800 to over 250 million today according to the FAO, much of it in drylands, creating an enormous potential for the problem.

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 mobilizes 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. 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. Here, the distinction between evapotranspiration by plants and evaporation from the soil surface is important.

Methodology

The degree of salinization has been taken as the relative change in the status of soil salinity over the last fifty years. Salinity can be measured in terms of electrical conductivity. Four classes of salinity, ranging from non-saline, slightly saline, moderately saline and severely saline have been defined in the international literature.

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

Light salinization is a change of one class (eg. from slightly to moderately saline), Moderate salinization is a change of two classes (eg. from non-saline to moderately saline), Severe salinization is a change of three classes (eg. from non-saline to severely saline), Extreme salinization is a change from non-saline to totally unproductive conditions.

Dryland Chemical Deterioration Assessment

The GLASOD study indicates that in the susceptible drylands, 23 million hectares in the dry subhumid zone are affected, 41 million in semiarid areas and 37 million in arid areas, with an additional 11 million hectares in the hyperarid zone. In percentage terms, 22% of semiarid areas, 2% of dry subhumid and arid areas and 1% in the hyperarid zone are affected. Map 14 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.

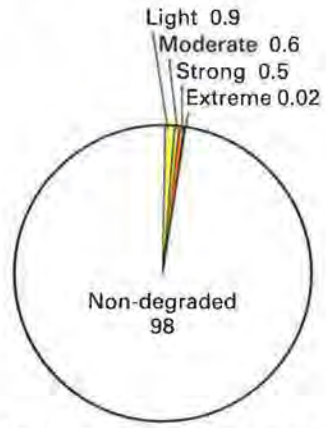
The map opposite indicates that very high severity chemical deterioration in the susceptible drylands occurs as pockets in Senegal and Sudan in Africa, in Iraq and Syria in the Middle East and in the Republics of Soviet Middle Asia. The Aral Sea Basin and the Euphrates valley are particularly affected. In Syria, it has been estimated that about half the irrigated lands are so severely salinized that crop production is substantially reduced. 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. 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.

Chemical deterioration reaches high severity status in many areas. UNEP-DC/PAC 1990 statistics indicate that irrigation supports nearly 75% of Pakistan's cropland, but the Indus Basin is now badly affected by salinization. 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 sediment, has deprived locations downstream of nutrient replenishment from river silt.

Chemical deterioration is not restricted to developing countries. The lower Colorado River, southwestern 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 has generated its own set of problems. The severity of soil degradation through chemical deterioration also reaches a moderate degree in part of western Australia. The Murray River catchment, near Perth, has undergone clearance of natural perennial vegetation and replacement with cereal crops and grazing land, which do not use available moisture leading to surface waterlogging and salt accumulation.

Table 6 Degree of chemical deterioration by region in susceptible dryland areas (millions of hectares)

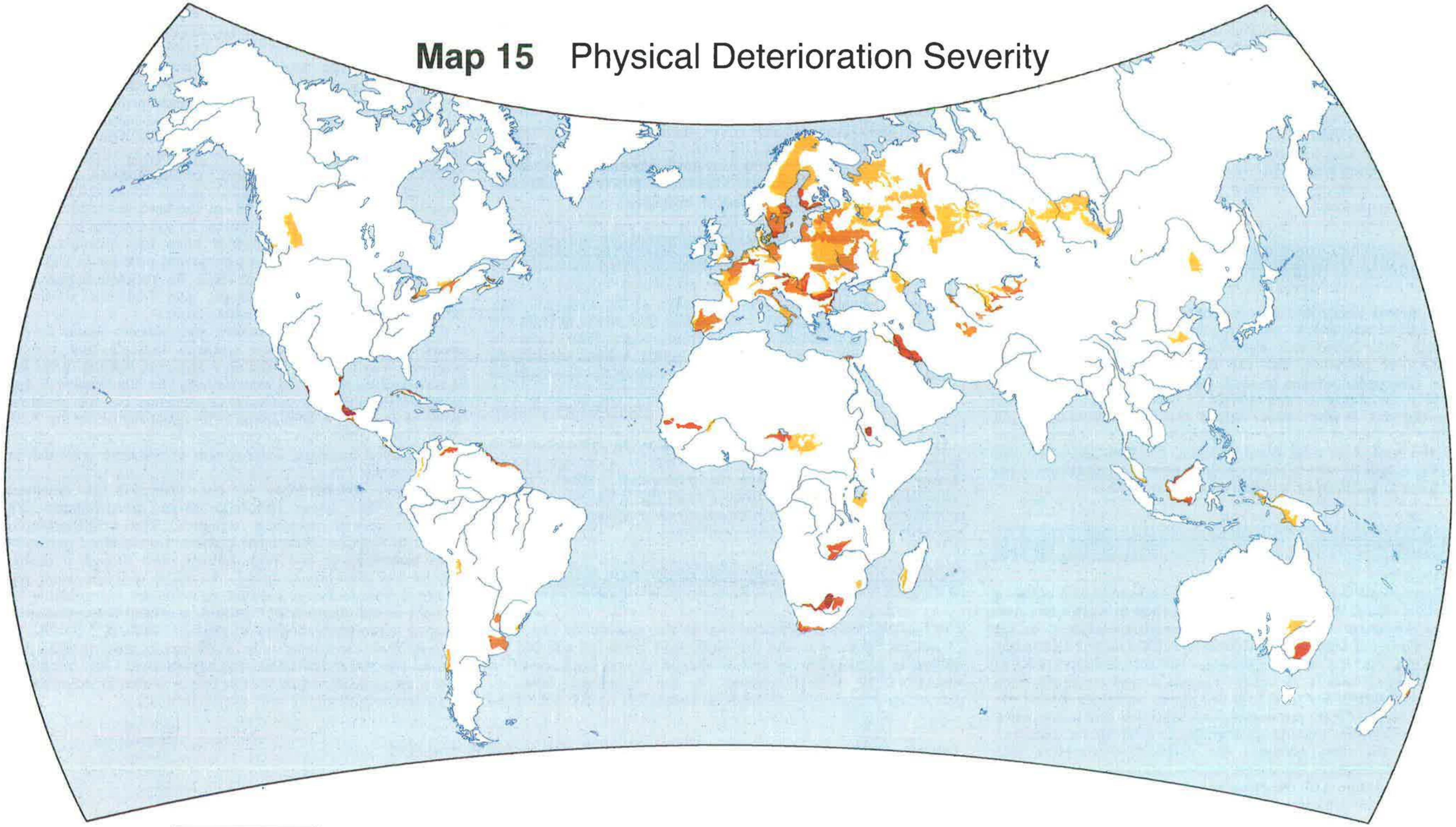
Degree	Africa	Asia	Australasia	Europe	North America	South America	Total
Light	10.2	22.2	0.0	1.5	0.3	10.1	44.3
Moderate	10.4	11.1	0.2	2.2	1.3	6.2	31.4
Strong	5.9	16.5	0.0	0.4	0.6	0.7	24.1
Extreme	0.0	0.4	0.4	0.0	0.0	0.0	0.8
Total	26.5	50.2	0.6	4.1	2.2	17.0	100.6

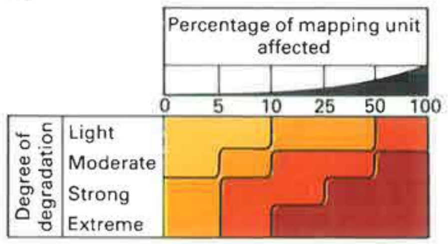


Global susceptible drylands degraded by chemical deterioration (%)

PHYSICAL DETERIORATION

Map 15 Physical Deterioration Severity





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

Source: UNEP/ISRIC
Approximate equatorial scale 1:115 million

Introduction

Six forms of *in situ* soil degradation by physical processes are recognized 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.

Compaction, Sealing and Crusting

The compaction, sealing and crusting of soil surfaces each 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. This effect commonly occurs in areas where vegetation does not adequately protect the soil surface from the impact of raindrops. The sparse vegetation cover may of course be naturally occurring, 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. Oxygen and carbon dioxide exchange between the root zone and the atmosphere is retarded, and a soil's water infiltration capacity is diminished, affecting soil moisture properties and causing increased surface runoff and often higher erosion. It is interesting to note however, that this last-mentioned effect of compaction, increased runoff, is sometimes actually encouraged by local occupants under certain circumstances. Such action is not uncommon in drylands where water is of course a scarce resource. The clearing of surface gravel deposits to expose finer soil beneath to raindrop impact and consequent crusting and sealing is an ancient dryland farming technique designed to enhance runoff which can be channelled to cropland. This practice has been carried out in the Near East for many centuries, whereas today a greater range of compaction techniques using heavy machinery and water-repellant 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 almost impermeable to water and unfavourable to root development.

Waterlogging

Waterlogging includes flooding by river water and submergence by rainwater when caused by human intervention in natural drainage systems. It usually results from over-irrigation and poorly managed irrigation systems and leads to the severe loss of soil air content and accumulation of toxic substances with consequent effects on plant growth. Waterlogging also causes problems of sodication and salinization; the latter is discussed in the chemical deterioration section.

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 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.

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. Peat is often highly productive in the early stages of post-drainage, so that its loss affects fertility. This sequence of events is not common in drylands however. Conversely, in many cases drainage may lead to subsidence but also to an increase in the agricultural potential of the land, in which case it is not shown on Map 15.

Table 7 Degree of physical deterioration by region in susceptible dryland areas (millions of hectares)

Degree	Africa	Asia	Australasia	Europe	North America	South America	Total
Light	1.2	4.4	0.2	4.8	0.2	0.0	10.8
Moderate	6.0	5.0	0.0	3.8	0.0	0.2	15.0
Strong	6.7	0.2	1.0	0.0	0.8	0.2	8.9
Extreme	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	13.9	9.6	1.2	8.6	1.0	0.4	34.7

Dryland Physical Deterioration Assessment

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 hectares, 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 hectares or 1% of the area) and semiarid (15 million hectares or 0.7%) zones, with arid areas experiencing relatively little degradation by physical processes (7 million hectares or 0.4%).

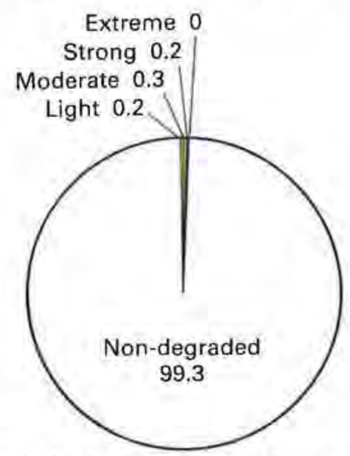
In Africa most of the 14 million hectares affected (see Table 7) are degraded to a moderate or strong degree. These areas are in the Cape region of South Africa and in the central parts of the Sahel around Lake Chad and in the western parts of the Sahel, largely in western Mali and on the Senegal/Mauritania border.

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 hectares 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 Spain and to the west of the Black Sea.

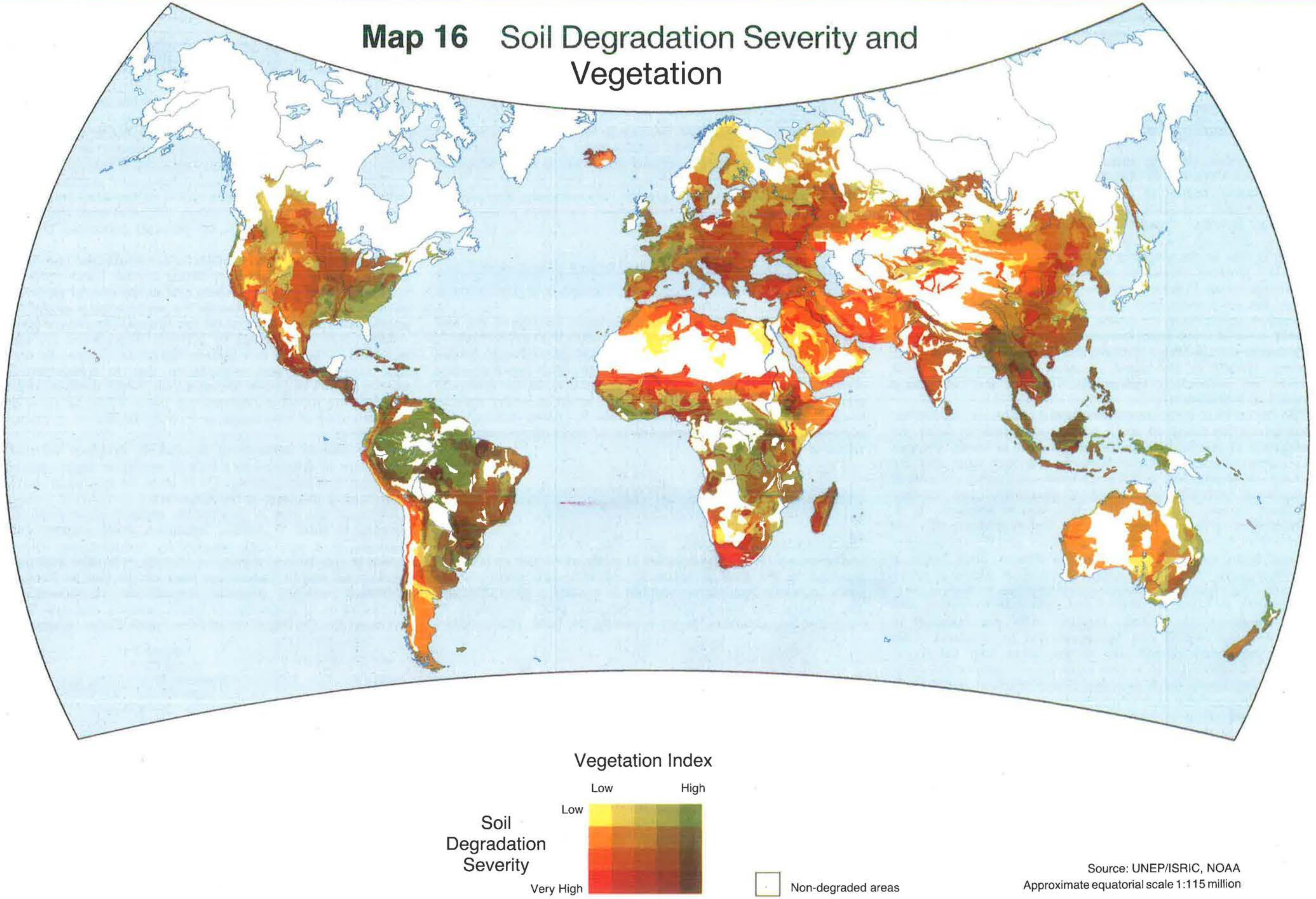
Although the area of susceptible dryland affected in North America is small (1 million hectares), these regions are all degraded to a very high severity by waterlogging. They are located in the dryland regions of Mexico, in Sinaloa State on the Pacific coast and in Tamaulipas State on the Gulf of Mexico.

Medium severity physical degradation characterizes the affected areas in Argentina in South America and low severity occurs on the Darling River in New South Wales, Australia.



Global susceptible dryland areas degraded by physical deterioration (%)

SOIL DEGRADATION AND VEGETATION



Source: UNEP/ISRIC, NOAA
Approximate equatorial scale 1:115 million

Significance of Vegetation in Soil Degradation Studies

Links between desertification, soil degradation and vegetation are complex. Many explanations of desertification have included vegetation degradation as a major direct component of the problem, but there are a number of practical and environmental reasons why it should be treated on a separate basis from soil degradation.

Vegetation and soils display differing resilience to disturbance. Although vegetation communities can be readily disturbed and degraded, recovery rates are relatively fast, though slower in drylands than in other environments, when compared to soil degradation. An effectively permanent undesirable change to vegetation can occur only when the soil resource itself has been severely degraded. In other situations, where rangeland degradation has occurred for example, it often appears to be the land use system that maintains the vegetation in a degraded state, rather than a change of soil characteristics that would make the vegetation degradation irreversible. Both soil and vegetation degradation are of great importance; however they are not necessarily coincident as indicators of land degradation.

Dryland vegetation generally displays a sensitivity to natural climatic variability. Reducing production and an ability to lie dormant are two strategies displayed by arid-land plants for survival at times of moisture deficiency. 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 if a particular vegetation state at a particular time is a consequence of natural short-term climatic variability or a longer-term trend induced by soil degradation.

These factors contribute to the absence of an adequate global database of vegetation degradation, but two useful relationships between soil degradation and vegetation can be determined. First, vegetation cover may help indicate vulnerability to soil degradation. A limited plant cover or low biomass, whether natural or resulting from human disturbance, can often indicate a greater susceptibility to degradation by soil displacement. 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 over a timescale that exceeds natural climatic variability, but useful information relating to the former relationship can be collected at the global scale.

Characterizing Vegetation

Vegetation can be characterized in many ways, by plant community composition for example. Production is another useful way of characterizing vegetation in a form that allows large-scale inter-regional comparisons to be made. Primary vegetation production can be defined in two ways:

Gross primary production: 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 estimated from remotely sensed data allowing vegetation patterns to be determined.

A Global Vegetation Assessment: NDVI and GVI

The Normalized Difference Vegetation Index (NDVI) is a qualitative index of photosynthetically active vegetation. 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 × 16 km spatial resolution and result from a screening process in which the cloud-free parts of all the images for a week have been combined to produce a cloud-free weekly scene. GVI values relate to the capacity of plants to photosynthesize and the relationship of plant canopy to evapotranspiration rates. The index can therefore be used as an indicator of vegetation biomass, though several studies suggest that the correspondence of the index with actual values is weak under some environmental conditions particularly outside dryland areas.

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 Map 16 as a 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. A part of the GVI surface covering Africa is shown in the continental Africa section of this atlas on page 36.

Interpreting the Soil Degradation and Vegetation Map

Map 16 provides an integrated assessment of overall soil degradation from the GLASOD survey and vegetation production from the GVI. The four degrees of degradation severity have been combined with five grades of the vegetation index to produce a twenty-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. The map gives no indication of vegetation quality nor whether vegetation has been influenced by human action. 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.

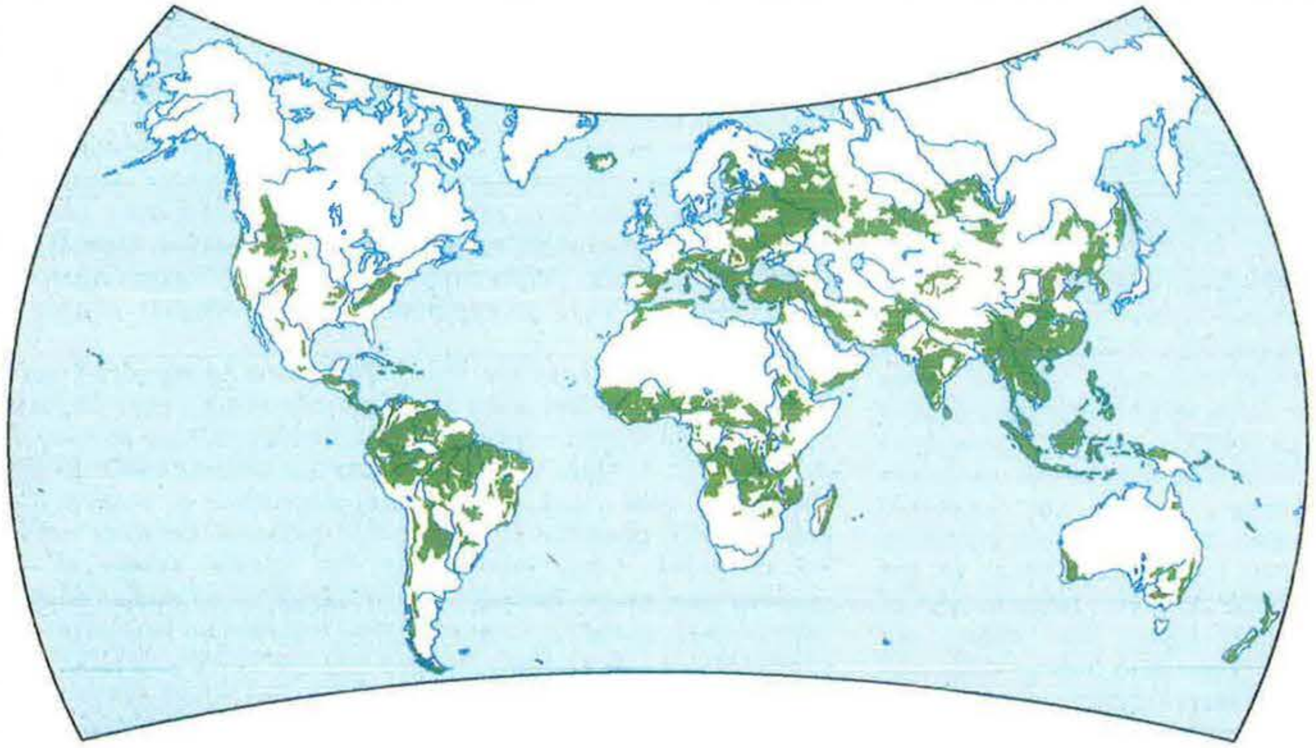
Best use can be made by taking the map to highlight areas within which susceptibility to soil or vegetation degradation may exist or have been realized. The most productive and least degraded environments are represented by colours from the top right of the key. With high GVI values, such areas also 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 most likely 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 realized 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. 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 indicating groundcover was probably restricted, creating soils vulnerable to wind or water erosion.

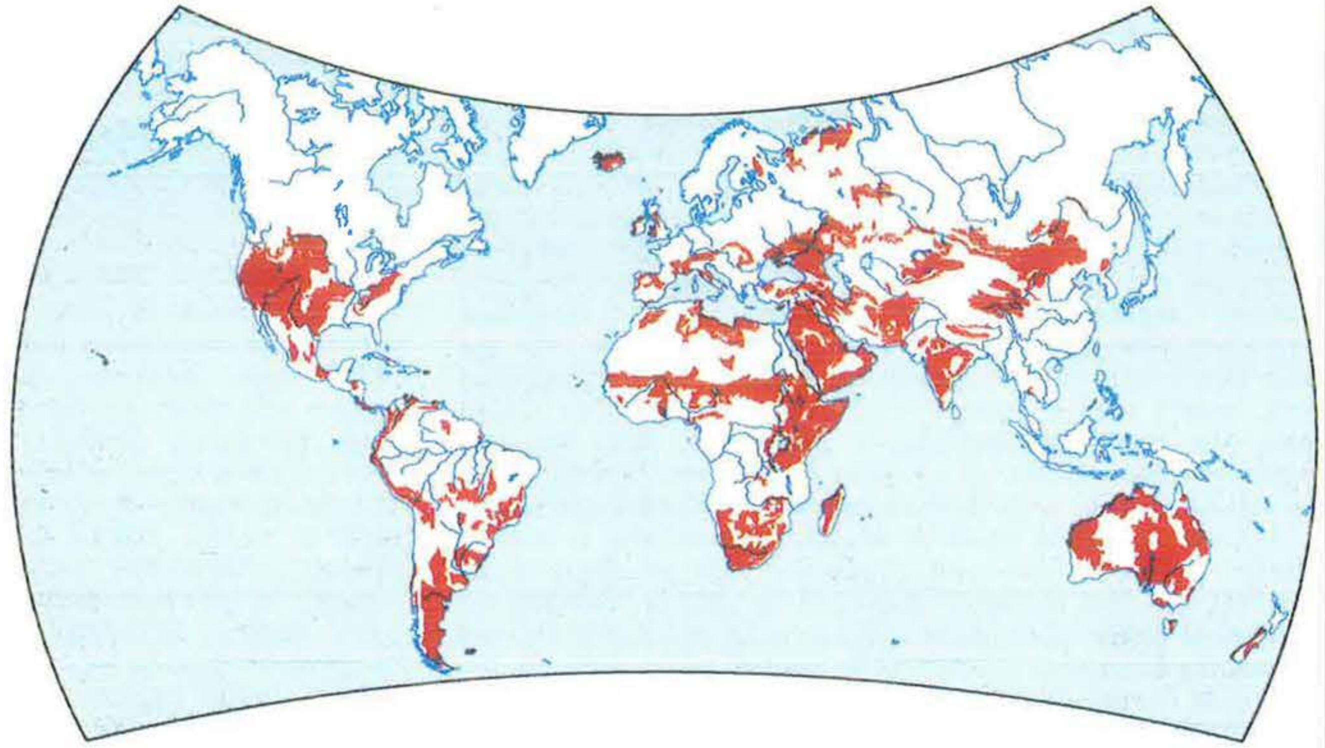
Spatial Patterns in Drylands

The map 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 to a more limited extent in Spain. These are the susceptible drylands containing areas where the greatest overall environmental degradation has occurred. Although many mapping polygons in Australia, North America (with the exception of the lower Colorado River basin and the Alberta badlands), and the Argentinian Pampas 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 usage were to intensify. Finally, the susceptible drylands in the rain-shadow area of southeastern Peru possess the unusual situation of lands that have been highly degraded but which also appear to have high GVI values. The ability of the map to highlight such an unusual situation points to a use in indicating areas where the status and origins of degradation warrant more detailed investigation.

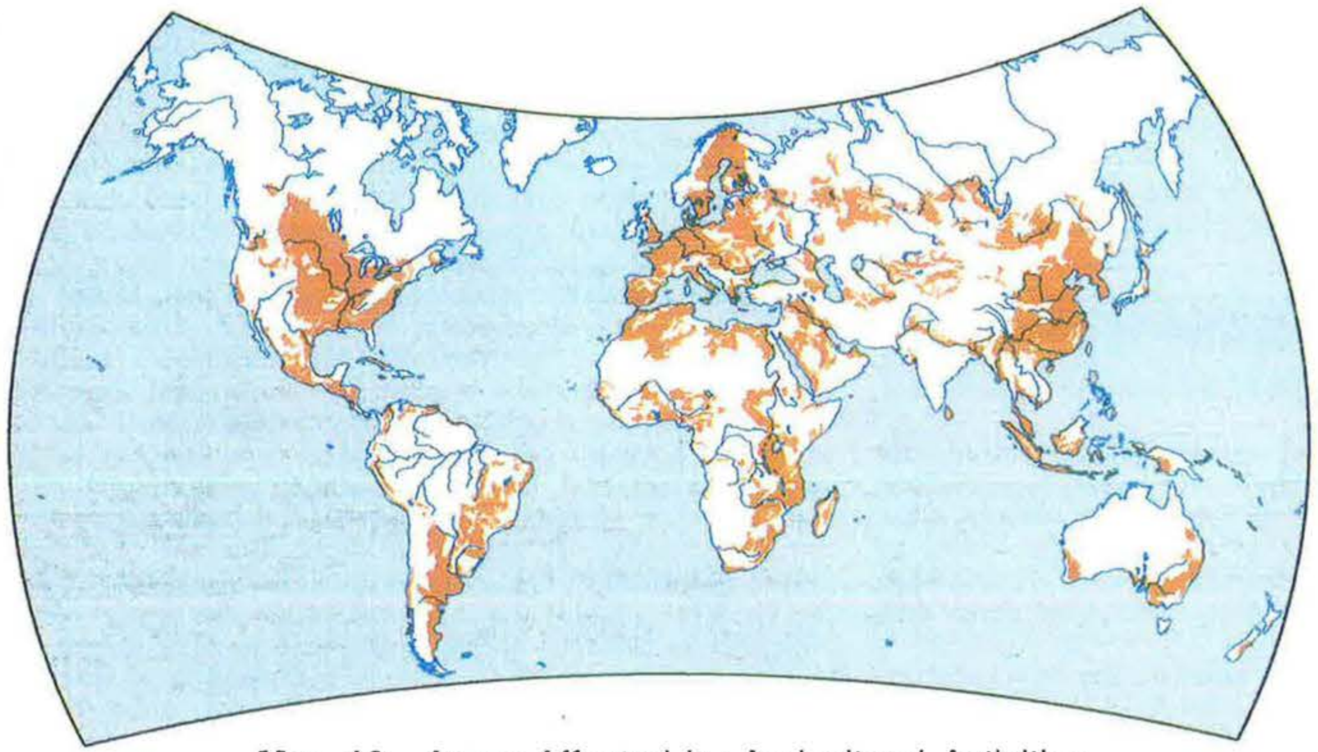
SOIL DEGRADATION CAUSES



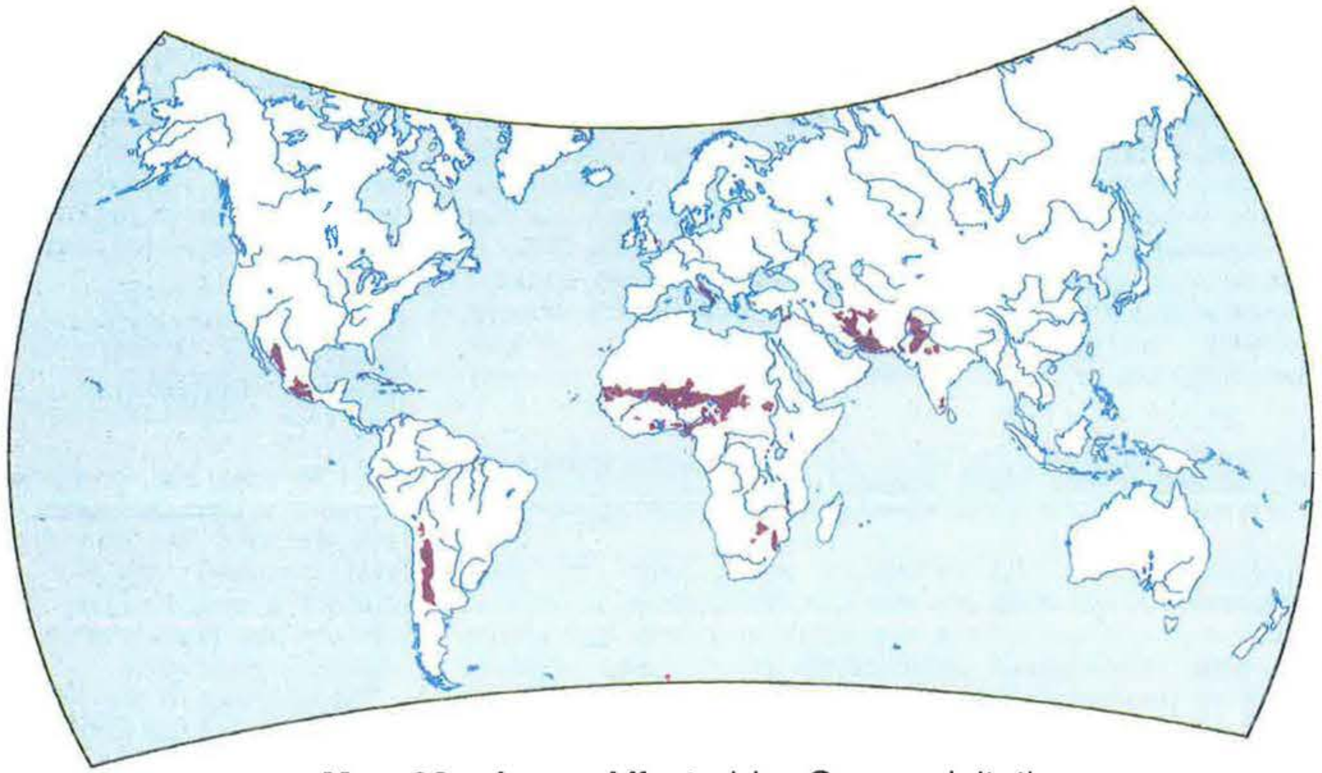
Map 17 Areas Affected by Deforestation



Map 18 Areas Affected by Overgrazing



Map 19 Areas Affected by Agricultural Activities



Map 20 Areas Affected by Overexploitation of Vegetation for Domestic Use

Source: UNEP/ISRIC Approximate equatorial scale 1:235 million

Introduction

The phrase "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 have been initiated or accelerated by human mismanagement in a particular area. Hence it is crucial to identify the nature of the land use that has led to soil degradation so that appropriate ameliorative management responses can be planned. Such responses must aim to make land use sustainable. This may either mean a complete change of land use or a moderation of the existing one.

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.

Deforestation and removal of the natural vegetation cover (see Map 17) is defined as the total removal of natural vegetation from stretches of land. In most cases this natural vegetation is forest or woodland. 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, or urban and industrial development.

There is a wide range of consequences stemming from such action. In areas where the vegetation removal is 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. Nonetheless, 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.

High rates of erosion and other degradation processes, such as compaction, can also occur in the interim period between clearance and the planting of a new vegetation cover. Once a new cover is established, however, different forms of degradation may occur as the soil establishes a new equilibrium with its vegetative overlay. Differences 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 to the soil.

Overgrazing (see Map 18) includes both the actual overgrazing of vegetation and other effects of livestock such as trampling and consequent compaction. Overgrazing and other forms of degradation due to livestock occur in areas either where too many head are being grazed or where the wrong sort of animals are being used. The most common consequence of overgrazing is a decrease in the vegetative cover, leading to increased erosion by water or wind. These effects may be extensive or concentrated in certain areas such as around waterholes. A widespread effect of overgrazing 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 since the soil itself is not affected.

Agricultural activities that lead to degradation encompass all aspects of improper agricultural land management (see Map 19). They include 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, the absence of anti-erosion measures, the shortening of fallow periods in shifting cultivation resulting in soil exhaustion, the insufficient or excessive use of fertilizers, and the improperly timed use of heavy machinery.

The overexploitation of vegetation for domestic use encompasses the use of vegetation for such purposes as fuelwood, fencing and construction (see Map 20). 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 of 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.

(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.

Soil Degradation Causes in Drylands

Overgrazing is the most important cause of degradation in the susceptible dryland areas of Australia, Africa, Europe and Asia where it affects 90%, 58%, 42% and 32% of the total degraded susceptible dryland area respectively. It is a problem in all susceptible dryland areas of Australia and Africa. In Europe it is largely confined to the Ukraine, and in Asia the Arabian peninsula parts of Soviet Central Asia and Pakistan/Afghanistan are particularly affected.

In European and Asian susceptible drylands deforestation closely follows overgrazing as the second most important cause of degradation, affecting 39% and 30% of all degraded susceptible dryland areas 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 and into Pakistan. Deforestation is the primary cause of degradation in South America, affecting 41% of the 79 million hectares of drylands damaged. These are largely concentrated in northeast Brazil and on the coasts of Venezuela and Colombia.

Agricultural activities represent the most important cause of susceptible 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. Agricultural activities are also important in Asia (26% of degraded susceptible dryland areas), Africa (19%), Europe (18%) and South America (15%). Among the Asian areas worst affected are Mesopotamia, parts of the Arabian peninsula, some areas in Siberia and Middle Asia, Mongolia and northern China. In Africa areas north of the Sahara are worst affected.

The overexploitation of vegetation for domestic use only accounts for more than a tenth of susceptible degraded drylands in Africa (17%), South America (12%) and Asia (11%). In Africa this is a problem predominantly located in the Sahel, in South America the problem is largely confined to northern Argentina and southern Bolivia. (Bio)industrial activities account for very small areas of dryland degradation in Asia (northern Iran) and the European part of Russia.

Table 8 Main causes of soil degradation by region in susceptible drylands and other areas (millions of hectares)

Region	Aridity Zone	Deforest-ation	Over-grazing	Agri-cultural	Over-exploitation	Bio-industrial	Total Degraded	Non-Degraded	Total
Africa	Susceptible	18.6	184.6	62.2	54.0	0.0	319.4	966.6	1286.0
	Others	48.2	58.5	59.2	8.7	0.2	174.8	1504.9	1679.7
Asia	Susceptible	111.5	118.8	96.7	42.3	1.0	370.3	1301.5	1671.8
	Others	186.3	78.5	107.6	3.8	0.4	376.6	2207.5	2584.1
Australasia	Susceptible	4.2	78.5	4.8	0.0	0.0	87.5	575.8	663.3
	Others	8.1	4.0	3.2	0.0	0.1	15.4	203.5	218.9
Europe	Susceptible	38.9	41.3	18.3	0.0	0.9	99.4	200.2	299.6
	Others	44.9	8.7	45.6	0.5	19.7	119.4	531.4	650.8
North America	Susceptible	4.3	27.7	41.4	6.1	0.0	79.5	652.9	732.4
	Others	13.6	10.2	49.1	5.4	0.4	78.7	1379.8	1458.5
South America	Susceptible	32.2	26.2	11.6	9.1	0.0	79.1	436.9	516.0
	Others	67.8	41.7	51.9	2.9	0.0	164.3	1087.3	1251.6
Total		578.6	678.7	551.6	132.8	22.7	1964.4	11048.3	13012.7

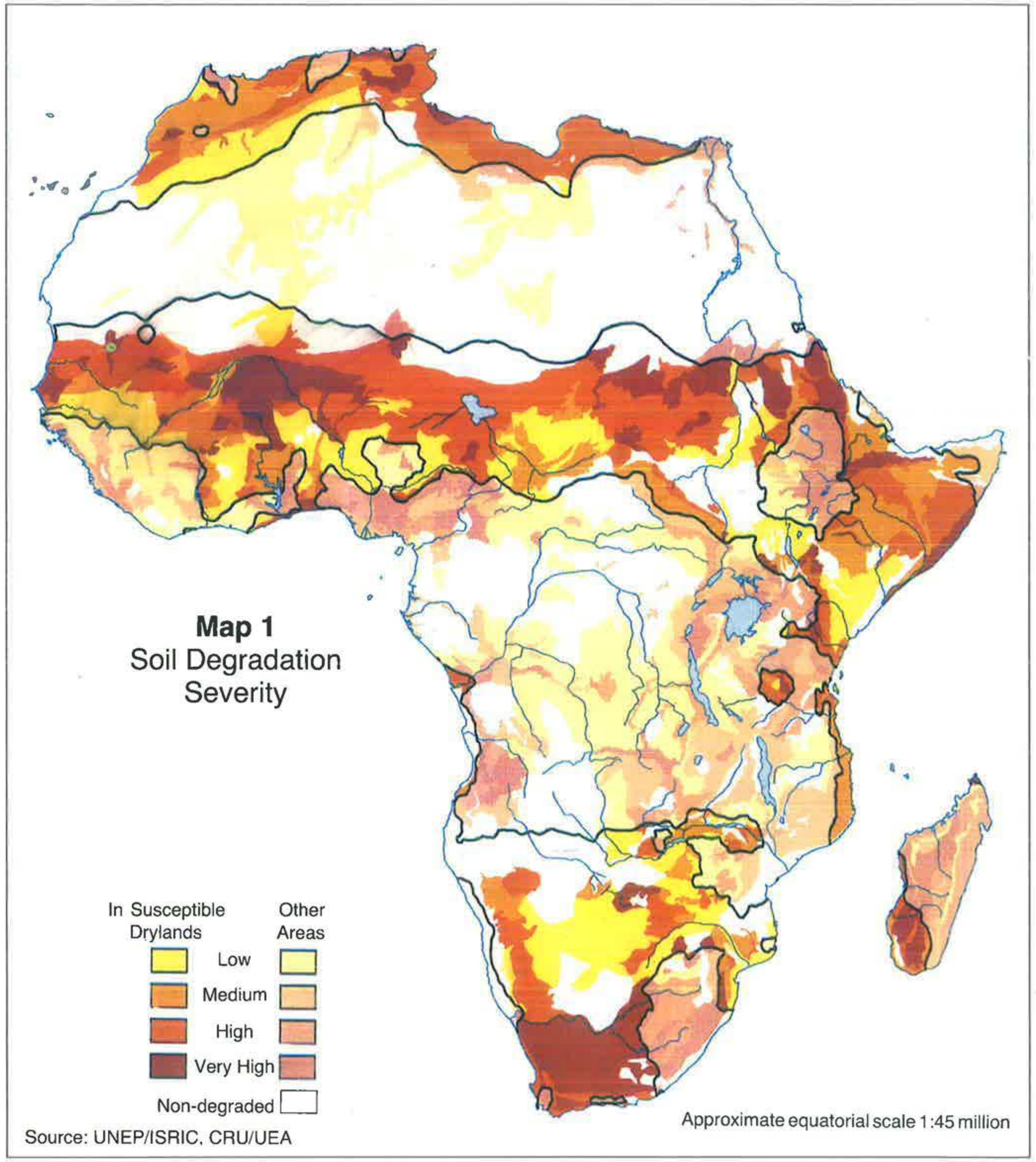
SECTION TWO

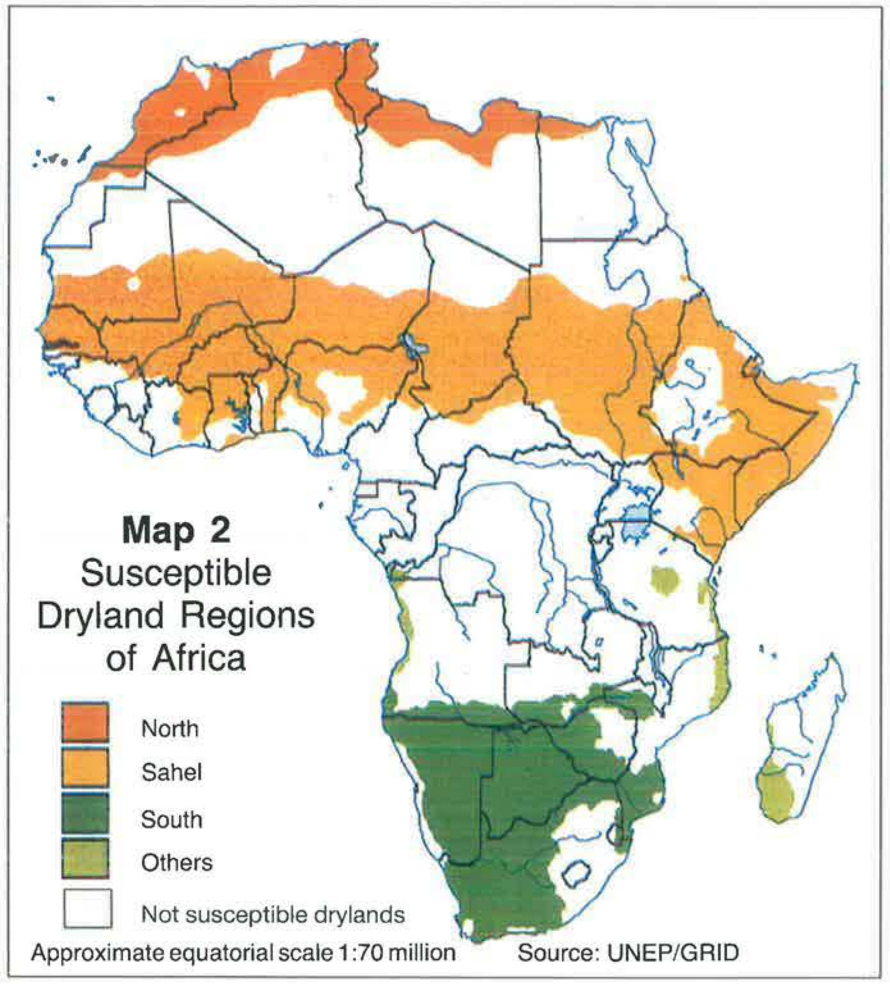
Continental Africa

As well as the global scale database for soil degradation, the GLASOD study has provided for a more detailed continental scale investigation of Africa. At the global level, the African land surface was divided into 383 map units, plus lakes, with the delimitation of map units based on natural physiographic regions, defined by homogeneity of factors such as soil type, climate and topography. In the continental database, the number of map units covering Africa 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.

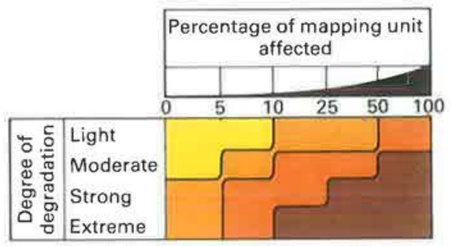
The maps that follow therefore have a greater resolution than the coverage of Africa in the global section. They should, however, be used primarily to provide continental and regional overviews of the degradation problem. The text accompanying each map provides examples of the issues under consideration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

SOIL DEGRADATION





The black lines shown in Map 1 correspond to the regional boundaries of susceptible drylands as presented in Map 2 and the rest of the maps in this section.



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

Interpreting the African Database

An important consequence of the change in the level of analysis is that it not only results in a greater spatial resolution but 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 generalization of the spatial extent of degradation occurs (see Map 1). More map units in the western Sahel, for example, mean that the area shaded as having very high severity degradation is smaller on the continental scale map than the global map, since a map unit with very high severity degradation may have been subdivided, for example, giving two units, one with very high severity degradation and the other with a lesser severity. Consequently a higher degree of spatial resolution is given to the visual interpretation of the Africa maps. In the hyperarid Sahara, areas with degraded land have appeared where they 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.

Geographical Regions

To facilitate description and explanation of soil degradation in susceptible drylands from the continental database, Africa has been divided into three geographical regions which cover most of the areas under consideration. A fourth category, "Others", covers the remaining areas (see Table 1, Map 2).

Africa north of the Sahara This region contains parts of the susceptible drylands of the countries of the Greater Maghreb: Morocco, Algeria, Tunisia, Libya and Egypt, plus Western Sahara and Cape Verde. 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 of Uganda and the Ethiopian Highlands, 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 however not been included in any of the tables.

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 ECOWAS (Economic Community of West African States) countries, of which Senegal, Mauritania, Mali, Burkina Faso and Niger in particular experience severe degradation problems, plus Chad, and the members of IGADD (Intergovernmental Authority on Drought and Development). On climatic grounds it also includes northeastern 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. During the period in which the information used for the compilation of the GLASOD database was collected, much of this region experienced intermittent drought, exacerbating the problems of human-induced land degradation.

Southern Africa This region covers the susceptible drylands of the SADCC (Southern African Development Co-ordination Conference) countries, plus South Africa. The susceptible area includes all of Botswana and Namibia, except the hyperarid Namib Desert; extends north along the Angolan coast where climate is affected by the aridifying effect of the cold Benguela current; and takes in 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 southwestern Madagascar, coastal Tanzania, including Zanzibar and extending into Mozambique, and an area in central Tanzania southeast of Lake Victoria. On physiographic and climatic grounds, it is not possible to include these areas in either the Sahel or southern African regions.

Table 1 Land area in Africa by aridity zone (millions of hectares)

Aridity zone	Region: North	Sahel	South	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

Vulnerability to Degradation

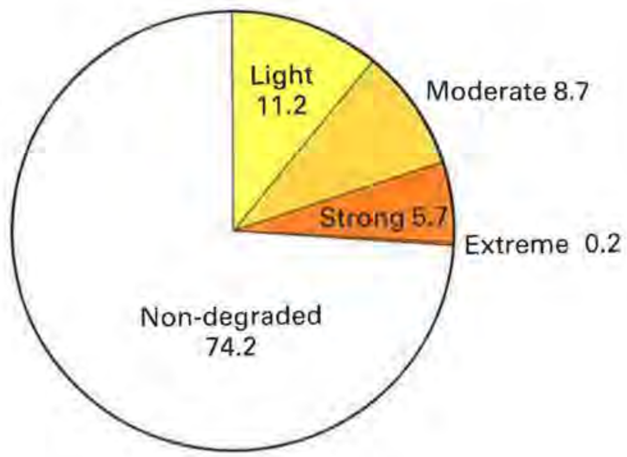
Map 1 and Table 2 show the severity of overall human-induced soil degradation. The distribution and density of the human population is obviously important in influencing where, to what degree and at what extent human-induced soil degradation occurs, a factor explored in a subsequent map.

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 even preclude irrigation because of their considerable permeability.

Second, natural environmental factors determine which degradation processes occur at specific locations, even where the cause is the same. As an example, overgrazing in Tunisia has led to water erosion but in Mali and Niger wind erosion has taken place. 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 prevails where the soil consists of ancient wind deposited sands: such deposits are readily remobilized by the wind when the protective vegetation cover has been disturbed.

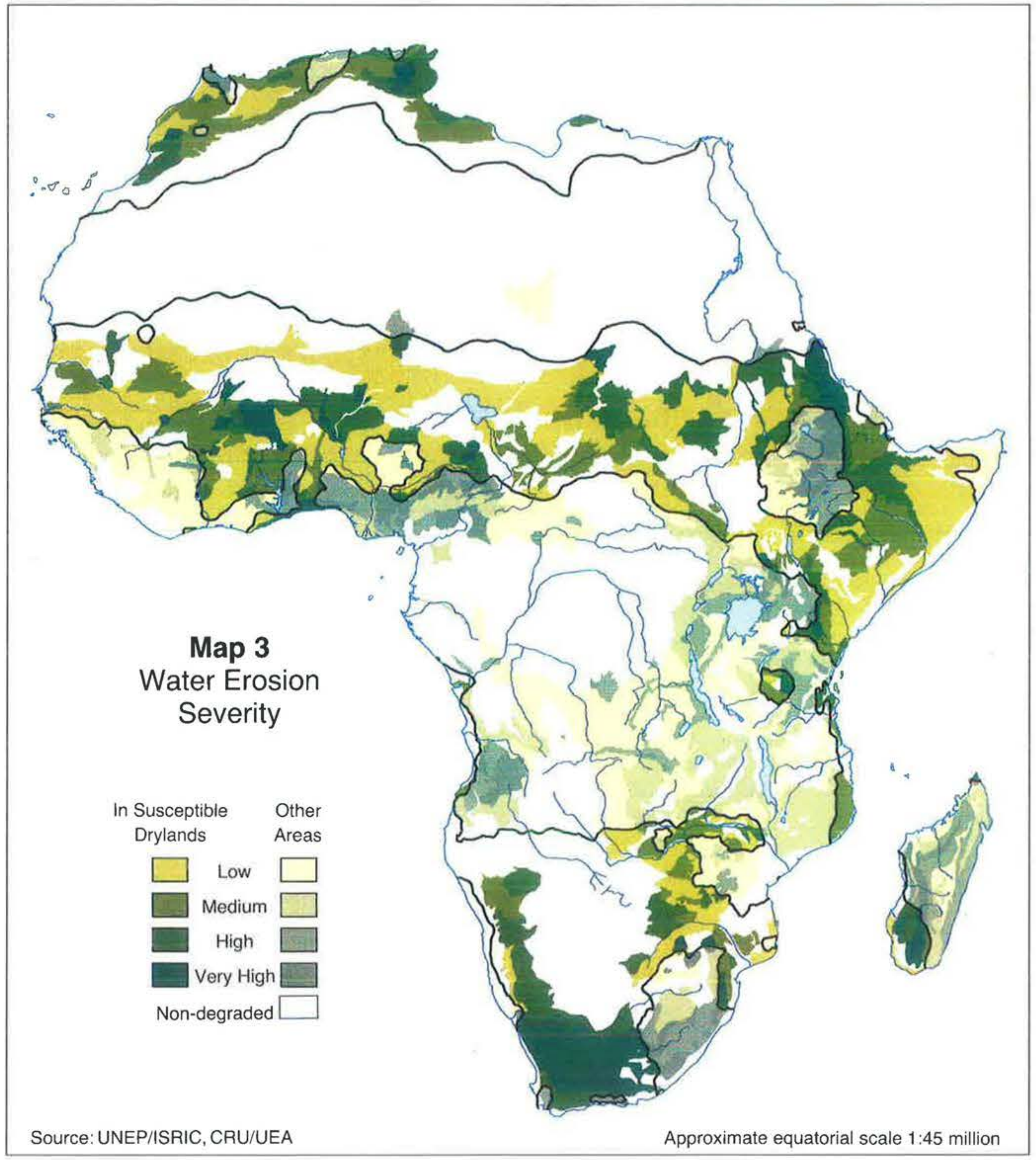
Table 2 Soil degradation degree in Africa by region in susceptible dryland areas (millions of hectares)

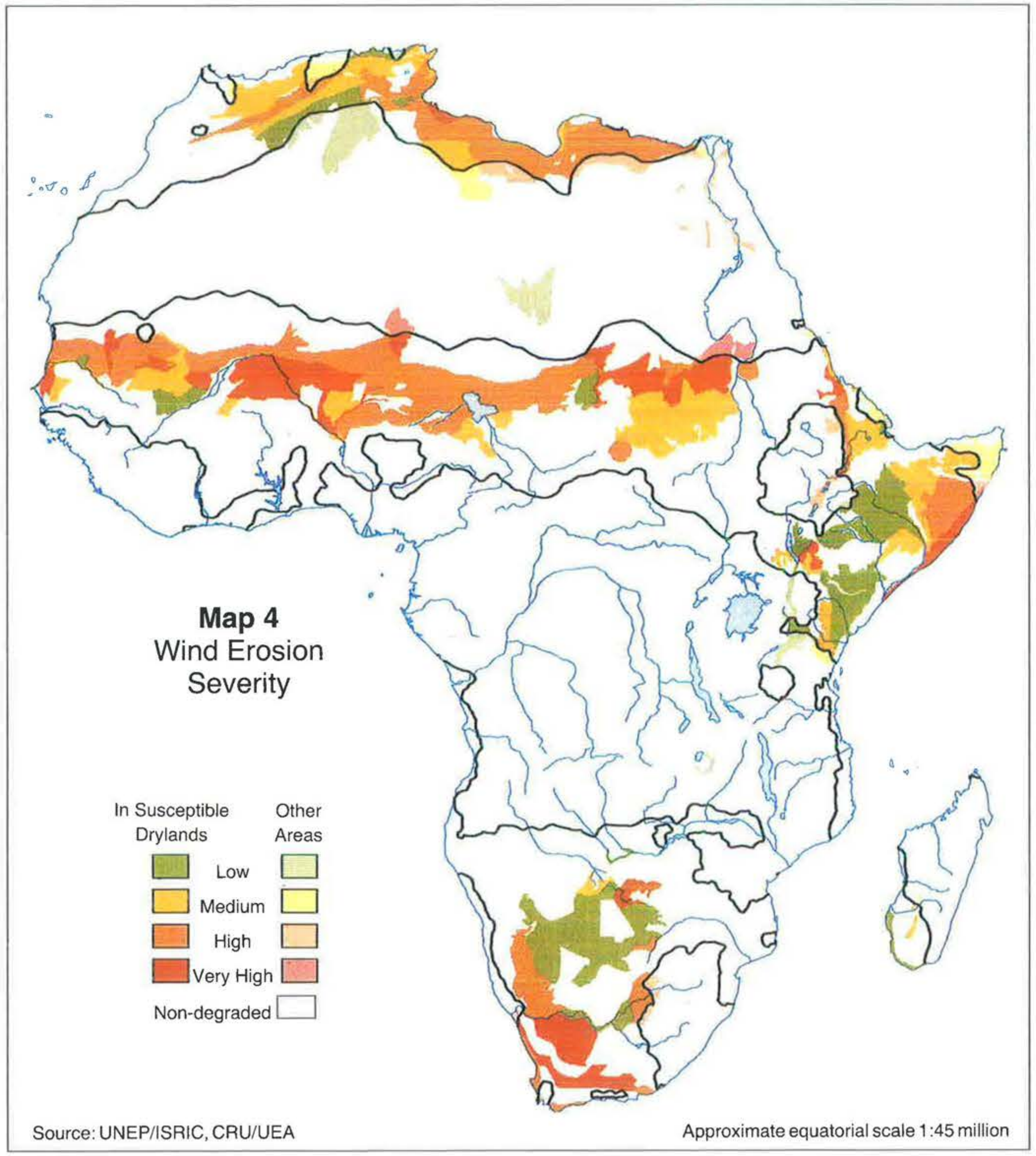
Degree	Region: North	Sahel	South	Others	Total
Light	25.6	109.8	6.4	2.4	144.2
Moderate	13.4	80.3	15.9	2.6	112.2
Strong	1.7	30.8	36.4	3.9	72.8
Extreme	0.0	3.1	0.0	0.0	3.1
Total degraded	40.7	224.0	58.7	8.9	332.3
Total non-degraded	109.9	578.4	236.3	29.1	953.7



African susceptible drylands by degrees of soil degradation (%)

WATER AND WIND EROSION





Water Erosion

Africa's susceptible drylands are widely affected by human-induced water erosion. The problem is not confined to the more humid drylands; indeed, the map shows that many of the localities where severity is greatest are within the arid climatic zone. Several underlying environmental factors affect the vulnerability of a given area to water erosion including soil texture and relative relief. These may present situations where runoff and erosion are particularly strong after human actions have disturbed the vegetation cover, particularly as dryland rainfall events tend to be intensive with a high erosive potential (see Map 3 and Table 3).

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 overgrazing, 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. Tree planting programmes have however been in operation for more than a decade in the Algerian Atlas and Moroccan Rif in an attempt to reduce runoff and degradation.

The Sahel

Many of the upland areas of the Sahel, such as the northern Ethiopian Highlands, the Ennedi Highlands of Chad and adjoining Darfur in Sudan, are 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 in Burkina Faso, indicating that even where all environmental criteria favouring vulnerability to water erosion are not fully met, poor land use practices and population pressures resulting in vegetation clearance can still lead to its significant operation.

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 areas 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. In 1990 IGADD estimated that soil loss was occurring at a rate between 1.5 and 2 billion m^3 per annum, with perhaps up to 4,000,000 hectares of the highlands irreversibly degraded.

Southern Africa

Southern Africa suffers water erosion in savanna areas caused by both pastoral and arable activities. Even in much of Namibia, where population densities are low, high stocking rates lead to overgrazing and vegetation depletion, exposing soils to runoff. Despite similar problems in much of western and central Botswana, sandy soils favour infiltration and therefore runoff is not generated, but wind erosion is a potential problem.

Table 3 Degree of water erosion in Africa by region in susceptible drylands (millions of hectares)

Degree	Region: North	Sahel	South	Other	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

Wind Erosion

Table 4 shows the regional breakdown of human-induced soil erosion by wind; Map 4 indicates that areas in the arid zone are most affected. Although the human activities that lead to enhanced wind erosion are well-documented, it is important to consider that many parts of African susceptible drylands have experienced prolonged drought during the period of the GLASOD study and that the natural response of ecosystems to drought, drier soils and less substantive vegetation cover, will also enhance deflation. The distinction in the field between human-induced wind erosion and naturally enhanced deflation can therefore be very difficult.

Africa North of the Sahara

Overgrazing is the major cause of wind erosion in Africa north of the Sahara, affecting large areas in the northern parts of Algeria, Tunisia, Libya and Egypt. Overstocking of sheep is the main problem in the northern steppe zone of Algeria and in the grasslands of Libya. Libyan pastures are also suffering from enhanced wind erosion as they are converted to grain cultivation.

The Sahel

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. Somali herds have greatly increased in the last thirty years as exports of livestock to the Arabian peninsula have risen. 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 overgrazing of the stabilizing herbs and grasses.

The arid parts of the Sudanese Provinces of Darfur and Kordofan are the site of much-quoted studies of desertification. The region suffers from very high wind erosion severity on the soils of ancient sand dune deposits. Here the causes can be attributed to overgrazing during times of drought. Some studies in Kordofan indicate that overgrazing has also caused declines in plant species diversity as well as vegetation coverage, with areas closest to centres of permanent population worst affected, highlighting the importance of the human element in land degradation.

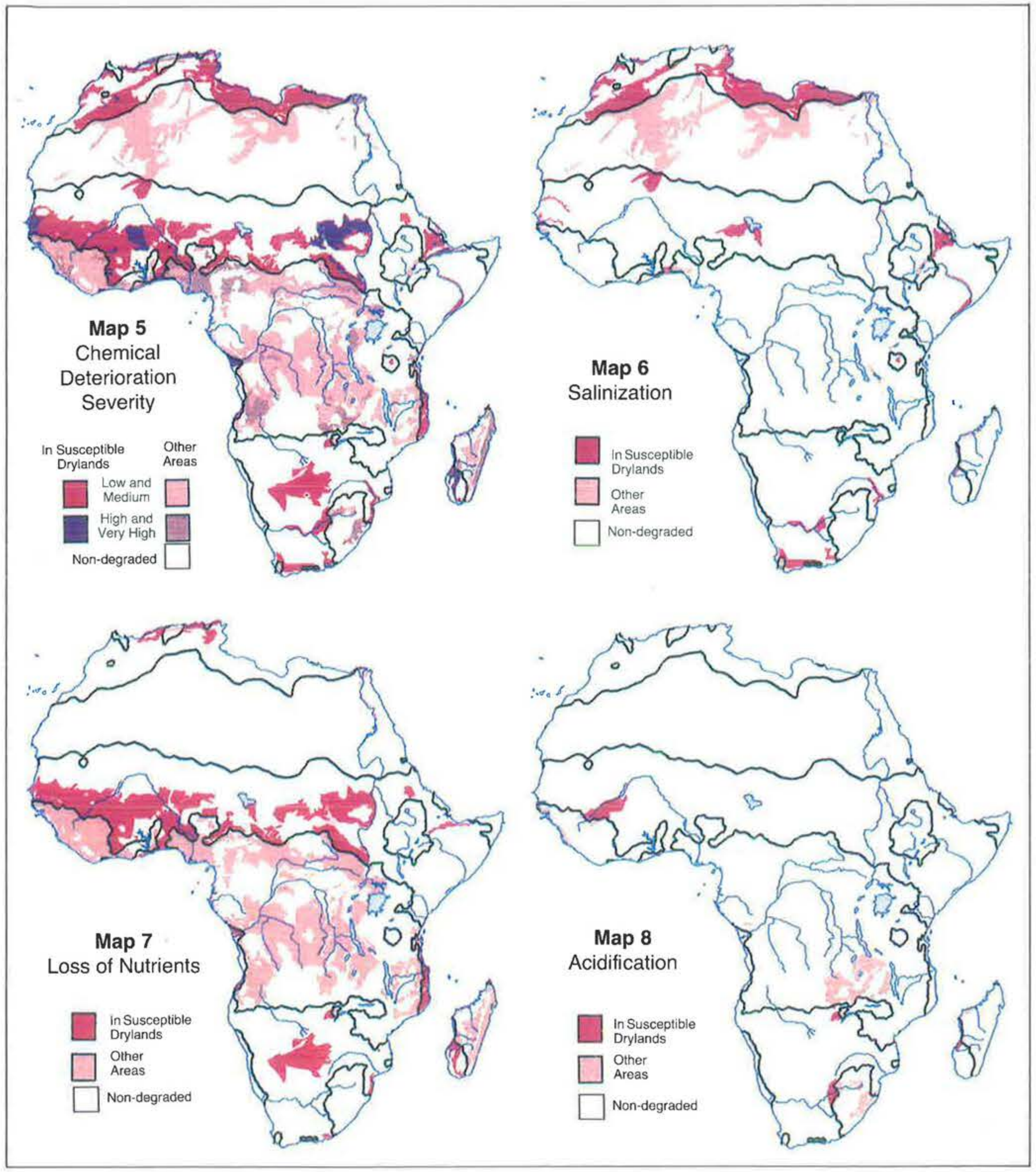
Southern Africa

Local overgrazing by cattle around boreholes in Ngamiland causes very high wind erosion severity in northern Botswana on particularly susceptible ancient wind-deposited sands. As with water erosion, overgrazing by cattle in the northern Cape area of South Africa and central Namibia has led to very high and high severity degradation by wind erosion.

Table 4 Degree of wind erosion in Africa by region in susceptible drylands (millions of hectares)

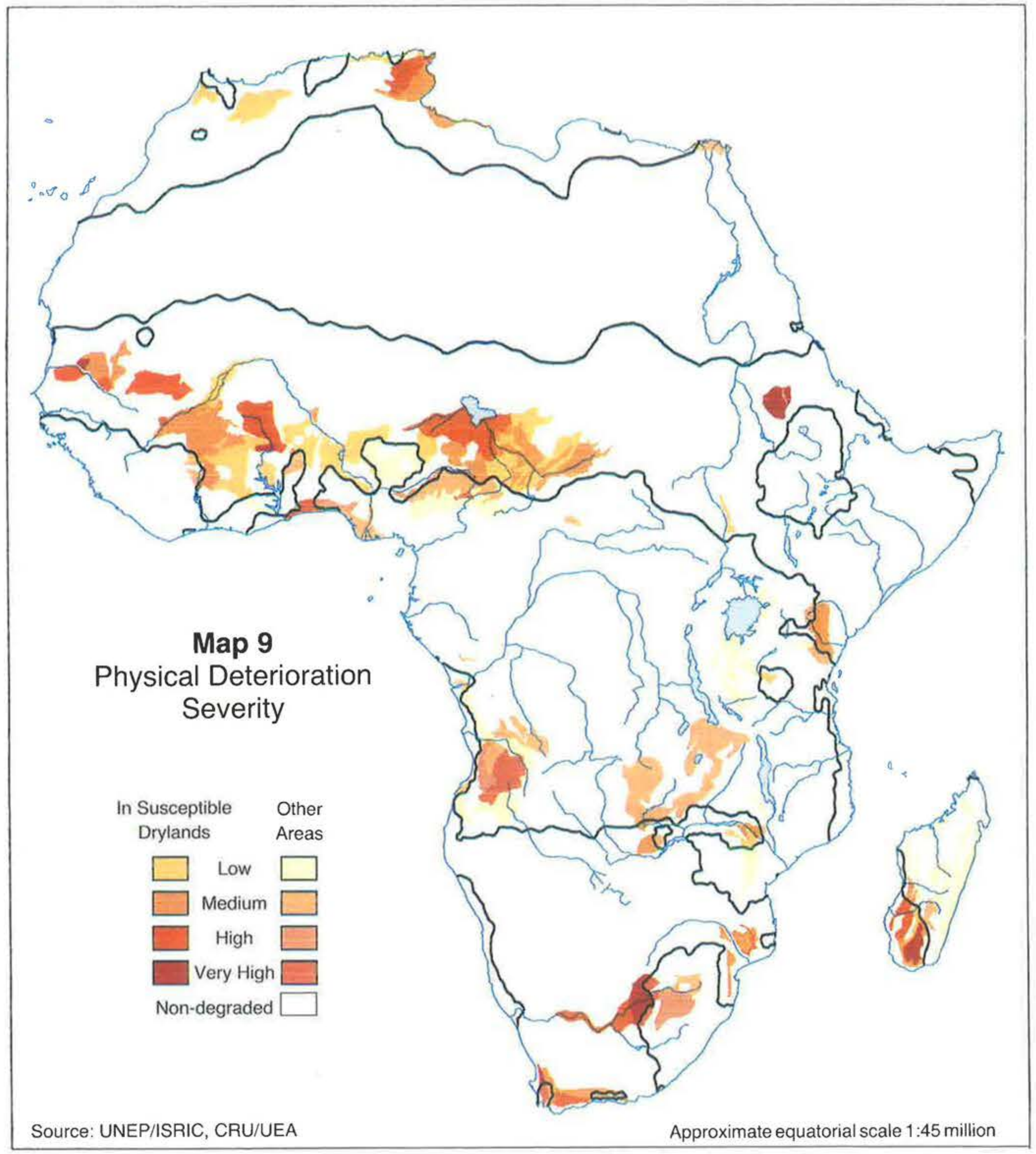
Degree	Region: North	Sahel	South	Other	Total
Light	18.0	156.2	5.7	0.2	180.1
Moderate	8.8	99.5	16.1	0.0	124.4
Strong	0.0	4.9	4.1	0.0	9.0
Extreme	0.0	0.8	0.0	0.0	0.8
Non-degraded	122.8	540.9	270.1	37.8	971.6
Total	149.6	802.3	296.0	38.0	1285.9

CHEMICAL AND PHYSICAL DETERIORATION



UNEP/ISRIC, CRU/UEA   Approximate equatorial scale 1:90 million

Maps 5–8 Chemical Deterioration Severity



Chemical Deterioration

Chemical degradation presents a serious problem in the susceptible drylands of Africa. Of the chemical degradation processes included in the GLASOD survey, nutrient depletion and salinization are especially relevant to drylands. Acidification, caused by excessive fertilizer application, also occurs but only affects a small number of locations in Africa (see Maps 5–8 and Table 5). It should be noted that the seemingly large parts of the Sahara affected by chemical deterioration by salinization in Maps 5 and 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 hectares of irrigated land and experiences substantial chemical degradation problems, involving both salinization and nutrient depletion. 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 50 million people 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.

The Sahel

Widespread salinization in the Sahel affects many irrigation schemes, such as the South Chad Irrigation Project in northwestern Nigeria. This scheme began in 1974 and was to have irrigated 106,000 ha, but the drying of Lake Chad has to date restricted this to 7000 ha; the lack of available water and high evapotranspiration rates has exacerbated salinization.

In Sudan's Kordofan and Darfur Provinces, population pressures have led to tree clearance for the introduction of mechanized agriculture, primarily for growing sorghum. Monocropping has led to degradation of the sandy soils by nutrient depletion through over-cultivation, with substantial soil depletion and land abandonment occurring as little as three years after the start of cultivation.

Table 5 Degree of chemical deterioration in Africa by region in susceptible drylands (millions of hectares)

Degree	Region North	Sahel	South	Other	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

Table 6 Degree of physical deterioration in Africa by region in susceptible drylands (millions of hectares)

Degree	Region North	Sahel	South	Other	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

Madagascar

Southwestern Madagascar experiences high severity degradation by nutrient depletion. The expansion and intensification of cultivation in Toliara Province, primarily of maize and manioc, through traditional and mechanized farming, has led to a shortening of fallow periods as well as the loss of nutrients through natural vegetation destruction. The extension of cattle raising into the area exacerbates the problem.

Physical Deterioration

Most areas of Africa worst affected by physical degradation are found in the continent's susceptible drylands (see Map 9 and Table 6). Although the physical degradation category is the least extensive of the four degradation categories recognized by GLASOD, it nevertheless presents serious problems in specific areas through compaction, sealing, crusting, sodication, waterlogging, aridification and soil subsidence.

Africa North of the Sahara

Much of a broad swathe of land stretching from Tripoli in Libya, through the "telle" zone and into the Tunisian Atlas Mountains is affected by medium or high severity physical degradation. In the Nile Delta, medium severity due to waterlogging has become a problem since the completion of the Aswan High Dam in the 1960s.

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 irrigation project in Kassala Province, northeastern Sudan, where irrigation water from the dammed Atbara River is fed by gravity flow to 150,000 ha of sorghum. 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 fifteen 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. 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 the excessive trampling of sandy soils by grazing cattle.

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 prolonged 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. The drought has also led to concentration of cattle around boreholes in Ferlo, leading to soil compaction by trampling. 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 overgrazing.

Southern Africa

Two areas in South Africa are badly affected by compaction and crusting. In the 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 from the Upper Karoo to the Namibian border.

SOIL DEGRADATION CAUSES

Maps 10–13 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.

Overgrazing

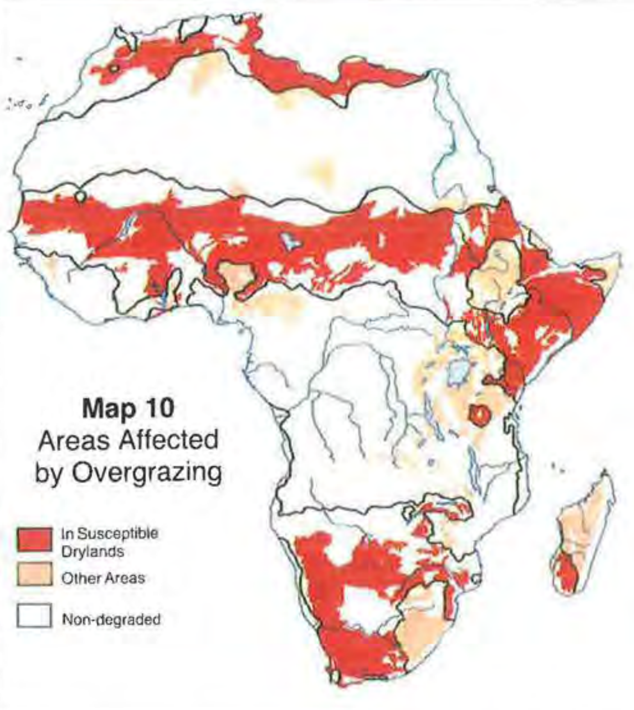
Overgrazing is the most widespread cause of soil degradation in Africa, affecting more than half of all degraded susceptible dryland soils (see Table 7). It is largely a problem of the arid and semiarid zones. The reasons for concentrating too many livestock in certain areas, leading to loss of vegetation cover and trampling of soil surfaces, can be socio-economic or political, or they may have their roots in environmental factors such as drought. Overgrazing around settlements in North Africa and the Sahel is often related to the sedentarization of nomadic herders. In Algeria, 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 in Mauritania; drought conditions have forced herders to concentrate their animals in the arid and semiarid 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 were generally due to insufficient grazing rather than a lack of water. Socio-economic factors can explain the increasing grazing pressures in the tribal areas of Hereroland and Damaraland in Namibia and some of the "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.

Agricultural Activities

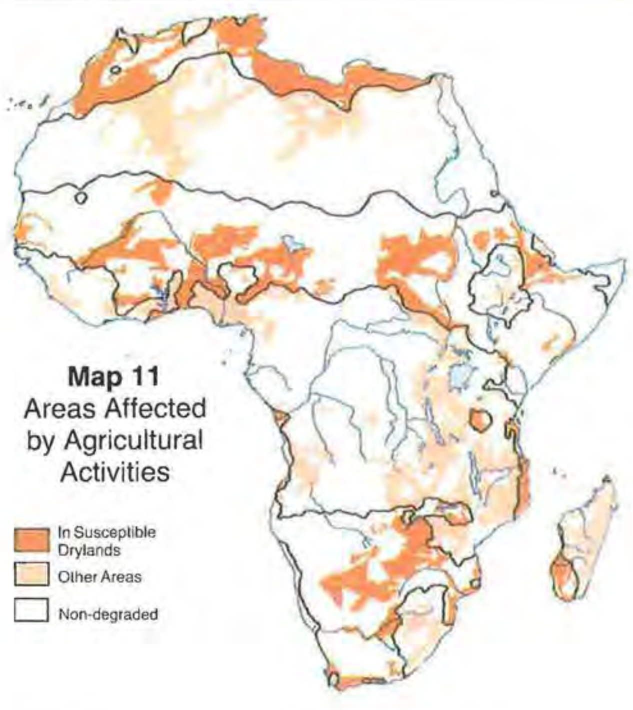
Degradation due to poor agricultural management is largely concentrated in the semiarid and dry subhumid zones (see Table 7) since these are the areas most suitable for dryland crops, although degraded soils on irrigated agricultural lands may also be located in more arid regions. Overirrigation and inadequate drainage are the most common problems leading to soil salinization and waterlogging in these areas, and these problems are highlighted in the irrigation schemes in the Nile basin, along the lower reaches of the Senegal River, the Juba and Shabelle rivers in southern Somalia, the Orange River in South Africa and the Limpopo River in Mozambique. Inappropriate management of dryland crops stems from a number of driving forces. Dryland farming in Algeria and Tunisia has been extended into increasingly marginal areas since the nineteenth century when agricultural machinery was introduced which was inappropriate to the fragile ecosystem. Dry cereal cropland continues to expand into the steppe using tractors and multidisc ploughs with consequent degradation largely due to wind action. Commonly quoted reasons for traditional rainfed farming practices becoming unsustainable are the expansion of cash cropping which pushes traditional farming into more marginal areas, and the pressure from a growing population which needs more food. The expansion of groundnut cultivation in Niger and Sudan, and cotton cultivation in parts of Chad have pushed subsistence crops into areas whose fragility 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. Seemingly large areas in the Sahara with soil degradation due to agricultural activities are in fact oases affected by salinization. Just as on Map 6, this exaggerated picture is a function of the mapping technique.

Overexploitation of Vegetation for Domestic Use

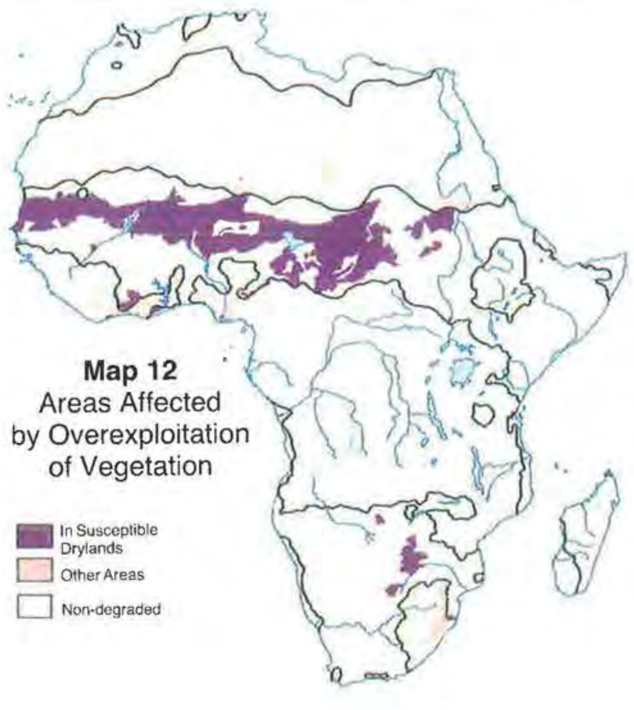
Soil degradation due to the overuse of vegetation for such domestic purposes as fuelwood, fencing and construction is common to the central and western Sahel region very largely concentrated in the arid zone (see Tables 7 and 8). This pattern is probably due to the simple fact that vegetation in the 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 fragile environment. Fuelwood collection is probably the most import-



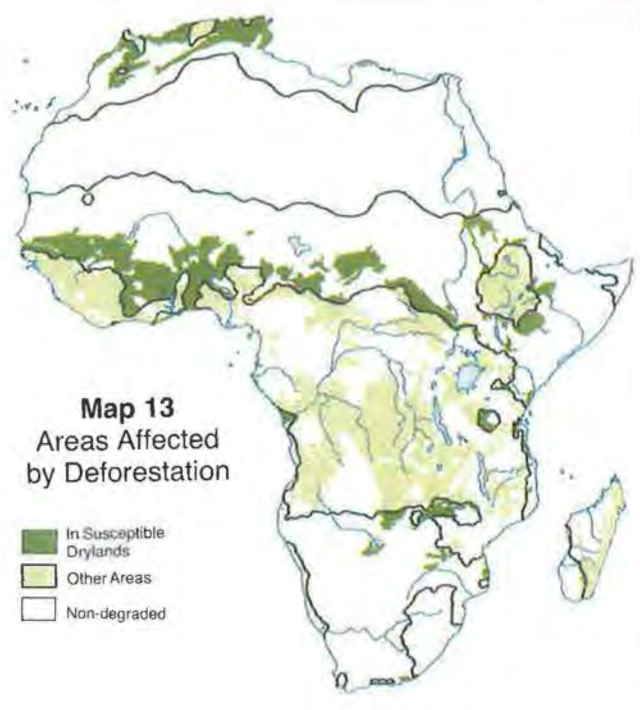
Map 10
Areas Affected by Overgrazing



Map 11
Areas Affected by Agricultural Activities



Map 12
Areas Affected by Overexploitation of Vegetation



Map 13
Areas Affected by Deforestation

UNEP/ISRIC, CRU/UEA Approximate equatorial scale 1:90 million ant domestic reason in Sahelian countries where imported fossil fuels are prohibitively expensive. Growing human populations in many areas have led to wholesale tree cutting taking over from collection of dead wood. In some parts problems are most critical on the periphery of urban areas where collection of woody vegetation leads to its complete clearance for many kilometres. City dwellers in general use more fuelwood per head than their rural counterparts. In Mali, for example, annual consumption rates are 360 kg per person in the cities and 270 kg per person in rural areas. The fuelwood demand of Bamako is about 200,000 tonnes a year and is expected to more than double by the year 2000. Further north in Mopti, where fuelwood is used to smoke fish, this industry has consumed the forest within 50 km of the city. Similar situations are found around other dryland cities such as Dakar, Niamey, Kano and Khartoum. In some countries such as Ethiopia 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 areas.

Deforestation and Removal of Natural Vegetation

Complete removal of the vegetation cover (see Map 13) as a cause of African soil degradation is largely confined to the Sahel region and the region north of the Sahara (see Table 8). 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 hectares of woodland was cleared every year in the early 1980s. Similarly, 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 northwestern Nigeria. Expansion of irrigation schemes in Sudan, along the Blue Nile downstream of the Roseires Dam and in the existing cotton-growing schemes southeast 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 fluvial activity is the main soil degradation process in parts of the Atlas Mountains of Tunisia, Algeria and Morocco where deforestation plays a contributory role. Bush and grass fires are a common management technique practised in the savannas of Africa, probably causing large losses of organic matter and nutrients. The exact impact of such excessive and repeated burning is poorly understood and deserves further study to improve our knowledge of the effects of human-induced vegetation clearance.

Explanations for Degrading Land Uses

Although many of the causes of human-induced soil degradation can be recognized and their operation understood, it is pertinent to investigate why it is that certain land uses, many of which have been carried out more-or-less sustainably for many generations, are now leading to the degradation of soil and other resources. G. Hardin's classic paper on the role of commonly owned property in resource degradation provides a useful basis from which to look at the problem. This view of pastoralists suggests that if a herder owns stock individually, but the land is communal, it is in the pastoralist's interest to allow overgrazing for personal short-term gain at society's expense. It has also been suggested that this "tragedy of the commons" becomes more likely when a society is under stress, rather than in the normal course of events.

Identification of the nature of the stresses a society is under should provide some root causes of degradation in African drylands. These stresses will have their origin in society, economics, politics and natural environmental aspects such as drought. It is tempting to point towards population growth as an all-important stress factor, and indeed population growth in many African susceptible dryland countries has been rapid in recent decades. But the relationship between population and degradation is by no means clear-cut as indicated on page 39.

In many cases, population numbers and densities must be considered in a particular environmental or political context. The increasing area of cultivated land in Kordofan Province of Sudan, for example, is certainly related to the rising number of mouths to feed, but a traditional response to declining yields of dryland crops per hectare during drought is to extensify production. The flocking of large numbers of refugees to Nouakchott, Mauritania, is mainly a classic population response to natural disaster: migration away from the hazard zone. The consequent concentration of people is putting undue stress on nearby regions, as sources of fuelwood for example. Similarly, refugees from political instability and civil war tend to concentrate in certain less hazardous areas, creating a much greater demand on local food and fuel resources. Global economic factors also play their role in creating degradation from sustainable land uses, such as the expansion of groundnut production in Niger and subsequent intensification of production by shortening fallow periods as world prices for groundnuts declined during the 1960s and 1970s.

Population, society, economics and politics have all played some role in the soil degradation caused by overgrazing. However, some words of caution need to be introduced into this issue. Although soil degradation may well occur after severe grazing leaves soils bare to erosion, the main desertification problem with overgrazing lies in the degradation of the vegetation itself, leaving rangelands that are able to support fewer livestock. But this concept deserves further scrutiny since it is based upon the idea of "carrying capacity" which is a complex criterion to ascertain in drylands with their inherent variability. Mainstream conventional ideas on dryland carrying capacity suggest that an average stocking should be below the maximum during good rainfall years to avoid overgrazing and population crashes during drought, but in fact an opportunistic grazing strategy such as is carried out by traditional pastoralists is probably more closely attuned to environmental fluctuations. Even when near-complete devegetation occurs, such as around boreholes, this may not be the disaster so often portrayed. Grass seed, either in the soils or from nearby less degraded vegetation stands, can usually recolonize soils quite readily. The population dynamics and strategies of dryland species are in harmony with the vagaries of the dryland ecosystem. Excessive trampling can, however, destroy soil structure and prevent plant growth which often results in a rapid change from grasses to bush encroachment in moister drylands. While this may be a disaster for cattle ranchers, traditional pastoralists often keep browsing animals as well as grazers and so are able to continue utilizing the environment by subtly changing land use. If bush encroachment serves to prevent cattle ranching it might alternatively be seen as the environment's way of returning to a balance. Since leaf litter from bush will contribute to increased soil fertility, eventual burning, whether natural or by humans, can readily return the land to grasses and renewed grazing.

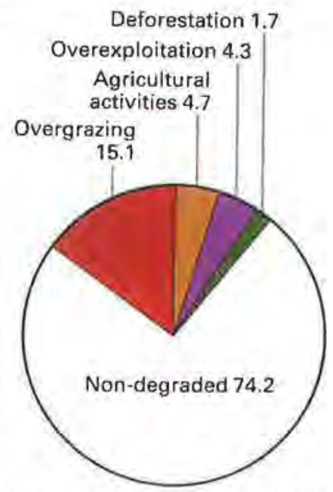
Table 7 Main causes of soil degradation in Africa by aridity zone (millions of hectares)

Cause	Region			Total
	Arid	Semiarid	Dry Subhumid	
Overgrazing	119.9	61.9	12.6	194.4
Agriculturall 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

Note: Bioindustrial activities do not occur

Table 8 Main causes of soil degradation in Africa by region (millions of hectares)

Cause	Region				Total
	North	Sahel	South	Others	
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



Main causes of soil degradation in African susceptible drylands (%)

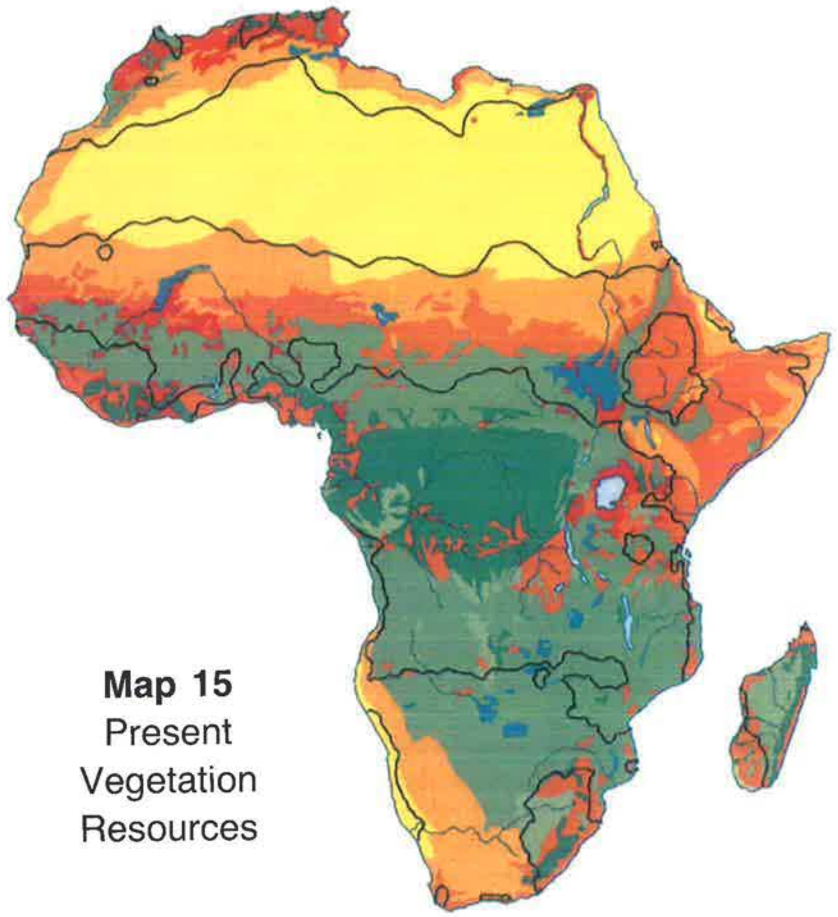
SOIL DEGRADATION AND VEGETATION

Map 14
Global Vegetation Index Average 1983–1990

Low — High

Source: NOAA, UNEP/GRID

Approximate equatorial scale 1:45 million



Map 15
Present Vegetation Resources

- Dense forest and other woody communities (mainly evergreen, and locally semi-deciduous) including tropical mountain forests and mangroves and dry or thorny tropical forests
- Predominantly wood land, savannawoodland, tree savanna
- Grass savanna and other mainly grassy plant communities
- Swampy areas with edaphic grassy types including continental halophytes.
- Predominantly dense dry thickets including Cape Shrubland (Fynbos)
- Mainly steppic vegetation and sub-desert
- Deserts including Saharomountain vegetation
- Mixed types and agriculture
- Agriculture

Source: ICIV

Approximate equatorial scale 1:70 million

Introduction

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 that vegetation can be characterized 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. The more detailed representation in this section of degradation at the African scale allows vegetation to be considered in terms of both community composition and biomass.

GVI Map of Africa

Map 14 shows the Global Vegetation Index (GVI) coverage of Africa, derived from 16 km × 16 km NOAA satellite data (see page 23). The vegetation index on the map varies from low to high on a continuous scale. 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. Generally, GVI however relates to the ability of plants to photosynthesize and the relationship between canopy and evapotranspiration values.

The map cannot be directly compared with the representation of African vegetation in the global section, because the map on page 22 shows the relationship between GVI and soil degradation severity. Map 14 opposite shows GVI alone. It is clear that biomass, as represented by GVI, generally varies in line with climatic zones, with lowest GVI in hyperarid areas. More detailed variations, within individual regions such as the Sahara, are a function of changes in environmental and human factors which cannot be determined without recourse to more specialized 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 indicate irrigated cropland.

Vegetation Map of Africa

While the GVI map gives a useful general indication of vegetation cover, it does not identify the plant species and communities that make up the vegetation of a particular area. Map 15, which provides a simplified assessment of African vegetation communities, has been produced by ICIV (Institut de la Carte Internationale de la Vegetation) at the Université Paul Sabatier, 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, supplemented by NOAA satellite data.

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 generalized classes being created.

The vegetation classes found in the susceptible drylands are as follows:

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 wet woodlands of subhumid areas in the Ivory Coast and Zimbabwe and the dry steppe woodland of Mali and Burkina Faso. These places include areas where domestic overexploitation and deforestation are major causes of soil degradation. This class presently covers 24% of the African intertropical land surface.

Grass savanna and other mainly grassy communities This class, well discriminated in satellite imagery, covers the almost treeless savannas. It includes the grasslands of the sandy Kalahari soils and the volcanic soils of east Africa where overgrazing is an important contributor to degradation.

Swampy areas with edaphic grassy 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. It also includes predominantly dense dry thickets such as Cape Shrubland (Fynbos).

Steppic vegetation and subdesert communities It is difficult to subdivide the range of communities covered by this class 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 of the southern hemisphere communities which contain an important succulent component (in Namibia, Botswana and South Africa) and the Acacia steppe communities of the Sahelian zone. Twenty-two per cent of intertropical Africa falls within this class.

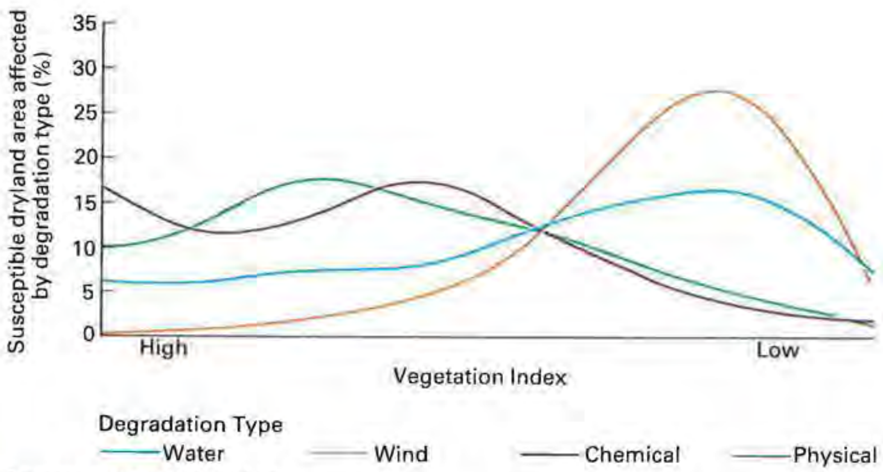
Deserts, including Saharomountain vegetation This broad class includes hyperarid areas and therefore extends beyond the susceptible drylands and desert mountain areas.

Vegetation and Soil Degradation

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 precludes 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. 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 1, 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 Map 14 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 protects soils against sediment transport by wind. Water erosion also peaks under low GVI conditions, though the peak is less strong. Again, low groundcover 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. The decline of all degradation types that occurs on the extreme right hand side of the diagram is due to the fact that these areas are in the hyperarid zone, where human-induced degradation is very scarce.

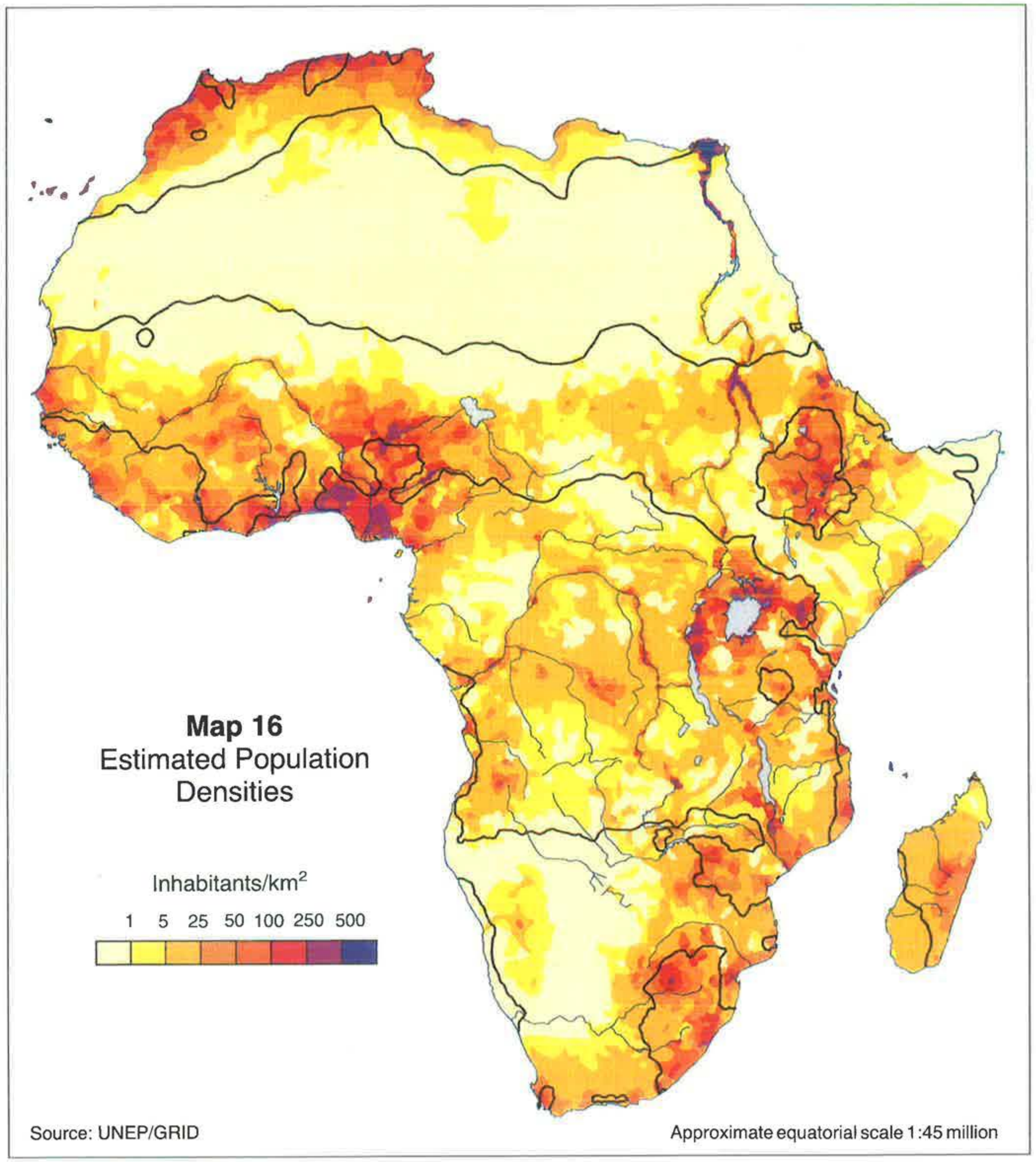


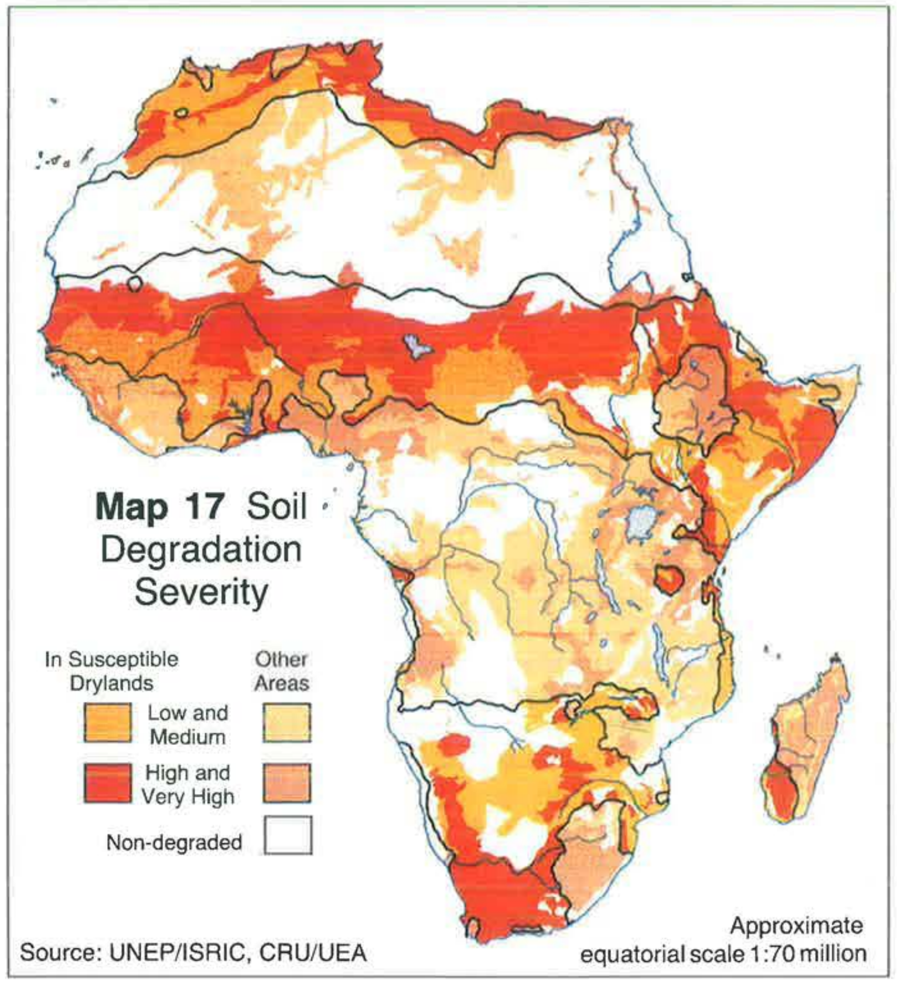
Source: UNEP/ISRIC, NOAA

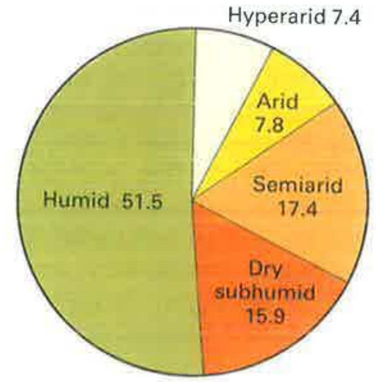
Figure 1 Degradation type by vegetation index in susceptible drylands

Explanations for the relationship between the distribution of soil 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. 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 nonetheless provides a useful indication of the general relationships that exist between vegetation and degradation causes in the susceptible drylands of Africa.

SOIL DEGRADATION AND POPULATION







Population by aridity zone (%)

Table 9 Population in susceptible dryland zones by region as a percentage of total African population

Zone	Region North %	Sahel %	South %	Others %	Total %
Arid	2.6	5.0	0.2	0.0	7.8
Semiarid	4.2	11.9	1.1	0.2	17.4
Dry Subhumid	2.3	9.5	2.6	1.5	15.9
Total	9.1	26.4	3.9	1.7	41.1

Introduction

It is clearly important to undertake an assessment of the spatial distribution and density of the population of Africa in order to examine a basic component of the anthropogenic aspect of human-induced soil degradation. To do so requires a continental scale population database, something that is not readily available. Consequently UNEP-GRID have developed an appropriate database from a variety of sources, standardized the data for compatibility, produced a model to represent the data spatially as population densities and expressed it on a regularly spaced latitude/longitude raster grid covering Africa with an approximate resolution of 10 km x 10 km at the Equator.

Expressing Population Characteristics

At its simplest level, human population can be expressed in terms of absolute numbers. From an environmental viewpoint, however, it is more 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, although it is by no means a full expression of population pressure, since it takes no account of land use, socio-economic factors or indeed the "carrying capacity" of the land. Population density, however, is a 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. Hence, if the population density is greater than the density supportable by the area's resources, degradation can be expected to take place.

Data Sources

Since compatible African population data for an appropriately sized enumeration atlas do not exist, UNEP-GRID utilized a number of existing data sets as inputs to a model aimed at expressing population density at a sufficiently high level of resolution appropriate for a continent-wide map. In all, five data sets were incorporated:

1. The Birkbeck College, London, African Cities Data set, covering 479 cities.
2. The PC Globe 3.0 data set, including 363 cities in fifty-one African countries.

These two sets have been combined so that, with overlap excluded, data for 600 African towns and cities have been used, with all figures standardized to 1988 values.

3. The UNEP-GRID database of administrative districts for African countries including total population at the last respective census, updated from several sources published in 1989 and 1990. The set contains a total of 599 administrative districts, but unfortunately for several countries, including Burkina Faso, Madagascar, Namibia and Somalia and Western Sahara in the susceptible drylands, only total country population data are available.
4. The Sierra Club Wilderness Area and IUCN Protected Areas in the Afrotropical Realm data sets, used to delimit those areas with extremely sparse populations and treated as having a density of less than one person per square kilometre.
5. UNEP/FAO 1984 African database, used to identify auxiliary factors affecting population distribution at the level of individual countries.

Determining Estimated Population Densities

The data sets above do not contain any indication of the spatial distribution of populations outside towns and cities. Therefore a set of procedures, based on accepted social science theory, were instigated and built into the computational model for determining a population density surface for Africa in 1988, the year to which all data were adjusted.

First, towns and cities exert an influence on the distribution of rural population – the idea of "urban pull" or "social gravitation". This can be related to the size (population) of the urban centre, though not linearly. This information was used to weight the individual raster cells in an administrative unit or country, creating a surface of "interactive potential of population".

Population distribution is also affected by natural factors and transport routes. Secondly therefore, environmental and communication factors were used to further weight individual rasters. Though the role of major rail and road routes can be standardized with a degree of accuracy commensurate with the scale of this study, that of environmental factors cannot and was therefore assessed for individual countries. For example, the Nile Valley is a major pull factor in Egypt, but river valleys in Ethiopia often possess characteristics that are not conducive to habitation. Hence, the individual pull factors had to be derived separately for each region. The data for these auxiliary modifications were derived from the 1984 UNEP/FAO African database, while a number of other minor modifications were also applied.

Finally, therefore, an adjusted African population potential surface was created, generating a weighting factor for each raster cell that indicated what proportion of the total population of the administrative district concerned should be allocated to it. This was computed, using the population figures from the UNEP-GRID database. The estimated population density for each raster cell could then be simply calculated as the allocated weighted population figure divided by the area of the grid cell. The range of densities has been divided amongst eight classes, as represented on Map 16.

African Susceptible Dryland Population Densities

Although more than 40% of Africa's population live in susceptible drylands (see Table 9), Map 16 clearly shows that African population densities are generally greatest outside the susceptible drylands, with one major and notable exception. The highest densities in Africa as a whole, in excess of 500 people km^{-2}, are found in the Nile Valley of Egypt because of its special life-supporting characteristics. This apart, dryland densities only exceed 250 km^{-2} in the vicinity of Mediterranean urban centres, Bamako in Mali, Accra in Ghana, Porto Novo in Benin, Kano and Kaduna in Nigeria, Khartoum and Omdurman in Sudan, Asmara and Dire Dawa in Ethiopia and Mogadishu in Somalia in the Sahel Region. The southern African susceptible drylands only support this density around Maputo in Mozambique.

While most of the locations mentioned above are associated with a surrounding area of variable size where densities fall to between 100 and 250 km^{-2}, it is clear that 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 5 km^{-2}.

Population Density and Degradation Severity

Several authorities have noted that there appears to be little relationship between the degree or severity of human-induced dryland degradation and population density, a view borne out by comparison of the overall degradation severity and population density Maps 16 and 17. While there are 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, there are other situations 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; others include the types of land use, the nature of agricultural systems (in some areas, for example, livestock density may be a more relevant factor than human population density) and the patterns of rural settlement, all of which can be considered at a larger scale, more appropriate for investigation of their complex interactions and impacts on the environment. In some areas low population density in highly degraded regions may indicate that people have moved from that region precisely because it has been degraded.

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.

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 the maps opposite shows no clear relationship, with the fuelwood problem being greatest in central and northern Sahel areas, 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.

SECTION THREE

Case Studies

It was noted in the introduction to this atlas that adequate assessment of desertification for specific plans to combat the problem can only be carried out at the local scale, be it national or sub-national. The global and continental Africa sections have given a broad picture of desertification, adopting a set definition of the problem, and using the information on soil degradation in the GLASOD databases. The following section, made up of eight national and sub-national case studies, provides more detailed information on desertification in a selection of national settings. They have also been selected to illustrate the use of a wide variety of methodologies and desertification definitions deemed appropriate to particular national circumstances. Since these examples are nationally based, they also adopt limits to their susceptible drylands that may differ from those based on the Aridity Index used in the preceding sections.

The case study from Syria, which employs the GLASOD methodology, can be used as a further spatial refinement of the preceding global and continental Africa sections. Case studies from Argentina's Mendoza Province and parts of China use national methodologies and definitions of the problem, and in the case of China illustrate some of the approaches used to recover desert lands that could be employed to reclaim areas degraded by desertification. The contribution from Kenya and two examples of studies in Mali all adopt the 1984 FAO/UNEP Methodology for Desertification Assessment. The case studies of central northern Tunisia and the Aral Sea region illustrate the use of the Present Status of Landscape Methodology used by the Faculty of Geography, Moscow State University.

SYRIA: Human-Induced Soil Degradation

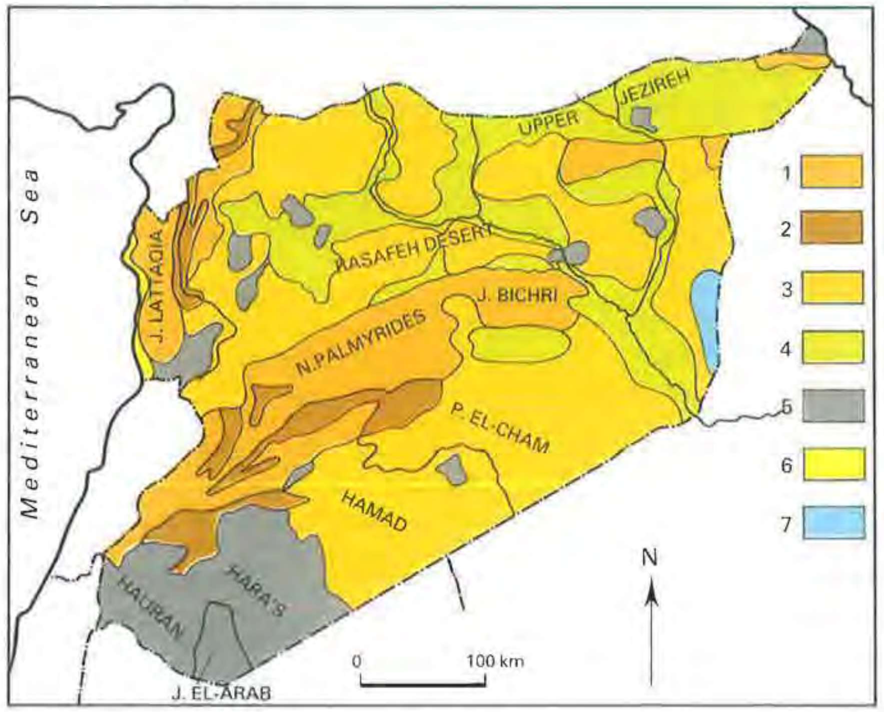
M. Ilaiwi, G. Abdelgawad (The Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD), Damascus) and E. Jabour (Ministry of Agriculture and Agrarian Reform, Damascus)

Introduction

The Middle Eastern country of Syria, with 12.1 million inhabitants and with an area of 185,100 km^2, lies between 32°19′ and 37°20′N and 35°43′ and 42°E. The type and severity of human-induced soil degradation processes in the country are determined by many factors, but it is appropriate to begin with an outline of the nature of the environment itself. A brief explanation of the most relevant environmental conditions is given below.

Geomorphology

Syria can be divided into seven major physiographic regions as shown in Map 1 below.



Map 1 Geomorphology of Syria

1. Mountainous regions: mainly located along the Mediterranean and in the central part of the country.
2. Depressions inside or bordering the mountains: mainly related to the Antiliban and the Palmyrides.
3. Plateaus and plains: covering most part of the country, mainly located in the east.
4. Alluvial and colluvial plains: mainly related to the terraces of the Euphrates and the colluvial sediment in upper Jezireh, originated from Taurus ranges in Turkey.
5. Volcanic mountains, plateaus and plains: because of their specific landscape they are separated from other regions and mostly located in the southwest.
6. Littoral plains: represented by the coastal plains.
7. Local lacustrine-saline basins: mainly located in the eastern part of the country.

Climate

The climate of Syria is generally considered to be a modified Mediterranean type. Four distinct seasons prevail in the country: a cool and rainy winter; a hot and dry summer, spring and autumn, the latter two seasons being relatively short and mild. The country can be divided into three broad climatic regions:

1. The coastal region, with mild winter and warm rainless summer, where annual rainfall averages from 800 to 1600 mm.
2. The desert region covering about 65% of the country with low relative humidity, cool winter and very hot dry summer. Average annual rainfall ranges from 100 to 200 mm.
3. The intermediate region, found between the previously mentioned regions as well as a strip of about 40–50 km along the northern boundary.

Average monthly temperatures range from a minimum of 4°C to 6°C during January in mountainous regions to a maximum of 26°C to 32°C during July in the southeastern part of the country.

Soils

The soils of Syria are spread over five orders of the 1975 United States Department of Agriculture Soil Taxonomy.

1. Aridisols are the most extensive soils covering about 50% of the country. Generally they occur where the annual rainfall drops below 250 mm. They are mostly characterized by Calcic or Gypsic horizons close to the soil surface, weak structure and relatively light texture.
2. Inceptisols are the second most extensive soils covering about 25% of the country. They are the prevailing soils in the rainfed areas west and north of the country. They are mostly characterized by Calcic horizon, heavy texture and moderate to strong structure.
3. Entisols represent relatively young soils, occupying about 15% of the country. They are mainly found as shallow soils over the coastal and the central mountains or as alluvial soils in lower river terraces.
4. Vertisols are heavy textured cracking soils which have a rather limited extension. They mainly occur as associated soils with the Inceptisols.
5. Mollisols with dark surface layer and well-developed structure have also limited extension. They are mainly confined to the coastal region.

Natural Vegetation

Natural vegetation is a function of climate and to a lesser degree of the soils. Considering the climatic conditions, five general zones of natural vegetation may be found in Syria. The important plant species in each zone are indicated below:

1. Forested areas in subhumid or humid climates (lower and upper stages): *Quercus calliprinos* and *Q. infectoria*.
2. Forested areas in subhumid or humid climates (upper stages): *Quercus infectoria*, *Cedrus libani* and *Juniperus excelsa*.
3. Trees or shrubby pseudosteppe in semiarid to arid climate: *Pistacia atlantica* as tree and *Rhamnus palestina* as shrub.
4. Shrubby or dwarf – shrub pseudosteppe in arid climate: *Salsola vermiculata*, *Stipa sp.* and *Poa sp.*
5. Pseudosteppe and desert formation in arid to very arid climate: *Artemisia herba-alba*, *Haloxylon salicornicum* and *Anabasis setifera*.

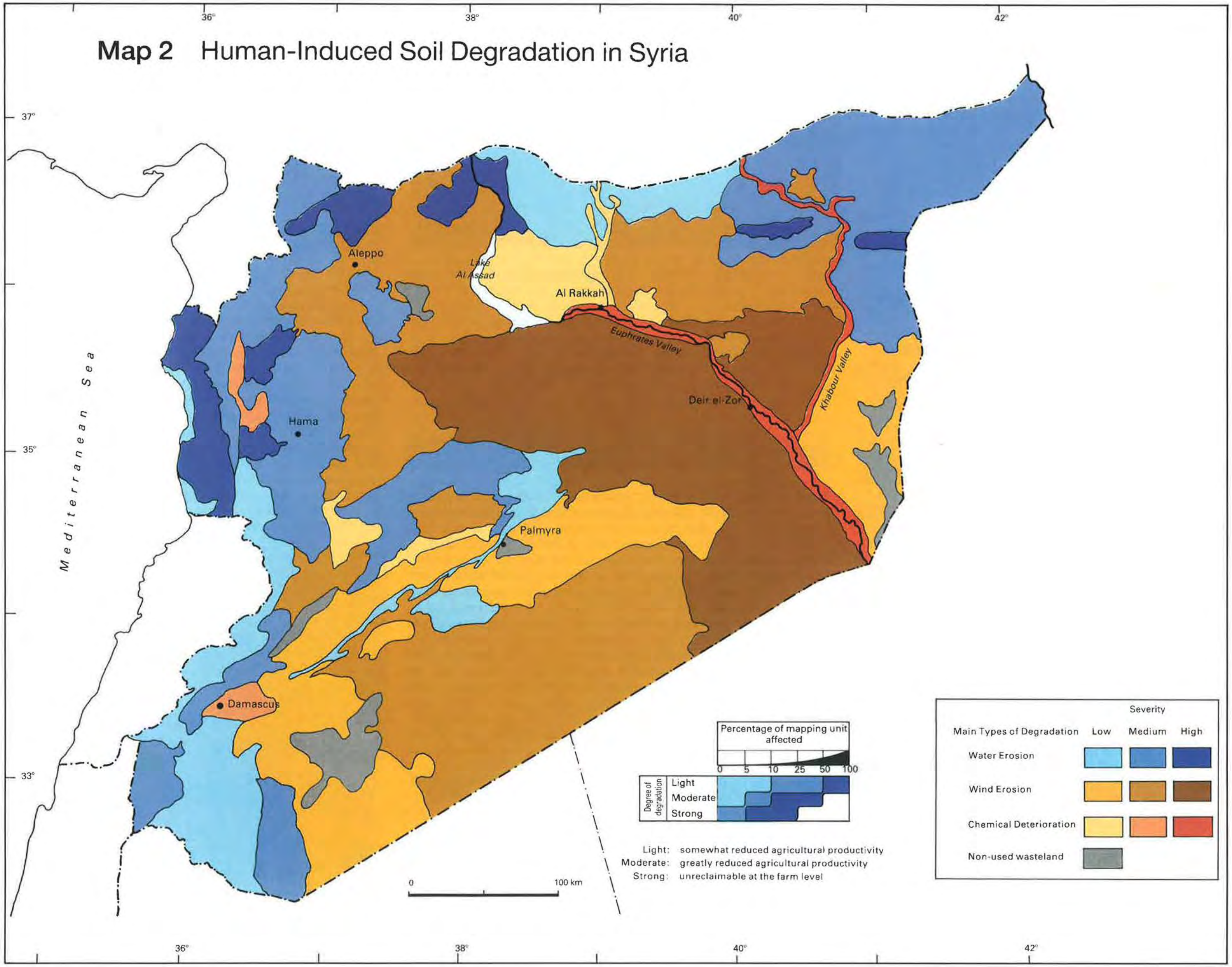
Degradation of the Vegetative Cover

Degradation of the natural vegetative cover has accelerated during the last few decades especially during the last few years, mainly due to human activities. Dry farming and overgrazing are the main causes of rangeland degradation. As a result the numbers of many good range plant species, such as *Dactylis glomerata*, *Orysopsis halciformis* and *Orysopsis milhaceae*, are seriously reduced and have disappeared in large areas where rainfed agriculture is practised. Consequently unpalatable plant species, such as *Anabasis syriaca*, *Astragalus spinosa* and *Cornulaca sp.*, have become dominant in large areas of the steppe.

A systematic survey of the vegetation cover has been carried out for 4.2 million hectares in 1984. The results indicate that the original perennials have disappeared in about 26% of the studied area. *Anabasis spp.* usually replace palatable perennials in the ploughed area. It is the prevailing shrub in about 7% of the surveyed area. Furthermore it has been noticed that in some degraded rangeland the amount of the available dry matter was reduced from 100 kg ha^{-1} to 30 kg ha^{-1} over a period of eight years.

Present degradation in the forest areas is mainly due to fire and land clearing. High quality forest trees, such as *Pistacia lentisens*, *Pinus broutia*, have also been replaced by low quality ones such as *Rhus cotinos*, *Peterium spinosa*.

Map 2 Human-Induced Soil Degradation in Syria



CHINA: Desertification Mapping and Desert Reclamation

Zhu Zhenda, with contributions by Wand Xizhang, Wu Wiei, Kang Guoding, Zhu Che, Yao Fafeng and Wang Tao (Institute of Desert Research, Chinese Academy of Sciences)

Introduction

Desertification can be considered to be the process of environmental degradation caused by human activities under fragile ecological conditions and imbalance between resource utilization and the environment. This ultimately leads to the diminution of productivity and the creation of desert-like conditions. From China's perspective desertification mainly concerns erosion by water and wind. It is exemplified in this study by three maps of increasing detail: a countrywide desertification map, a regional desert control study and a local control study, the last two from the Tengger Desert of northern China.

Desertification Map of China

Based on ground survey and analysis of aerial photographs and Landsat TM data, 1,483,000 km^2 experience desertification processes in China. Aeolian processes actually or potentially affect 334,000 km^2 of this area; water-affected areas (430,000 km^2) occur in the loess plateau region. For the purposes of this case study it should be noted that water eroded areas in the humid southern parts of the country were included in the assessment of desertification.

Map 1 shows a range of landscapes which are briefly summarized below.

Wind Erosion Areas

These are arid and semiarid areas with natural sandy surfaces. There are two distinct types of area in this category:

Areas already desertified West of longitude 105°E desertified sandy areas mainly occur in the lower reaches of inland rivers due to pressure on the water resources or they are found around oases where vegetation destruction has reactivated stabilized dunes. The lands east of 105°E constitute the main area in China experiencing desertification, forming about two thirds of all desertified lands in the north of the country.

Three distinct landscapes exist: wind eroded, surface roughened, sand sheets formed through over-cultivation of sandy grassland; gravel and sand sheets in overgrazed grasslands; and naturally stabilized sand dunes that have been reactivated due to over-cultivation, overgrazing and vegetation clearance. The first two categories have formed in the past 100 years whereas the last, though reactivated over the same time period, represents the reworking of ancient Quaternary dunes.

Areas prone to desertification These areas have the ecological system and dynamics (wind regimes, recurrence of droughts) 49 Wheat or rice straw was used to construct 1 m^2 checkerboards laid on the mobile dune surfaces inside the shelterbelts. These between the semiarid and subhumid zones, where animal husbandry is currently widely practised. Susceptible lands include the areas around wells in arid and semiarid areas where overgrazing is beginning to appear and the "blownsand" lands in the subhumid and humid areas, mainly in the plain of north China, the western part of the northeast China Plain, the middle reaches of the Changjiang River and the coastal plain.

Water Erosion Areas

Water erosion mainly affects the middle reaches of the Huanghe River in the loess region, mountainous areas of southwestern China and hilly areas in the northeast. Four different landscapes can be identified:

1. Ridge and badland areas formed by water erosion in the semiarid and subhumid loess plateau.
2. Badlands in humid areas where runoff has affected granitic and lateritic landscapes.
3. Rocky desert-like landscapes in limestone areas of the mountain region where desertification is indicated by vegetation removal, severe soil erosion and loss of productivity.
4. Gravel desert-like landscapes in humid areas where debris flows in mountain regions have led to the blanketing of valley floors with sand and gravel.

Map of Desert Control in the Southeast Tengger Desert

Although the methods described below have been applied to the reclamation of natural desert, they may be applicable to the reclamation of land desertified by human actions. The Tengger Desert is situated in the arid–temperate zone of northern China, has a mean annual precipitation value of around 200 mm and sparse scrub vegetation. Sand dunes, dominated by transverse forms, cover 71% of the area. Over 90% of these are active, migrating at a rate of 2–5 m per year in a southeasterly direction. The remaining dunes are stabilized or semi-stabilized (see Map 2).

The encroachment of dunes causes problems for the oases on the southeastern fringe of the desert and for a 52 km length of the Baotou–Lanzhou railway. Since 1956 the Chinese Academy of Sciences, in co-operation with the Railway and Forestry Departments and Zhongwei County, has attempted to establish and evaluate four different sand control measures:

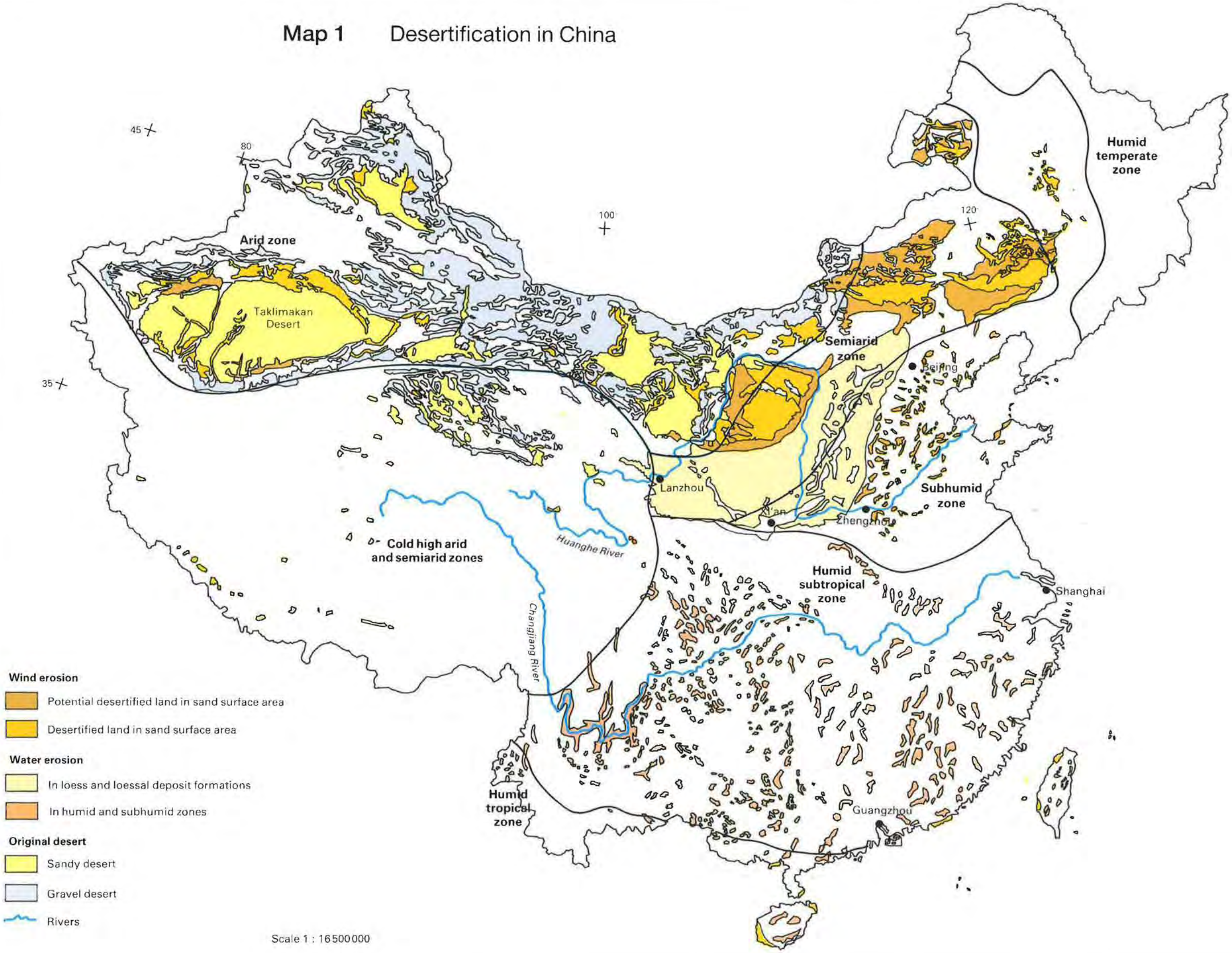
1. Tree and shrub shelterbelts to protect farmland from encroaching sand.
2. Methods of fixing dune surfaces, using straw checkerboards and tree and shrub planting, to protect the railway;
3. Checkerboard establishment bordering the main highway;
4. Dune levelling on the terrace of the Huanghe River to establish a new irrigation scheme.

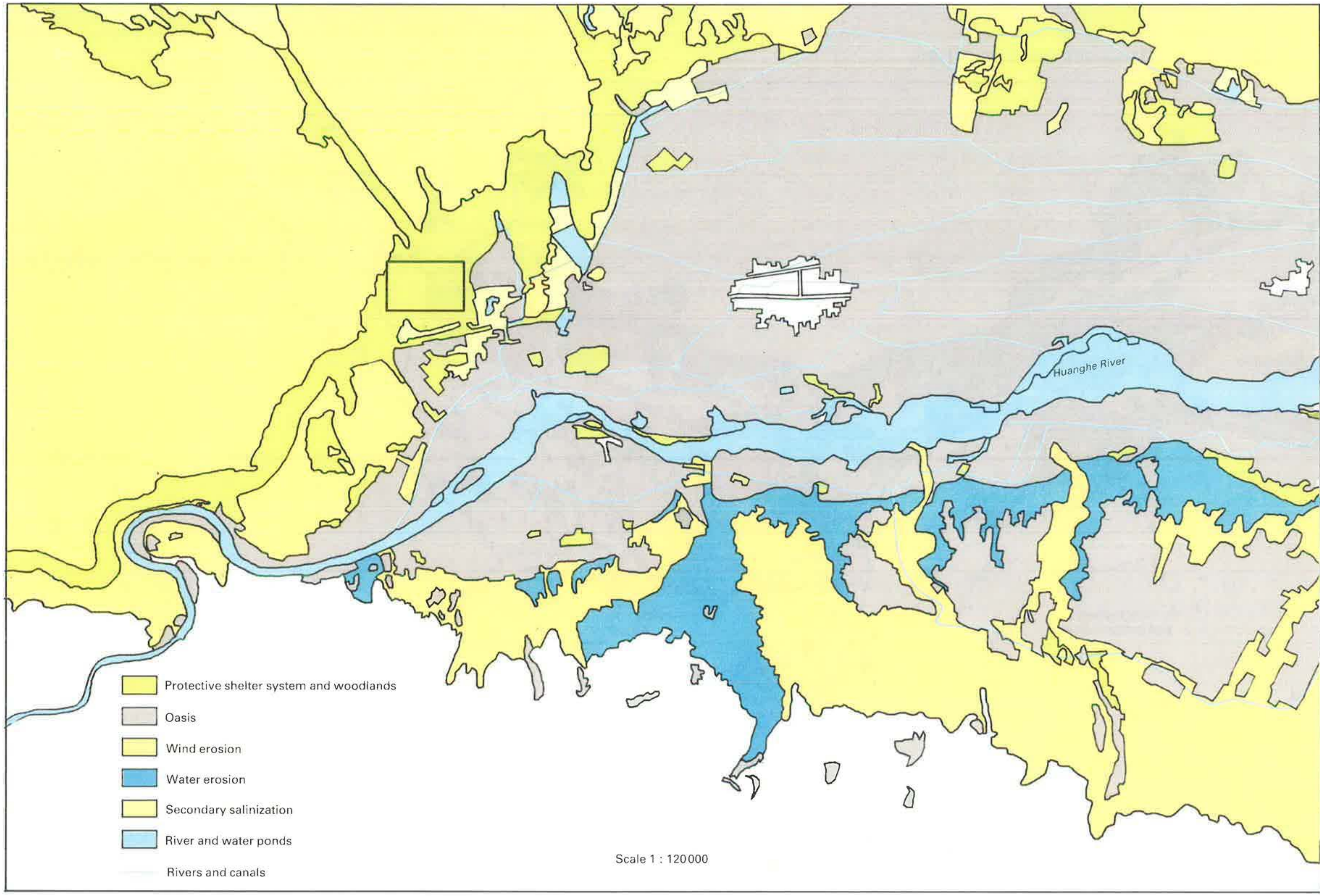
The schemes have proved successful in terms of protecting the main communication routes in the area and in recovering and creating new agricultural land. Between 1959 and 1990, for example, the area shown as oasis on the map has been enlarged from 215 km^2 to 335 km^2. A detailed breakdown of the land use changes in the oasis area is given in Table 1.

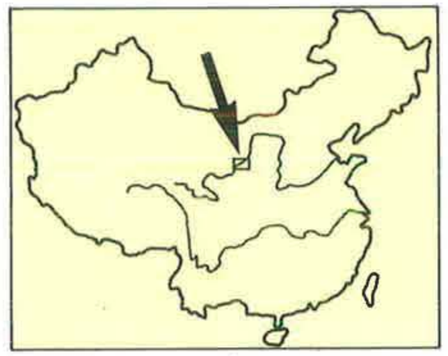
Table 1 Changes in oasis land due to desert control measures in the Southeast Tengger Desert (km^2)

	Farmland	Orchard	Woodland	Shelterbelt	Mechanical Shelterbelt
1959	210.9	3.9	0.7	0.0	0.0
1990	285.3	5.0	3.8	40.5	12.5

Map 1 Desertification in China



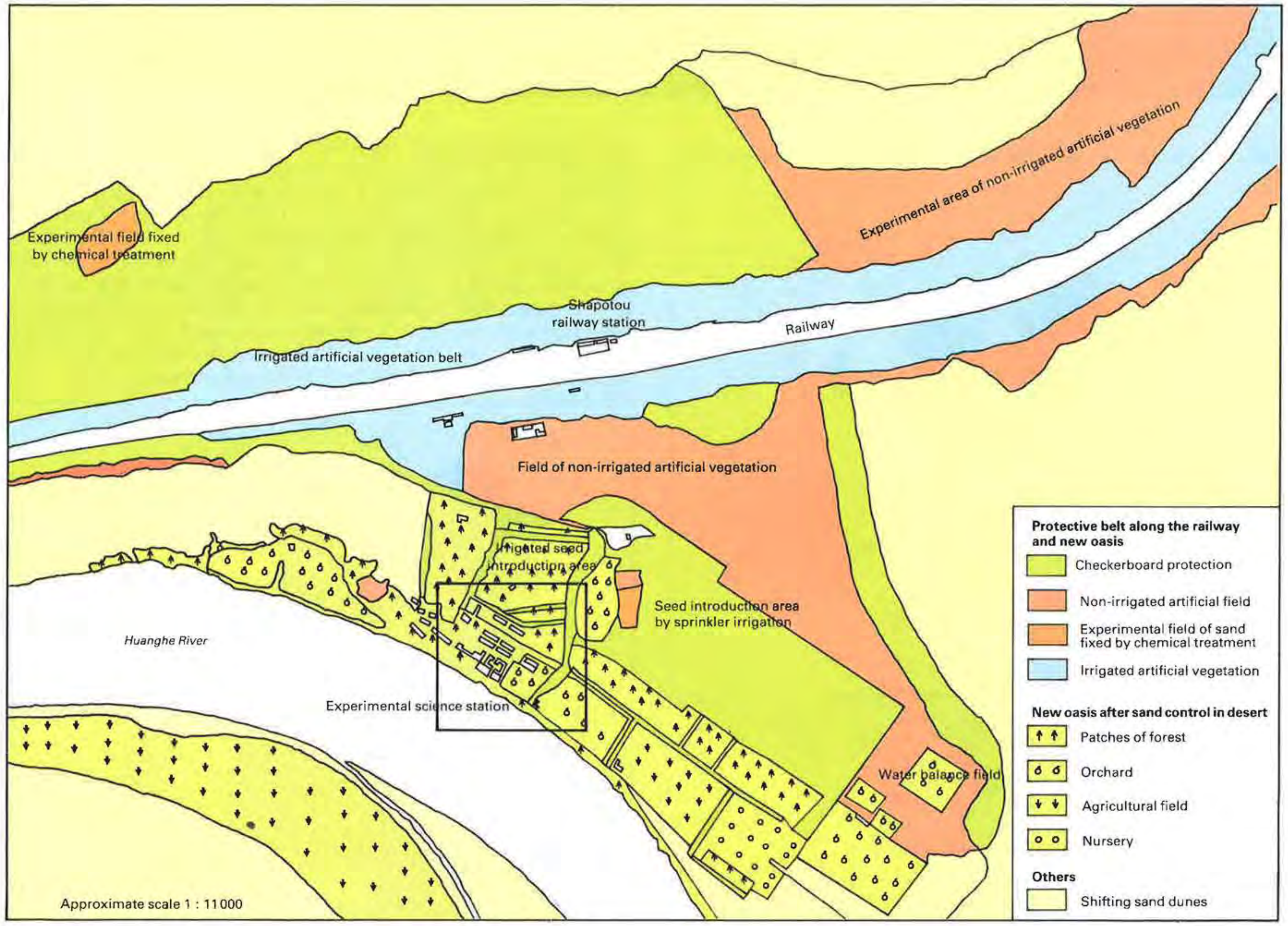




Locator for map 2

Map 2 Status of desertified land control in Southeast Tengger Desert

These photographs depict the area located in the small framed section of this map. The top photograph was taken in 1959 and the photo beneath it was taken thirty years later.

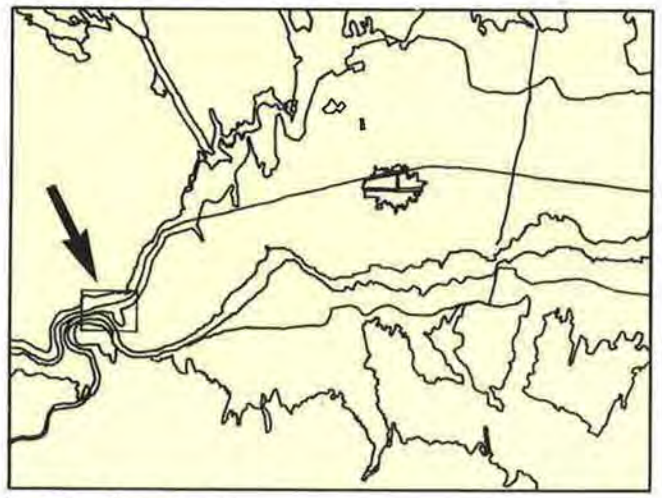


Desert Control in the Shapotou Area of the Southeastern Tengger Desert

Map 3 gives details of the control methods established at Shapotou on the north bank of the Huanghe River to deal with the problems of shifting sand described in the preceding section. In order to prevent burial of the railway line by sands moving from the northwest, protective shelterbelts were planted on both sides of the track, the belts having widths on the windward and leeward sides of 500 m and 300 m respectively. Wheat or rice straw was used to construct 1 m^2 checkboards laid on the mobile dune surfaces inside the shelterbelts. These boards are successful in reducing boundary-layer wind flow and therefore in reducing sand entrainment. Suitable sand-holding species (*Salix flavida, Hedysarum scopariu, Caragana korshinskii*) were planted inside the boards in order to give more substantial and longer-term surface protection. Vertical sand barriers were constructed at the front of the windward barrier to encourage sand deposition.

After being in place for thirty years the measures taken have proved to be an effective ecological control of the shifting sand. The checkerboards have reduced wind velocity by 10% at a height of 2 m and by 20–40% at 0.5 m above the ground surface, reducing the potential for sand entrainment and transport. Sand transport in the checkerboard areas is 1% of that on the mobile dune surfaces. The organic content of the surface sand crust comprises 16% of the total sediment, twenty-three times that of the mobile dunes, and surface vegetation cover has increased from 5% to 20–40%.

The mobile dunes on the terrace of the Huanghe River have been mechanically flattened, planted with shelterbelts and supplied with water and sediment pumped from the river for fifteen years. This has led to topsoil development to a depth of 20 cm and an increase in the silt and clay content of the soil from less than 0.5% to 6%, and of the organic content from 0.08% to 1.3%, providing sufficient initial nutrients for the establishment of agricultural land.



Locator for map 3

Map 3 Desert control in Shapotou area of Southeast Tengger Desert. The photographs (below) taken in 1958 (left) and 1983 (right) are located within the framed section of the map above.

ARGENTINA: Desertification Hazard Mapping of Central-Western Argentina

IADIZA (Instituto Argentino de Investigaciones de las Zonas Aridas)
IADIZA Specialists:
Fidel A. Roig, M.M. González Loyarte, E.M. Abraham de Vazquez, E. Martínez Carretero, E. Méndez and Virgilio G. Roig, with the co-operation of N.B. Horák, M.C. Scoones and SEDIGRAF

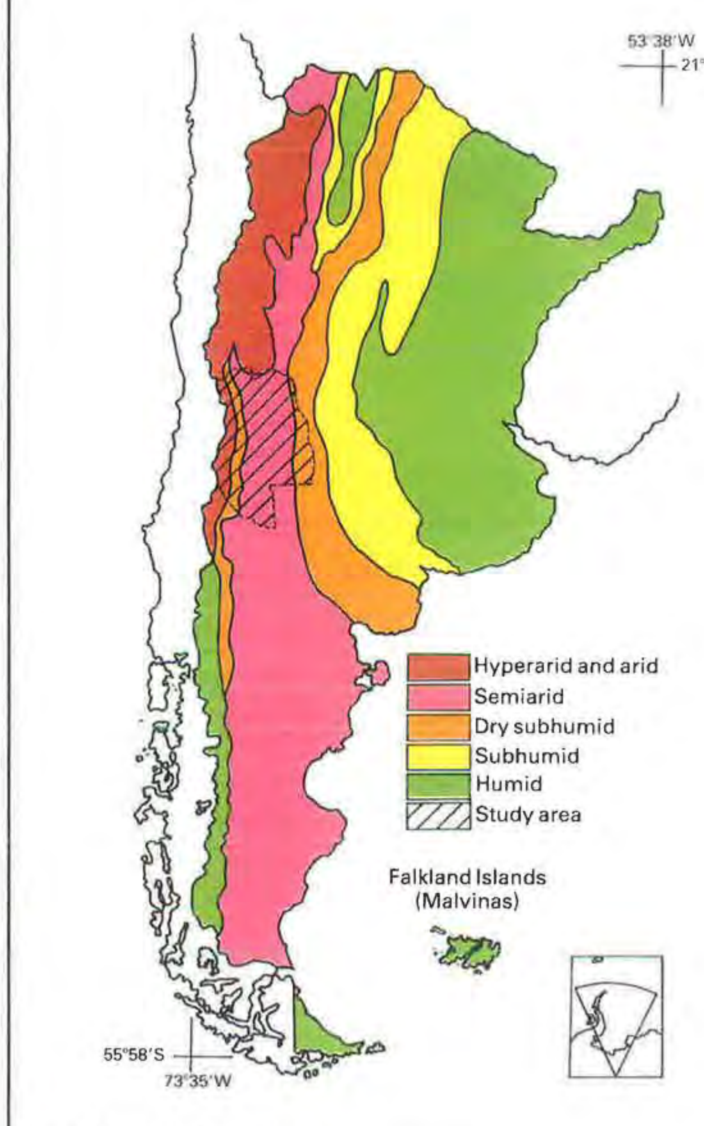
Introduction

Much of Argentina is made up of drylands (see Map 1), with about 75 per cent of the national territory in the arid, semiarid, and dry subhumid bioclimatic zones. The origins of desertification in the country can be traced back to the Spanish conquest and subsequent colonization, which involved substantial changes to the native way of life, and the desertification process has been accelerated in the last 150 years by a new phase of European immigration into the country. These immigrants have pursued a policy of irrational natural resource extraction through expansion of crops, deforestation, overgrazing, field burning, and the consequent impoverishment and marginalization of the rural population.

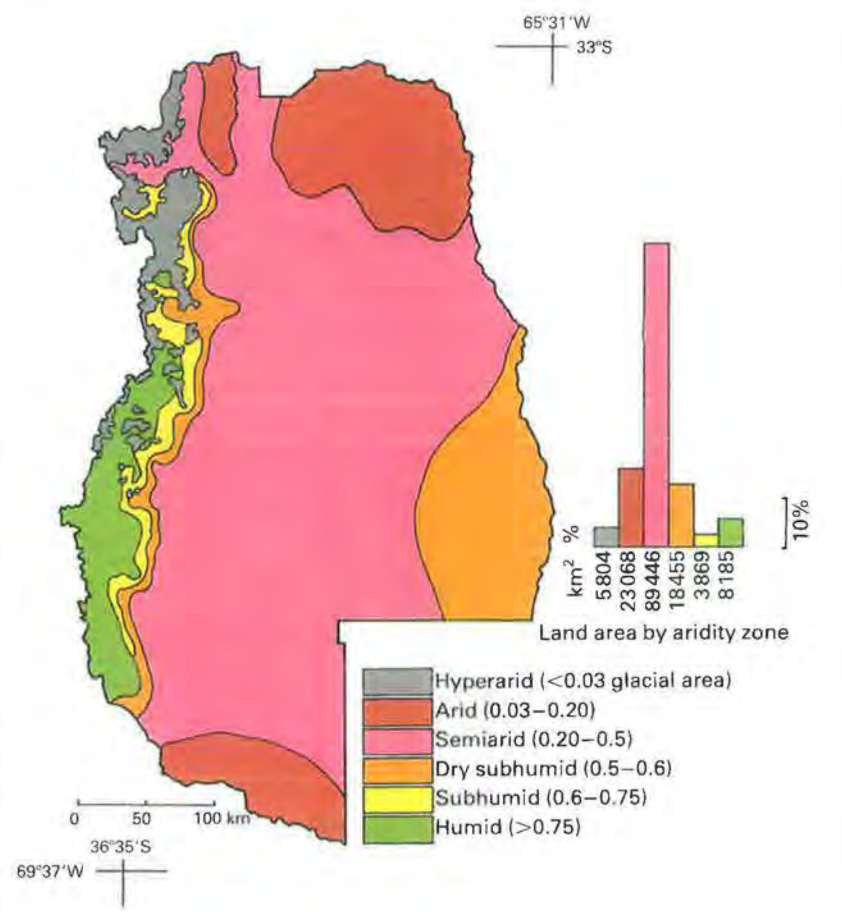
IADIZA has established that desertification has led to a loss of productivity of between 20 and 40% of natural resources of Argentina.

Study Area

The province of Mendoza was selected as the study area. Arid and semiarid zones comprise 76% of its territory (see Map 2) and show a marked heterogeneity, ranging from the Andean desert, with the highest peak in America, the Aconcagua (6959 m above sea level), to the vast alluvial plains in the east (less than 500 m above sea level). Human population is largely concentrated in oases where irrigated land is farmed, but extensive livestock raising is practised in the drylands, where the number of rural settlements is low. The irrational management of resources brings about increasingly critical situations: the expansion of saline areas and exodus of rural people; decreased carrying capacity of the grazing lands due to their loss of productivity; increased natural disasters (avalanches in the mountains, increasing effects of torrential rains and floods in the plains), and the consequent concentration of the rural population in cities, under poorer living conditions.



Map 1 Argentine bioclimatic zones and location of case study area



Map 2 Aridity zones in Mendoza, Argentina (index $\frac{P}{PET}$)

Map Methodology

The method used for desertification hazard assessment is essentially cartographic. The information is arranged in analytic thematic maps and transferred to synthetic maps in progressive stages to achieve the final map of desertification hazards (see Figure 1). As a result of the different degradation processes, the set of maps published in this case study are designed to test the methodology applied by IADIZA for determining regions prone to desertification.

Stage 1 (Inventory)

a) *Basic thematic maps*
All basic aspects of physical and human geographic information are gathered at this stage. With the aid of aerial and satellite material and subsequent field work (see Figure 2), a first set of maps of both aspects is accomplished (see Map 3).

b) *Map of ecosystems*
The map of ecosystems is based upon the physical information gathered. This map provides the basis for the following steps.

Stage 2

a) *Thematic maps of physical and human factors and processes*
Factors and processes responsible for desertification in the study area were determined from previous experience. Only those which meet the following requirement have been selected:
i capable of being quantified as a percentage;
ii amenable to an easy, quick and cost-effective assessment.
For each of the selected processes and factors a corresponding thematic map was worked out. Following the same criteria, the human factors and processes were selected and also represented in maps.

b) *Synthetic maps of physical and human factors and processes*
By superimposing the maps of factors and processes on the base map of ecosystems, we obtain the values of each ecosystem for every ecological unit. This information is transferred to a double-entry chart in which the sum of the values of each ecosystem gives both its degree of vulnerability and the intensity of human pressure. These parameters are then mapped (see Maps 4 and 5).

Stage 3

Desertification hazards
The following formula is used to designate the desertification hazard for a particular ecosystem:

Vulnerability + Human pressure = Desertification hazard

With this new set of values a composite map of desertification hazards can be derived (see Map 6).

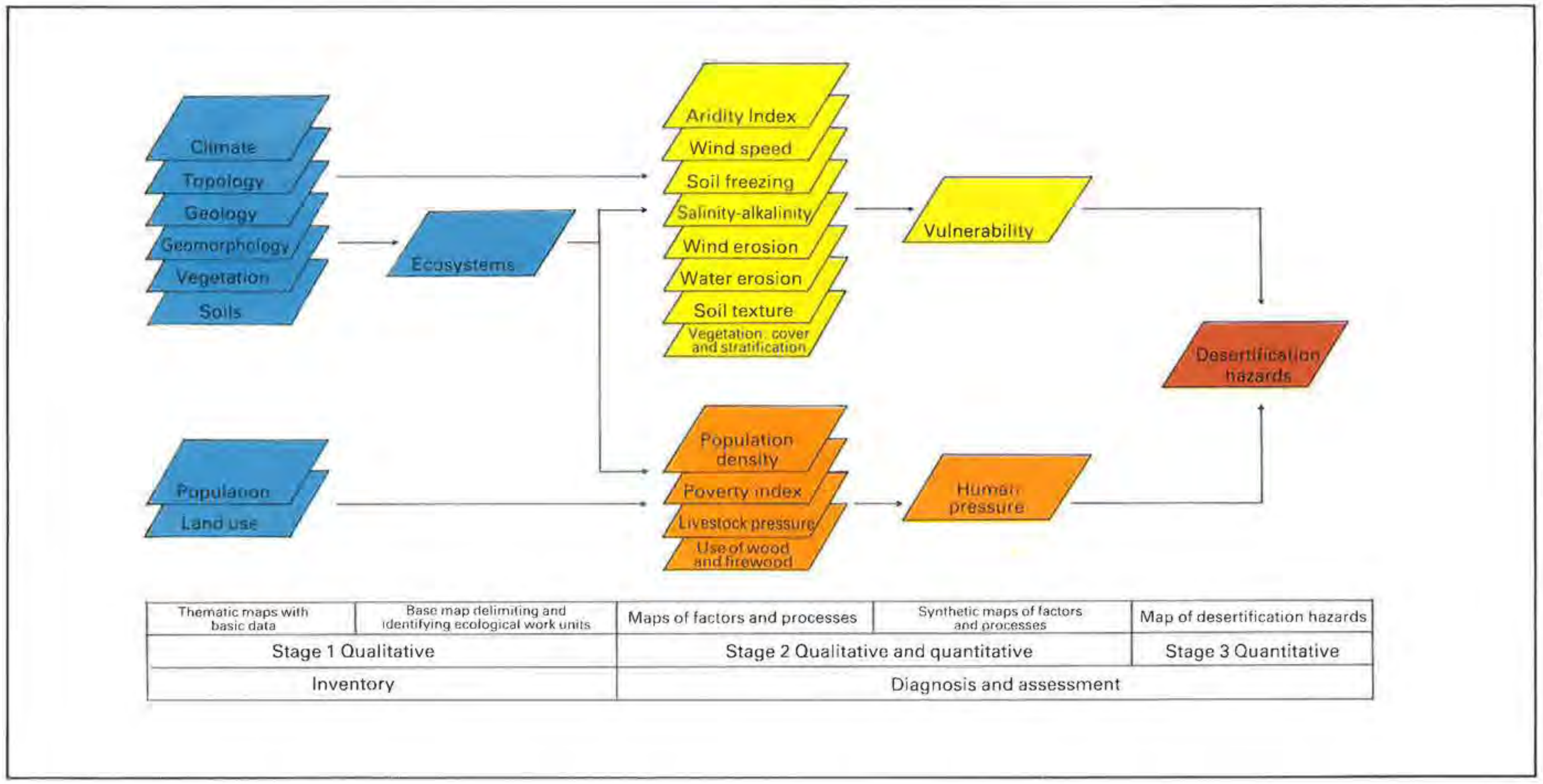
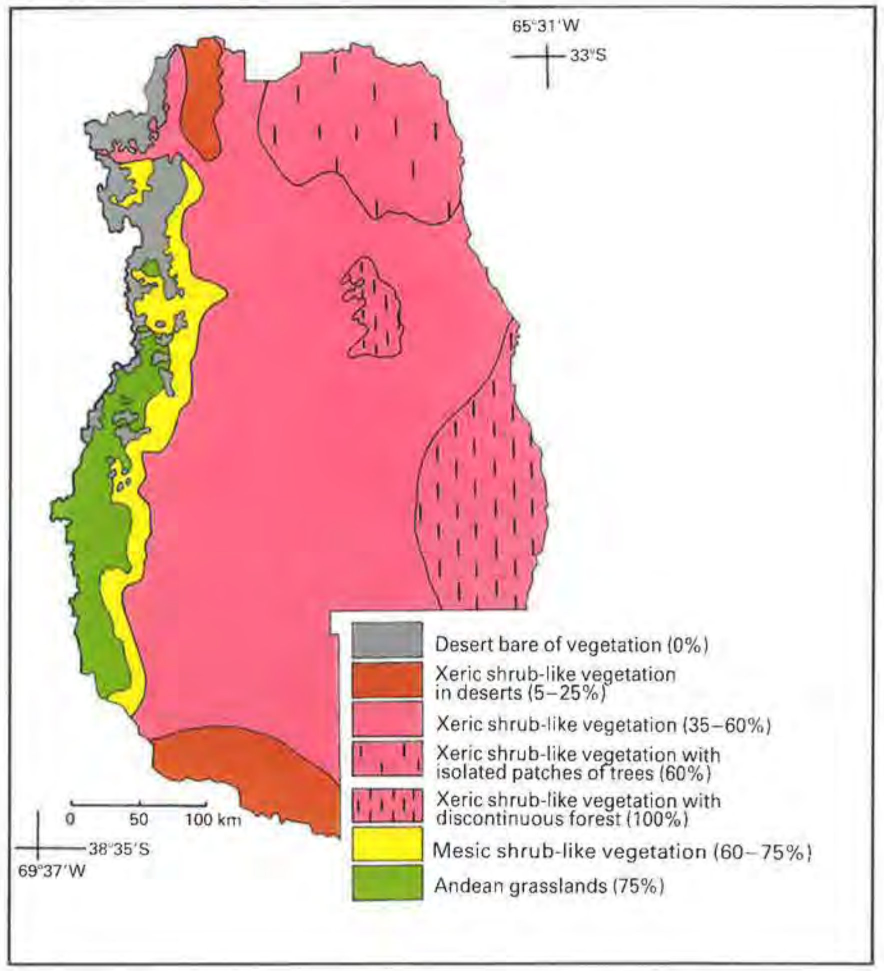
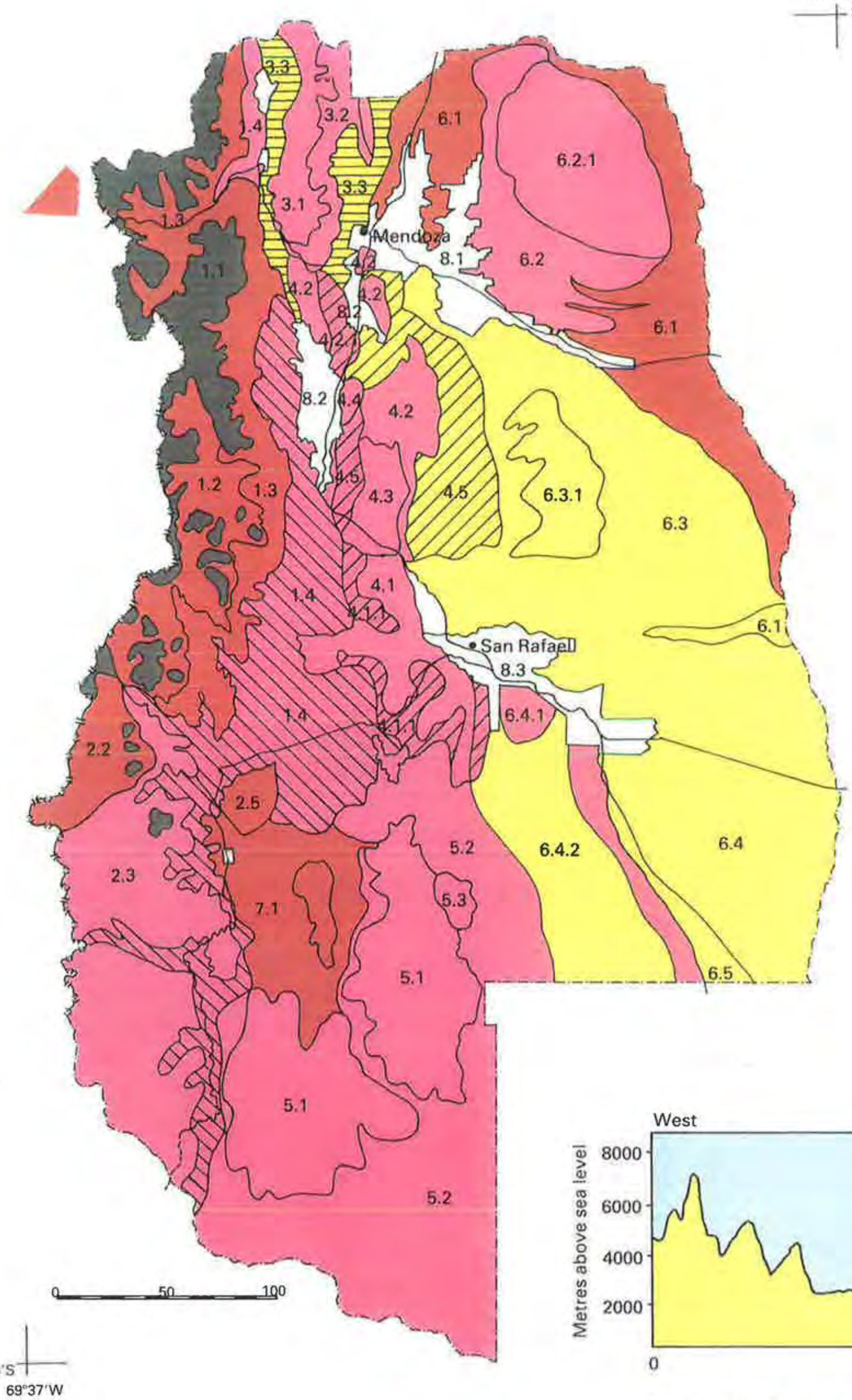


Figure 1 Methodological approach

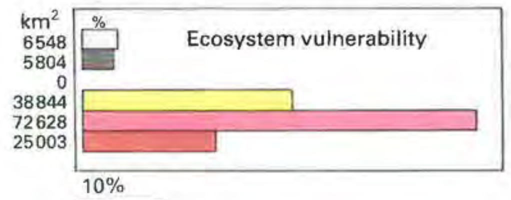


Map 3 Types of vegetation and cover (%)

Figure 2 Determination of plant cover



Ecosystems	km²	%
1 High arid mountains 4000–6000m asl	26342	17.7
2 High snow-covered mountains 3000–4000m asl	13990	9.4
3 Highlands 2000–3000m asl	5209	3.5
4 Hills 800–1200m asl	11906	8.0
5 Volcanic relief	26938	18.1
6 Plain with meandering allochthonous rivers	53280	35.8
7 Depressed plains	4614	3.1
8 Irrigated oases	6548	4.4
Total	148827	100.0



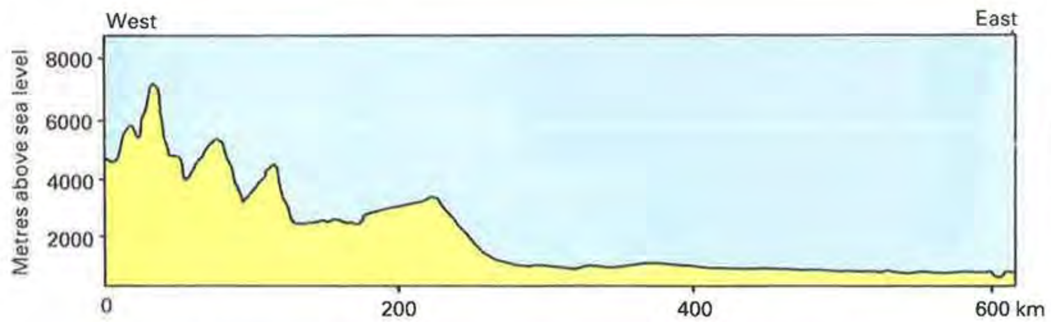
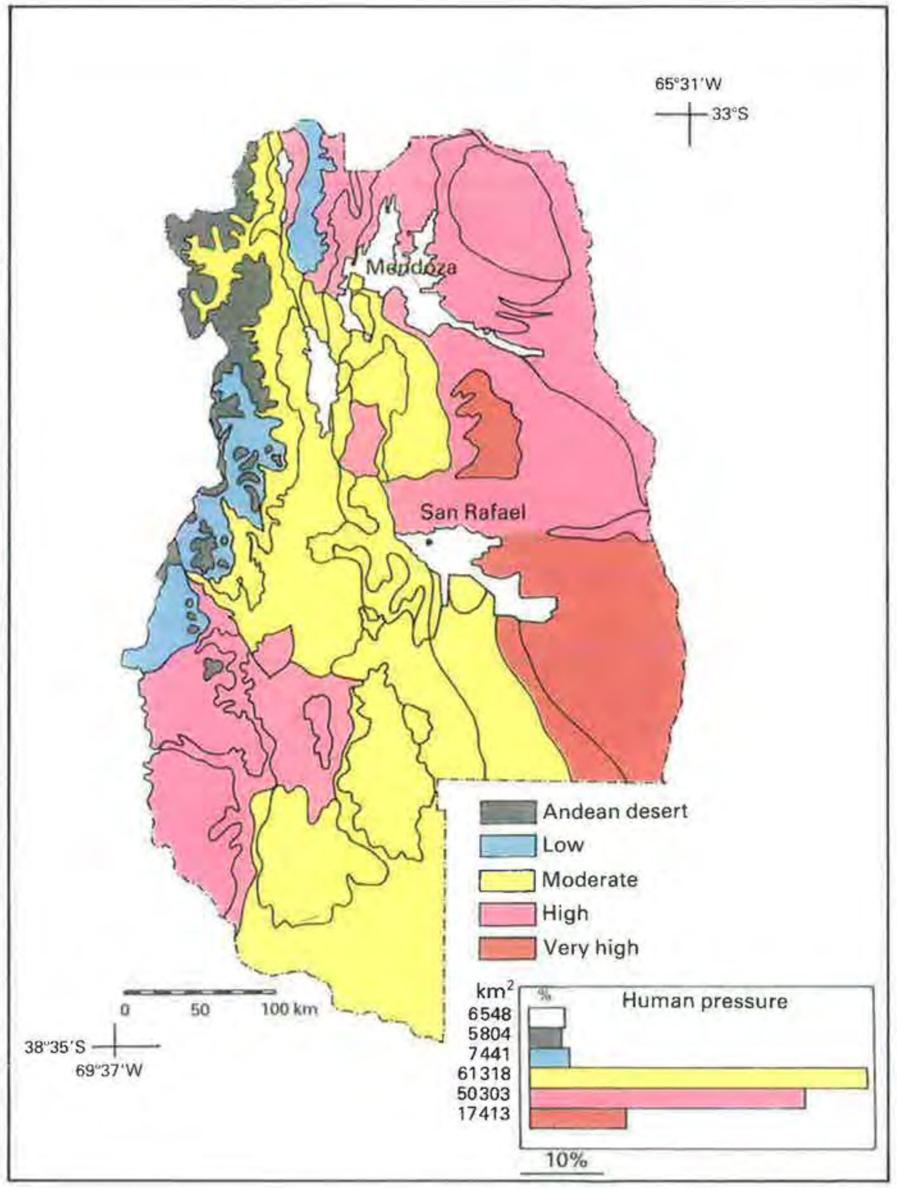


Figure 3 Topographic profile of Mendoza at 32° 39'S

Map 4 Ecosystem vulnerability



Map 5 Human Pressure

Figure 4 Field in poor condition owing to anthropogenic degradation. *Cactacea* are dominant.

Maps of Desertification Hazards, Ecosystem Vulnerability and Human Pressure

Except for the uninhabited Andean desert – with low human pressure – the entire territory of Mendoza province shows widespread deterioration. Comparative analysis of the maps indicates that the most fragile ecosystems correspond either to areas where the Andean relief is strongly marked, or to plains showing intense processes of salinization and alkalinization, with unfavourable climatic conditions in either case. The vast piedmonts, hills and pediplains of the volcanic relief are also highly fragile.

The highlands (3.1 on Map 4) show high fragility, but since they offer sparse resources to development, they are only moderately prone to desertification hazards.

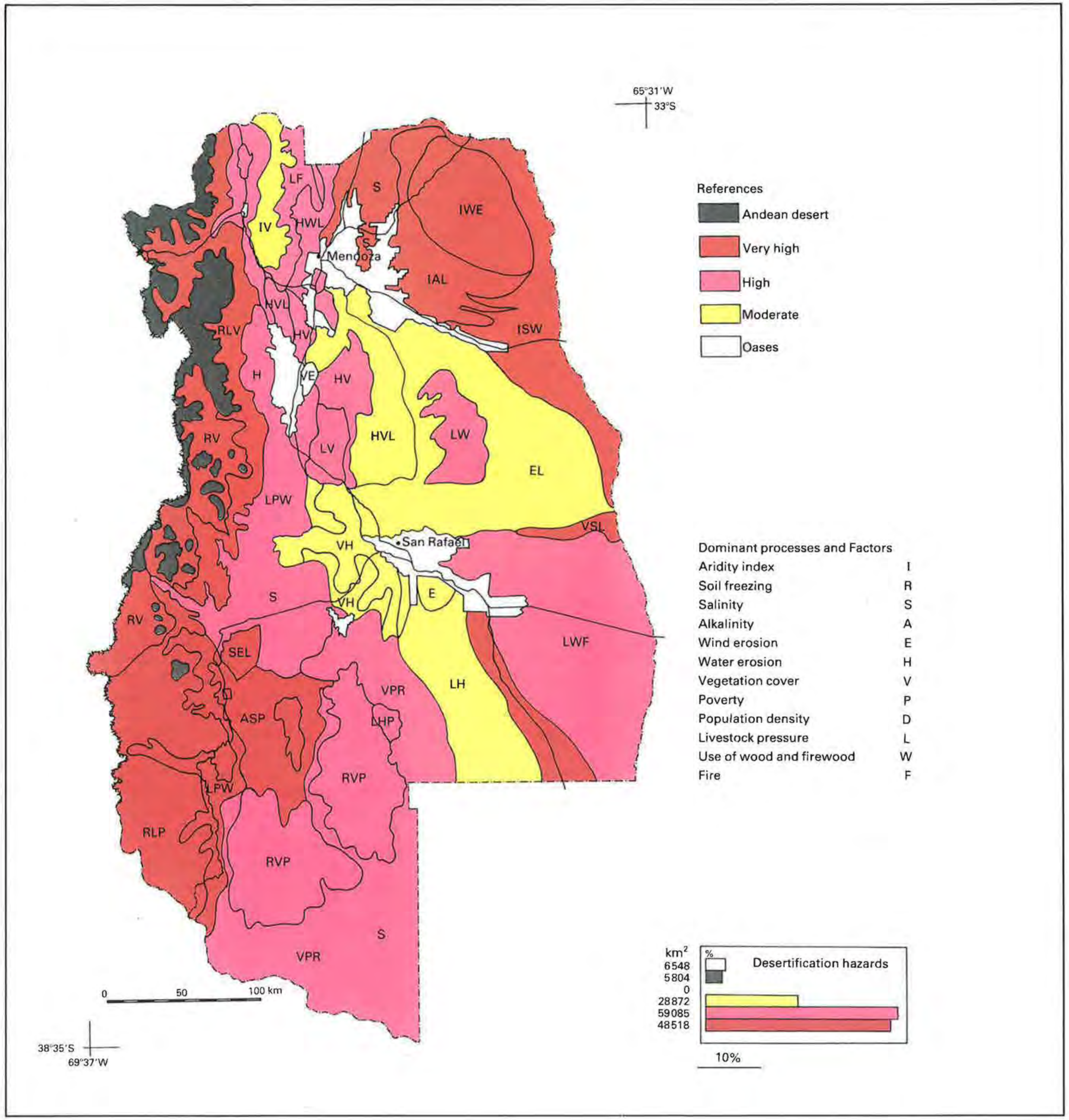
In the map of human pressure (Map 5), the most attractive ecosystems (6.4 and 6.3.1 on Map 4) are the richest in forests and forage, but fortunately, owing to their greater stability and more rational use, they only reach a minor degree of desertification hazards.

In the six most critical ecosystems (6.2, 6.2.1, 6.1, 2.3, 2.2 and 7.1) the povety of their inhabitants is connected with extensive livestock raising. They find it difficult to change routine procedures or to incorporate techniques for desertification control.

The map of desertification hazards (Map 6) indicates that the areas highly prone to desertification not only coincide with the most fragile ones, but also stretch considerably over the whole of the Andean region and of the northeastern area.

In the oases, crop farming has often been expanded onto unsuitable soils and used inadequate techniques, resulting in severe salinization of irrigated soils.

Figure 5 Nebkas caused by overgrazing.



Map 6 Desertification Hazards

KENYA: Pilot Study for Desertification Assessment and Mapping, Baringo

J. Grunblatt, W.K. Ottichilo, R.K. Sinange and H.A. Mwendwa (Department of Resource Surveys and Remote Sensing), and J.H. Kinuthia (Kenya Meteorological Department)

Introduction

Kenya lies astride the Equator in east Africa. It is a country of many peoples, prolific wildlife and diverse landscapes covering an area of 583,000 km^2. Approximately 20% of the country is considered to have a high agricultural potential, receiving over 1000 mm of rainfall. The remaining 80% is arid and semiarid rangelands with a predominantly pastoral/grazing land use.

Tourism and agriculture form the cornerstones of the Kenyan economy. The rangeland gameparks and coastal areas are international tourist destinations. Over 730,000 people from throughout the world visit Kenya annually and the number is expected to reach over one million by the year 2000. The high potential areas of the country support the domestic agricultural needs of the nation and supply important export commodities such as coffee, tea and horticultural crops.

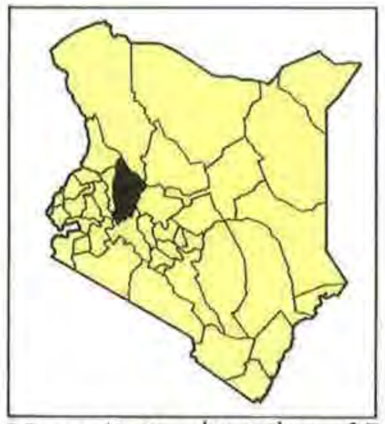
Currently the national population is estimated at 21.4 million people. The growth rate is estimated at 3.34% (1989 census) and over 52% of the population is less than fifteen years old.

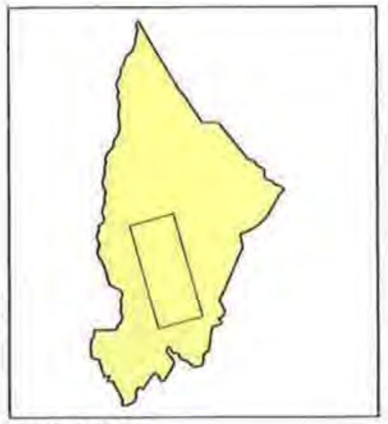
The combination of population growth and economic development is placing new pressures on the fragile land resources of Kenya. Increasingly people are turning to the rangeland areas to satisfy these growing demands. The arid and semiarid rangeland areas of the country have long been used by pastoralists for livestock grazing, but intervention in the form of nature reserves, dryland agriculture, waterhole boring and settlement schemes are changing the nature of land utilization in these areas. Scientists and administrators are being called upon with greater urgency to evaluate and prioritize land use policies with regard to the development of the rangelands.

The goal of this study was to contribute toward a methodology that would both allow reliable evaluation of resource utilization and degradation in the Kenyan rangelands and would facilitate evaluation of relative impacts of mitigation policies. The FAO/UNEP Methodology for Desertification Assessment (1984) served as a starting point for this study.

Approach

Desertification is here defined as land degradation in arid, semi-arid and dry subhumid areas resulting mainly from adverse human impact, in accordance with the definition used throughout the global and continental Africa sections of this atlas. Desertification assessment can be seen as a problem of landscape ecology and therefore as one of holistic processes involving physical, biological, climatic and human influences. Although such processes are very complex it was felt that simple models could be constructed that approximated the processes of interest. In addition it was felt that only simple models could be practically applied and broadly applicable. Models can serve as tools to facilitate an integrated assessment of resources and human use. Resource demand models can be developed that allow insight into the impacts of human use of resources and the implication of management decisions.



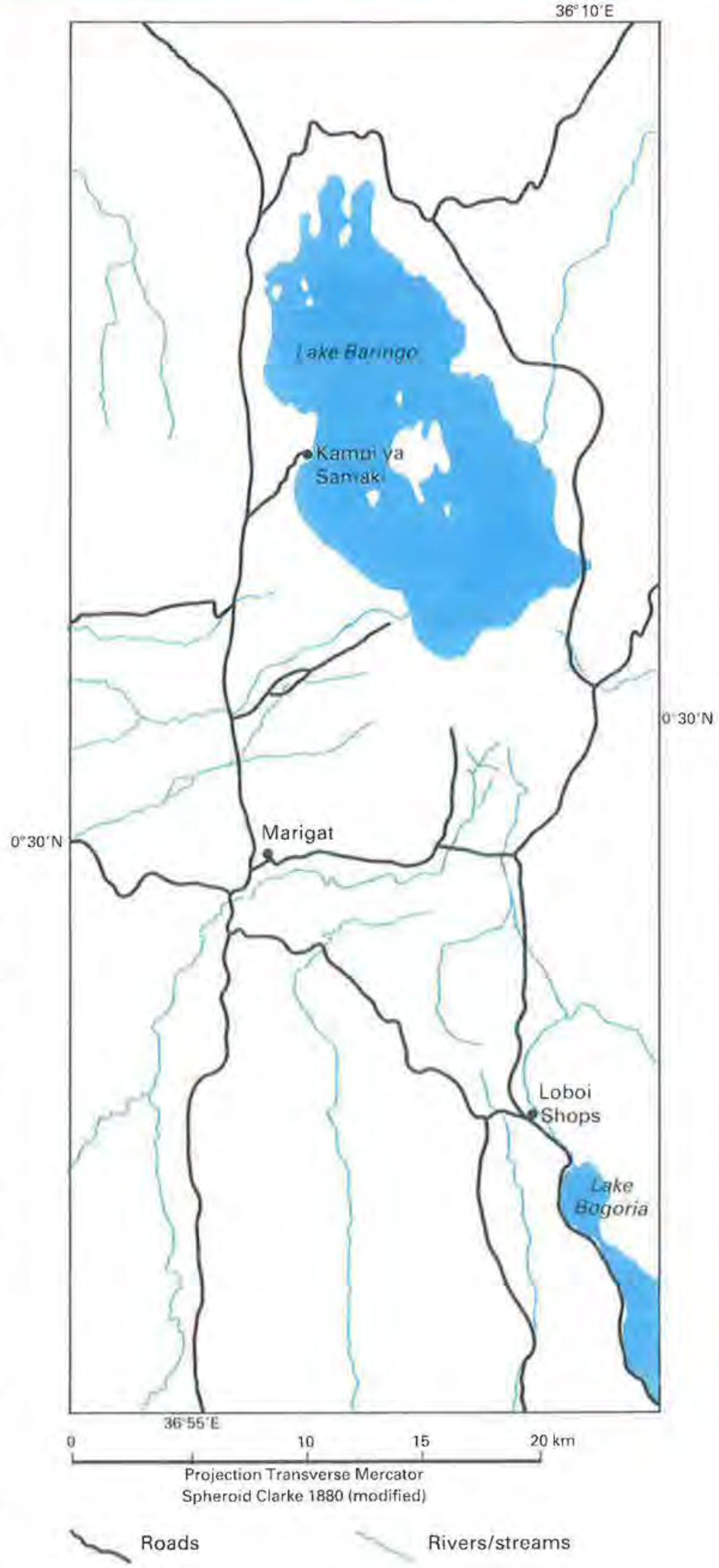


Map 1 (*left*) Location of Baringo district;
Map 2 (*right*) Location of study area in Baringo district

In developing models it was necessary to generate criteria against which the results of the modelling could be evaluated. It was assumed that many of the desertification indicators were related, as each was describing another aspect of the same overall phenomenon. Consequently the model results could be compared with relevant field data and other model output. It is recognized that such relationships are not necessarily continuous, particularly in extreme cases. Also when comparing modelled indicators, sufficient bias due to similarity of factors might arbitrarily produce correlation. However careful comparison of indicators can prove extremely useful.

Within a large study area, small areas can be defined that are representative of the diversity of the larger area. Such areas can be used for more detailed data gathering and provide a basis for model development. Derived models can then be applied over the study area. Similarly, verification areas can be identified to validate model performance and facilitate required modifications.

A computer geographic information system (GIS) was used in this assessment. Desertification is a spatial phenomenon and a GIS is specifically designed for handling spatial data. The analysis tools of a GIS provide a capability for evaluation of spatial correlations as well as process oriented modelling. Use of a GIS also stimulates a view toward the overall integration of data and consequently encourages the establishment of a systematic database. Beyond the immediate need of assessment such a database can provide important baseline data for future work such as the determination of desertification rate or evaluation of mitigation efforts.



Map 3 Baringo study area

The approach adopted in this study stresses a hierarchical view toward desertification assessment. Three levels of hierarchy can be considered:

1. Local assessment with specific detailed data collection. Such assessment can be expected to guide specific management intervention.
2. In a broader geographical assessment less detailed data can be collected. However models can be developed to extrapolate data collected at specific test sites throughout the study area. In particular resource demand models can be used to evaluate management alternatives.
3. At an even more general level, much data may no longer be available. General policy oriented descriptions of desertification can be generated.

Study Area

The study area lies within 0° 15'N–1° 00'N and 35°30'E–30°30'E. Topographic elevations vary from 900 m on the Njemps flats to 2000 m in the Puka, Pokot and Tangulbei Highlands (see Maps 1–3 and Figure 1).

The average annual rainfall within the project area is 600 mm, however rainfall increases with increasing elevation. Rainfall variability within the study area is high. The main land use within the study area is grazing, however limited dryland agriculture and irrigated farming are also found.

Soil and range vegetation resources are of primary importance to the pastoralist tribesmen of this area. Consequently the primary focus of this study was to evaluate application of the desertificaton methodology to these rangeland resources.

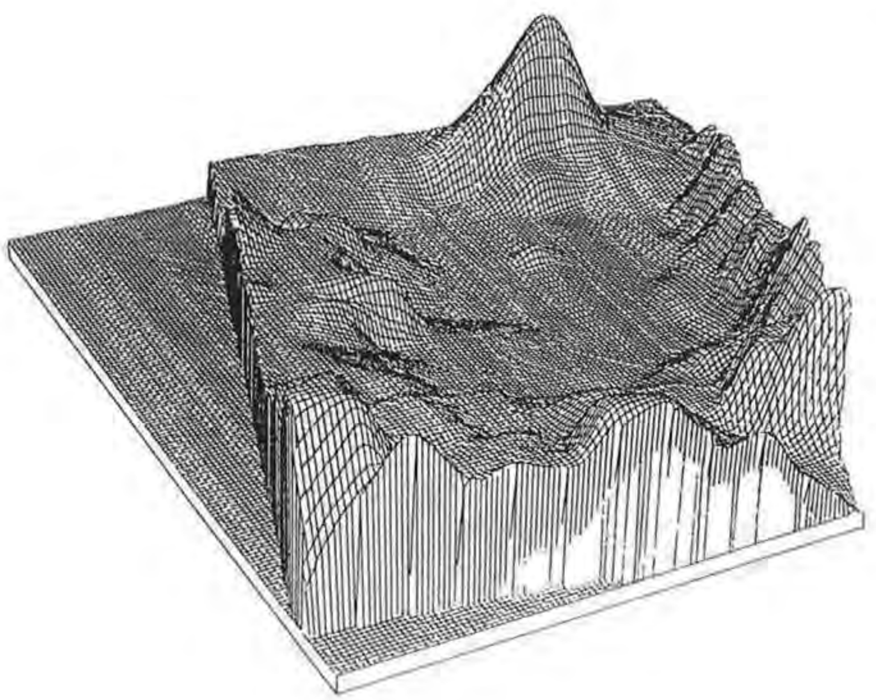


Figure 1 Terrain model for Baringo study area

Methods and Results

Five desertification indicators were selected for investigation. These were water erosion, wind erosion, vegetation degradation, range utilization and human settlement (see Maps 4–8). Models for the first four indicators were developed while the human settlement indicator was taken directly from existing data on houses determined from systematic reconnaisance flights. The maps of range utilization and human settlement (Maps 7 and 8) are based on a sample grid. The data collected for modelling desertification indicators are given in Table 1. Desertification hazard was calculated as the summation of the individual indicator values (see Map 9).

The water erosion model (see Map 4) is based on a modification of the Universal Soil Loss Equation (USLE) which was used to derive erosion intensity according to five categories. Because of the general nature of data used, this model was used to predict areas of surface deformation (Table 2) rather than actual soil loss (tonnes/hectare/year). Vegetation degradation (see Map 6) was calculated using field measurements of actual herbaceous biomass and potential herbaceous biomass production calculated using rain use efficiency. Range utilization (see Map 7) was determined by subtracting predicted annual herbaceous biomass consumption from the measured available herbaceous biomass. Herbaceous biomass consumption was calculated by summing the herbaceous biomass requirements of the livestock species in the study area. Livestock populations were estimated using systematic reconnaissance flight census methods. Wind erosion potential was modelled by multiplying wind erosion potential by the measured percent bare ground.

Using the spatial correlation capabilities of the GIS, the model results were compared with relevant field data and other model output. The modelled water erosion results were compared with actual field mapped water erosion features. Similarly vegetation degradation was evaluated with desirable/undesirable species data (Table 3). Through such evaluations, model performance could be refined and validated. From these evaluations 979 km^2 (66%) of the area were found to have no significant level of desertification; 275 km^2 (18%) were found to be slightly desertified; 74 km^2 (5%) were found to be moderately desertified and 162 km^2 (11%) were found to be severely desertified.

The Baringo Study area served as a training area for model development. Detailed data were collected to provide a basis for the model development (see Table 4). These derived models can now be applied over a broader study area. Similarly verification areas can be identified to validate model performance and facilitate any required modifications.

Table 1 Data collected for modelling indicators of desertification

Physical
1 Climate
   a) Rainfall
   b) Temperature
   c) Windspeed, direction, frequency
   d) Rainfall erosivity (calculated)
   e) Sunlight duration
   f) Potential evapotranspiration (calculated)
   g) Vorticity
   h) Sandstorm/duststorm frequency
2 Soils
   a) Surface rockiness
   b) Texture
   c) Organic matter
   d) Structure
   e) Permeability
   f) Erodability
   g) Alkalinity
   h) Soil type units
   i) Water erosion
   j) Wind erosion
3 Surface terrain
   a) Elevation
   b) Slope

Biological
1 Vegetation
   a) Herbaceous canopy cover
   b) Herbaceous biomass
   c) Percent bare ground
   d) Species composition (desirable/undesirable species)
   e) Vegetation type units
2 Livestock
   a) Distribution
   b) Abundance

Socio-economic
1 Human population
   a) Density of permanent structures
   b) Transhumance
   c) Environmental perception

Table 2 Water erosion mapping categories

Erosion category	Description
None	No visible erosional features
Slight	Sheet erosion
Moderate	Rill erosion
Severe	Gully erosion
Very severe	Badlands

Table 3 Required computerized desertification data sets

Physical
1 Climate
   a) Rainfall and Erosivity Map
   b) Wind erosion potential
2 Soils
   a) Soil Units Map (soil type, erodibility, coarse fragments)
   b) Water Erosion Map
   c) Wind Erosion Map
3 Surface terrain
   a) Terrain Model (elevation, slope, aspect)

Biological
1 Vegetation
   a) Vegetation Unit Map (vegetation type, herbaceous biomass, herbaceous canopy, desirable herbaceous species, undesirable herbaceous species, percent bare ground)
   b) Livestock Density Map

Socio-economic
1 Human population
   a) Density of Permanent Structures Map

Table 4 GIS models

Water Erosion Potential (WaEP)	= Soil Erodibility	× Slope	× % Bare Ground	× % Surface Coarse Fragments
Vegetation Degradation (VD)	= Potential Herbaceous Biomass Production		− Actual Herbaceous Biomass Production	
Range Utilization (RU)	= Actual Herbaceous Biomass Production		− Predicted Herbaceous Biomass Consumption	
Wind Erosion Potential (WiEP)	= Wind Erosivity × % Bare Ground			
Human Settlement (HS)	= Density of Permanent Structures			
Desertification Hazard	= WaEP + VD + RU + WiEP + HS			

Conclusions

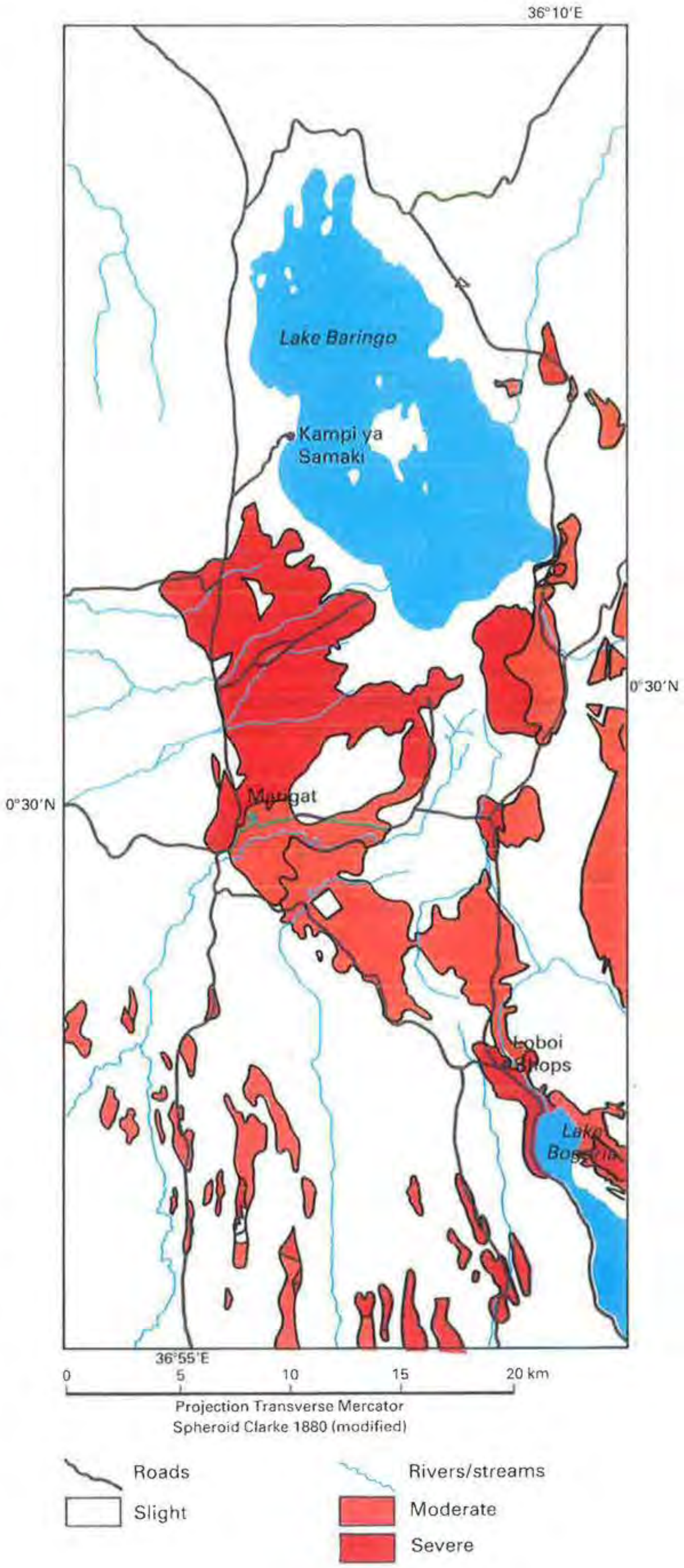
To a certain degree, desertification is associated with human activity. Indeed it could be argued that one force behind desertification may be the social transformations produced by development. What is particularily relevant to desertification assessment is how change causes deviation from normal mechanisms of resource utilization and the resulting impacts such changes have on the environment. Using models, relationships among resources and use can be evaluated. Increased range utilization can be simulated and used to predict vegetation degradation. Similarily vegetation degradation can be used to evaluate soil erosion potential. Modelling can facilitate evaluation of management alternatives and development intervention.

Simple models can provide a useful context for desertification assessment provided model results can be verified. Interactive methods using pilot areas allow refinement and verification of models. Models can be evaluated through spatial correlation analysis and inspection of results in map form. The FAO/UNEP Methodology provides a useful basis for model development.

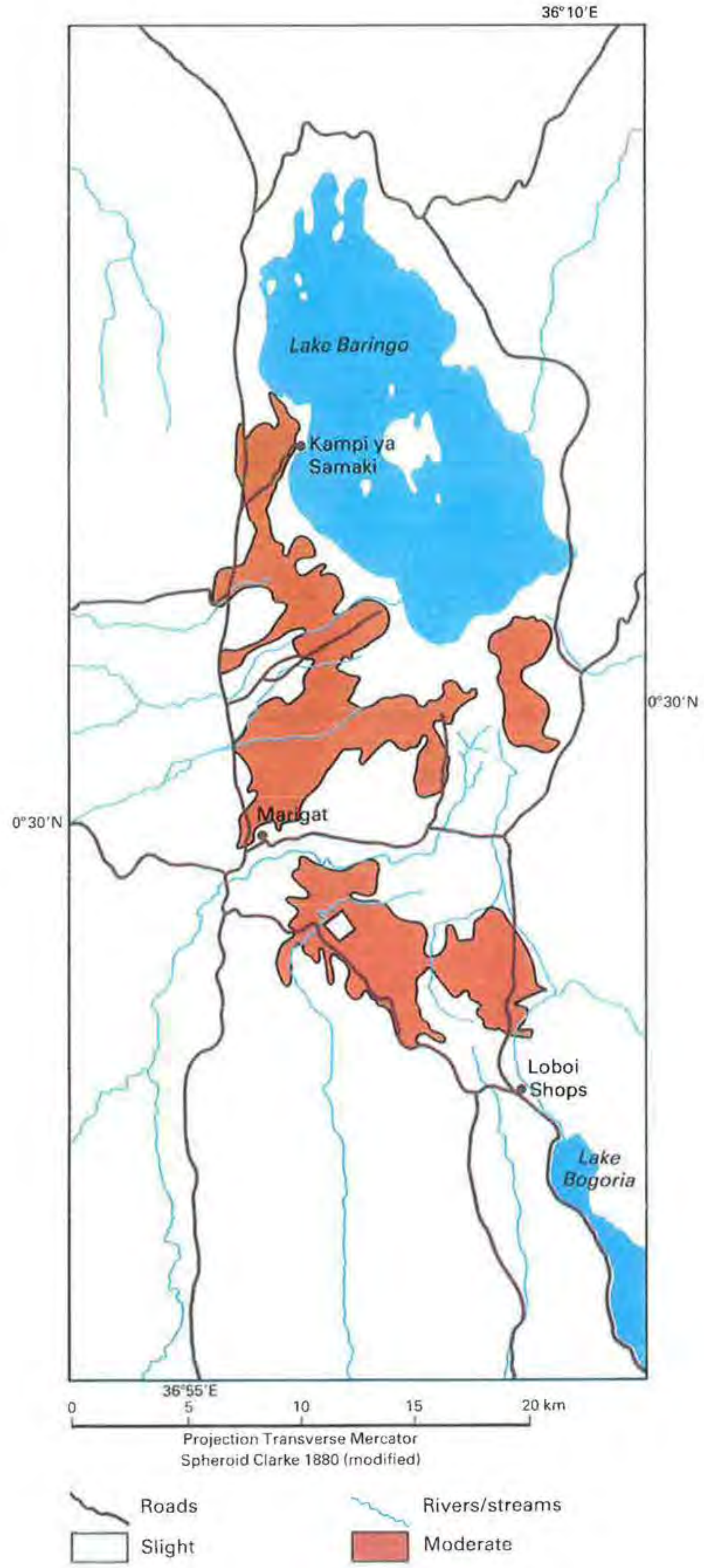
The models presented in this study are intended to be illustrative of a general approach to desertification assessment. Many additional models could be developed or different model parameters might be more appropriate in different circumstances.

Resource demand models can provide another view on desertification status beyond strict resource orientated evaluations. Desertification assessment needs to address itself not only to the cataloguing of resource decline but to begin to confront the issues of adaptation and social change with which human populations confront their environment. Integration of resource orientated and socio-economic analyses should be encouraged. Resource demand models are one such approach.

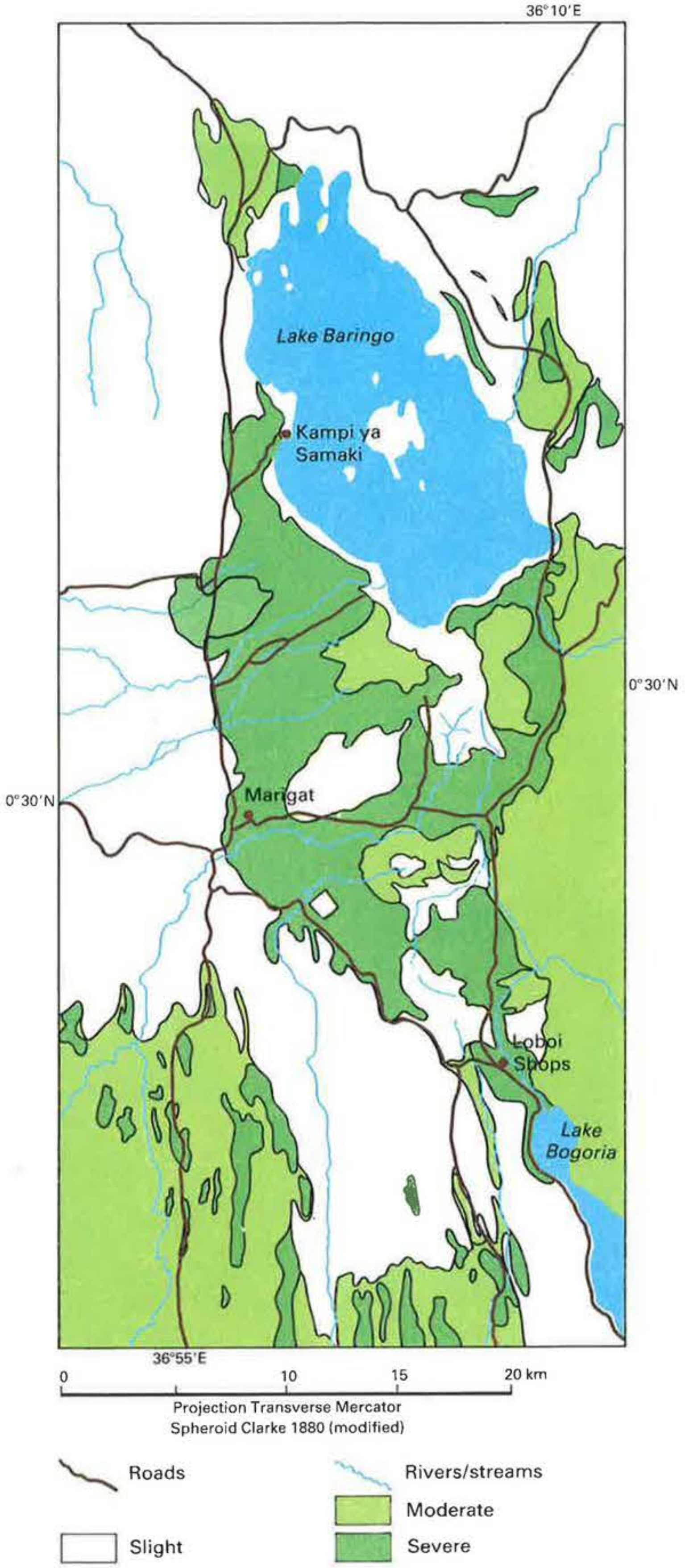
As a result of these investigations, a national desertification assessment (Level 3) is planned. The methodology developed in this study (Level 2) can be used to further evaluate areas identified by the national assessment as prone to desertification. Together they can lay a basis for effective management of resources.



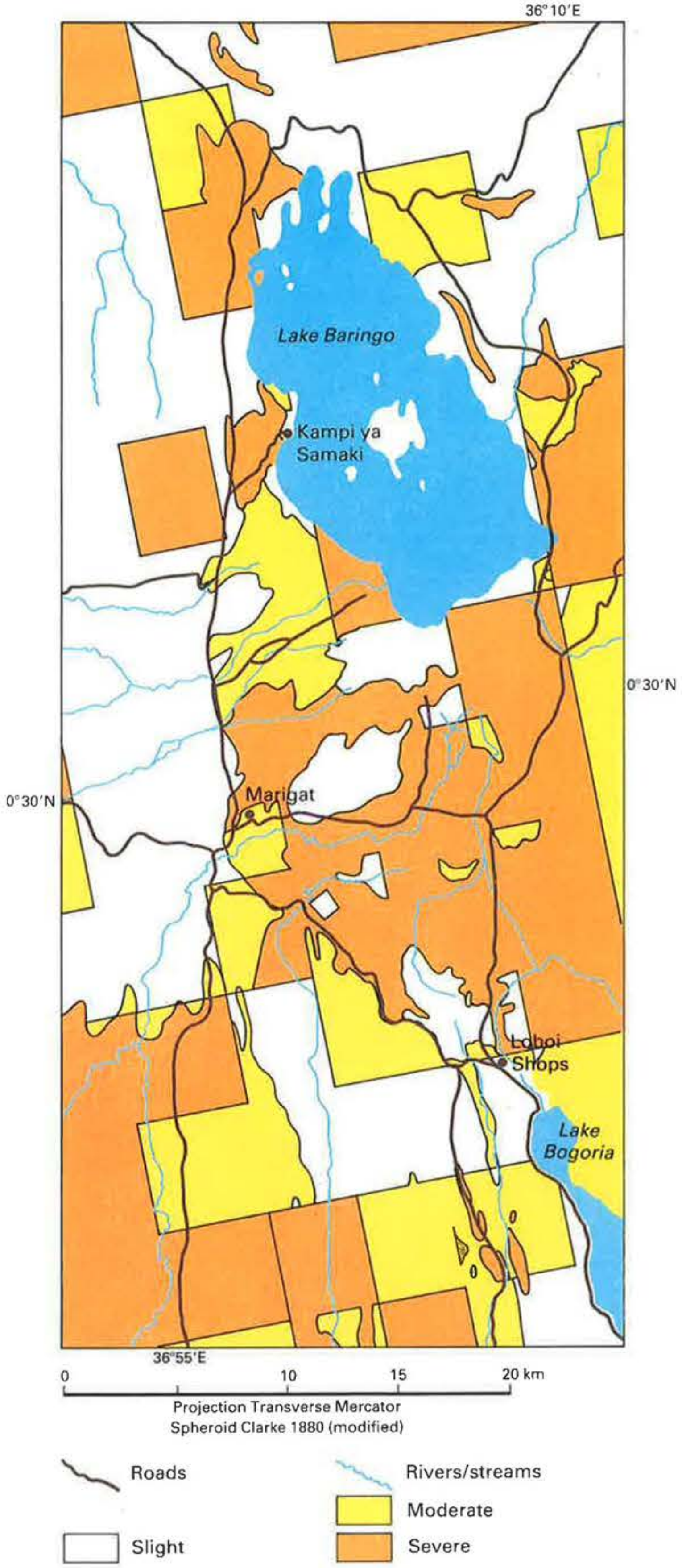
Map 4 Modelled water erosion



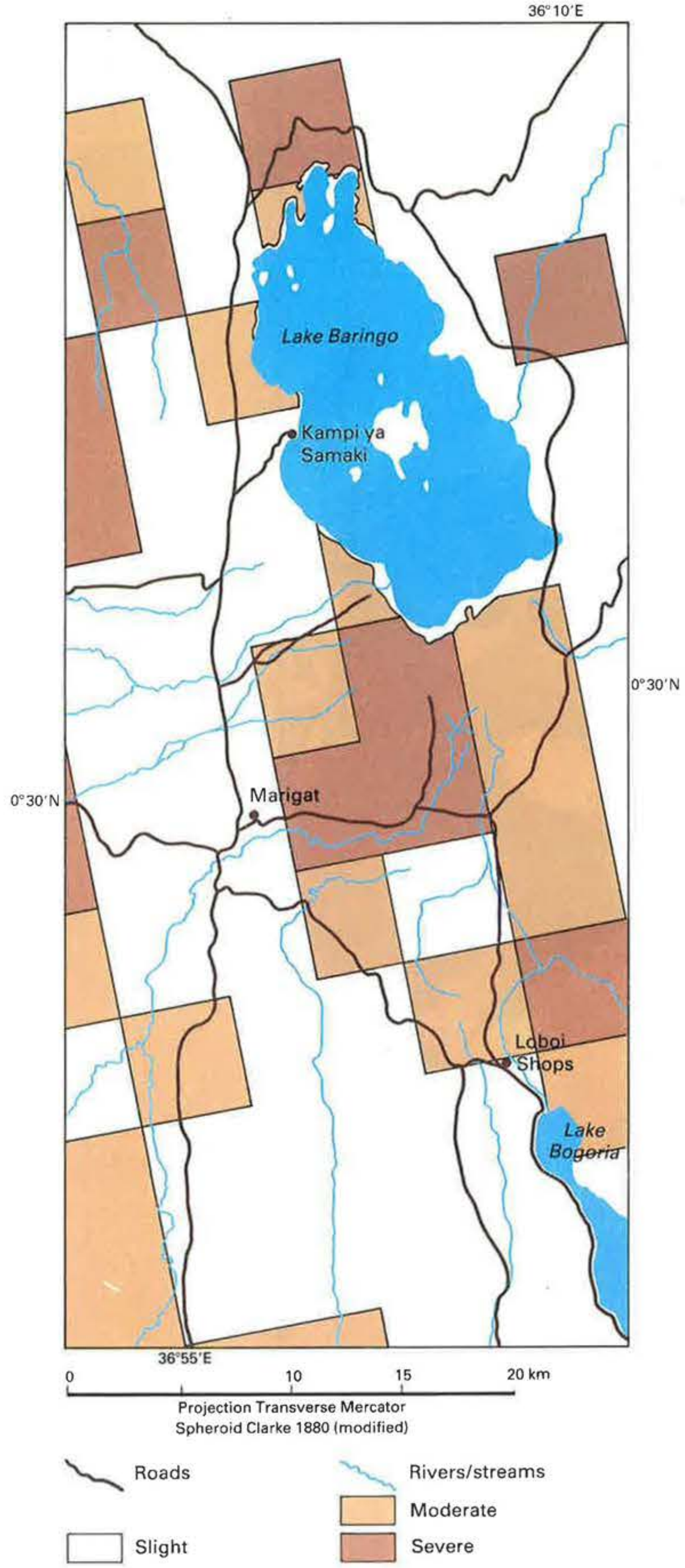
Map 5 Modelled wind erosion



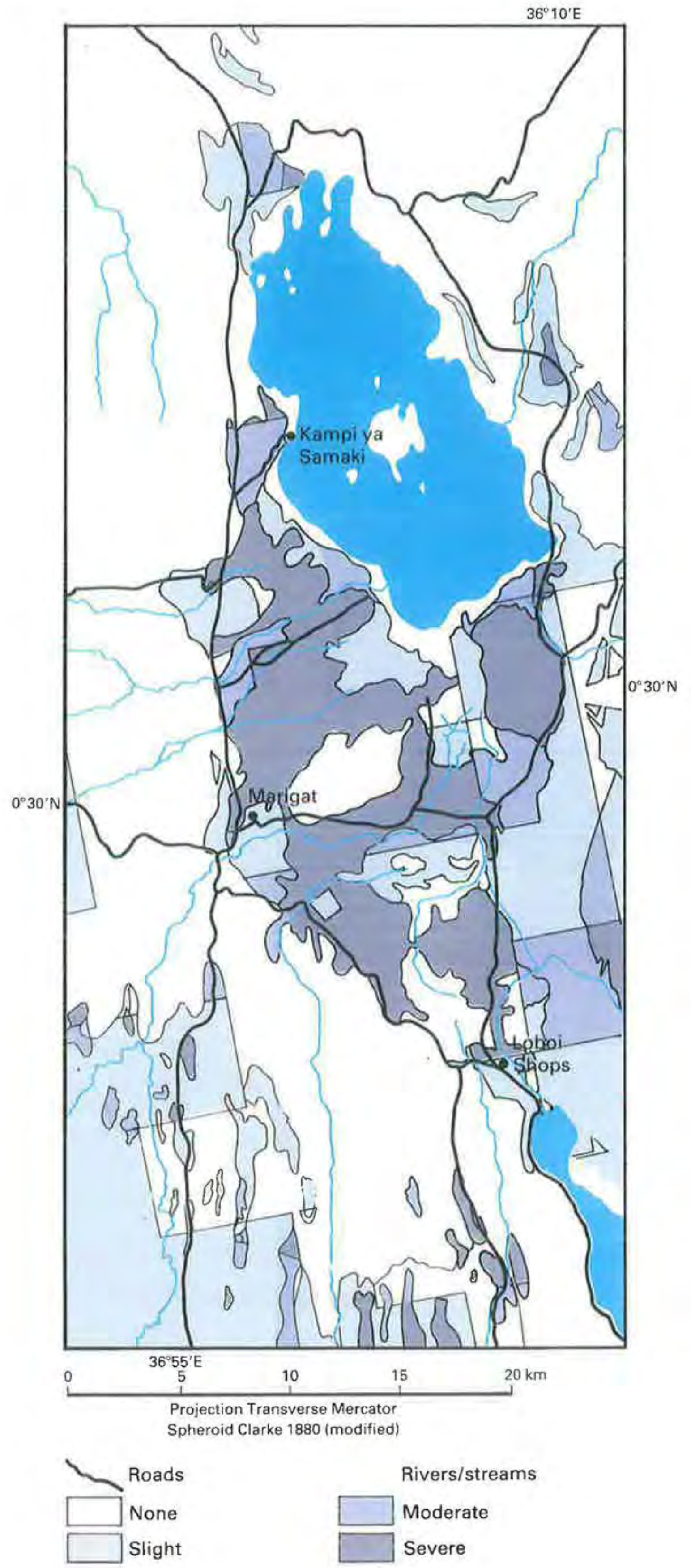
Map 6 Modelled vegetation degradation



Map 7 Modelled range utilization



Map 8 Human settlement



Map 9 Desertification hazards

Acknowledgements

Special thanks are due Mr. D.K.Andere, Director of the Department of Resource Surveys and Remote Sensing for his support during this research.

MALI: Desertification Maps of the Western Area

N.G. Kharin, N.G. Orlovsky, P. Esenov, T. A. Babaeva and A.A. Kiril'tseva (Desert Institute, Academy of Sciences of Turkmen SSR)

Introduction

The study area is situated in the western part of Mali and includes the two administrative regions of Kayes and Yelimané. The area occupies 27,890 km^2, and has a human population of 367,253.

Precipitation in the area varies from 400 mm in the north to 700 mm in the south, and mean annual temperatures are in the range 22–30°C. The rainy season lasts from June to September in the north and from May to October in the south. The seasonal nature of the rainfall and periodic droughts characteristic of the region means that this dryland area is susceptible to desertification. This vulnerability is enhanced by the light mechanical composition of the soils, strongly degraded savanna vegetation and continuous population pressure.

Red brown sandy and sandy loam soils dominate in the dry savanna areas. Laterite formation is common due to the high iron dioxide content. Brown tropical soils are formed in the southern part of the area where tree savanna vegetation is typical.

The main types of land use include pastoral (with pure pastoral production), agropastoral (with rainfed cultivation) and agricultural (with mixed agriculture and rainfed cultivation). The main crops are millet, sorghum, cow peas, maize, wheat, tubers, calabash, bambara peas and tobacco. Cultivation is prevalent on the lowlands where soil conditions, especially moisture content, are better. These areas are not prone to erosion and they provide the only annual harvest without irrigation.

The productivity of agriculture is very low. Land is usually used for agricultural production for three to five years, then is left fallow for fifteen to twenty years. Camels and goats are raised in the area around Yelimané, while cows, sheep and goats are kept in the Kayes area.

Methodology

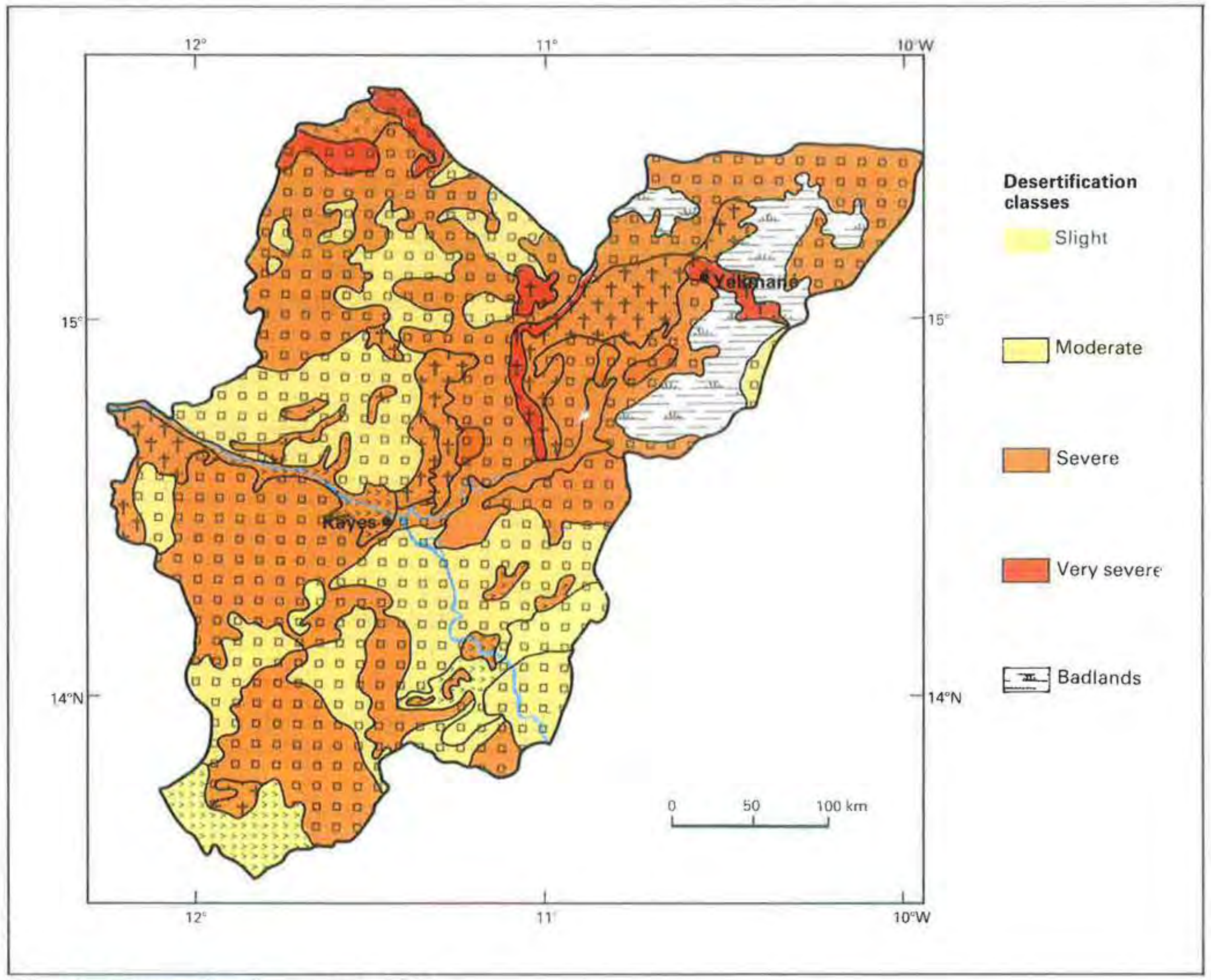
The study aims to measure the extent of desertification over the period 1980–89 employing the 1984 FAO/UNEP Provisional Methodology for Desertification Assessment. Desertification maps were prepared using information from field studies and remote sensing data from 1980 Landsat and 1989 Soviet MSU-S satellite images. Digitized imagery was produced and Normalized Difference Vegetation Index (NDVI) values were calculated for each mapping unit.

The criteria used for the designation of desertification status are given in Table 1. Criteria of desertification rate (DR) include data on expansion of areas subject to desertification from 1980 to 1989. Inherent risk (IR) was estimated as an index of ecosystem stability (topography, soil, vegetation). Animal pressure (AP) was calculated as the ratio of present livestock to the potential livestock carrying capacity. Population pressure (PP) was estimated by popultion density, and desertification hazard (DH) was calculated using the equation DH=DS+DR+IR+AP+PP.

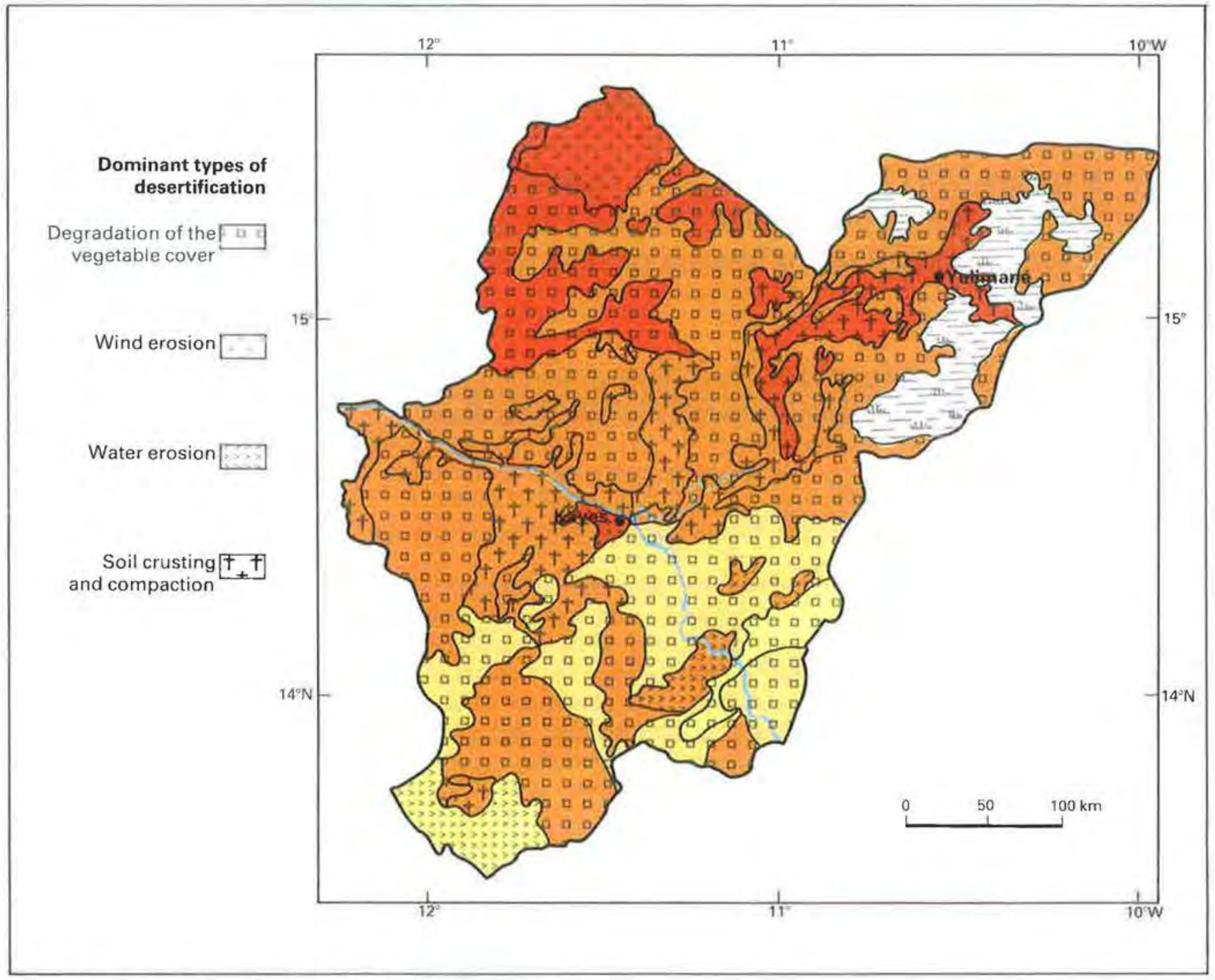
The size of areas subject to desertification is given in Table 2.

Table 1 Criteria for assessment of desertification status

Classes Criteria	Slight	Moderate	Severe	Very Severe
Degradation of the vegetative cover				
Status of vegetation	Plant cover slightly destroyed by man, density of tree and shrub layer more than 10%, herbs more than 40%	Destroyed by man, density of tree and shrub layer 5–10%, herbs 20–40%	Strongly destroyed by man, density of tree and shrub layer 2–5%, herbs 5–20%	Very severely destroyed by man, density of tree and shrub layer 1–2%, herbs less than 5%
Annual biomass, metric tonne per hectare per year	>4.0	4.0 – 2.5	2.5 – 1.0	<1.0
Water erosion				
Type of erosion	Surface wash and rill erosion from slight to moderate	Surface wash and rill erosion from moderate to severe	Surface wash, rill and gully erosion, strong	Surface wash and deep gully erosion, strong
Thickness of surface soil layer washed by erosion, percentage of area	<10	10 – 25	25 – 50	>50
Percentage of area with developed gullies	<2	2 – 5	5 – 10	>10
Wind erosion				
Percentage of the area prone to erosion	<5	3 – 15	15 – 30	>30
Surface soil layer destroyed by erosion, cm	<5	5 – 15	10 – 20	>20
Thickness of the accumulated soil layer on the ground surface, cm	<5	5 – 10	10 – 20	>20
Volume of soil blown out, metric tonne per hectare per year	<0.5	0.5 – 1.0	1.0 – 3.0	>3.0
Soil crusting and compaction				
Accumulation of iron, on the depth, cm	Nodules and concretions, 30–50 cm	Crusts, nodules and concretions, 30 cm	Iron ore (10–30 cm), crusts, 30 cm	Iron ore 10 cm



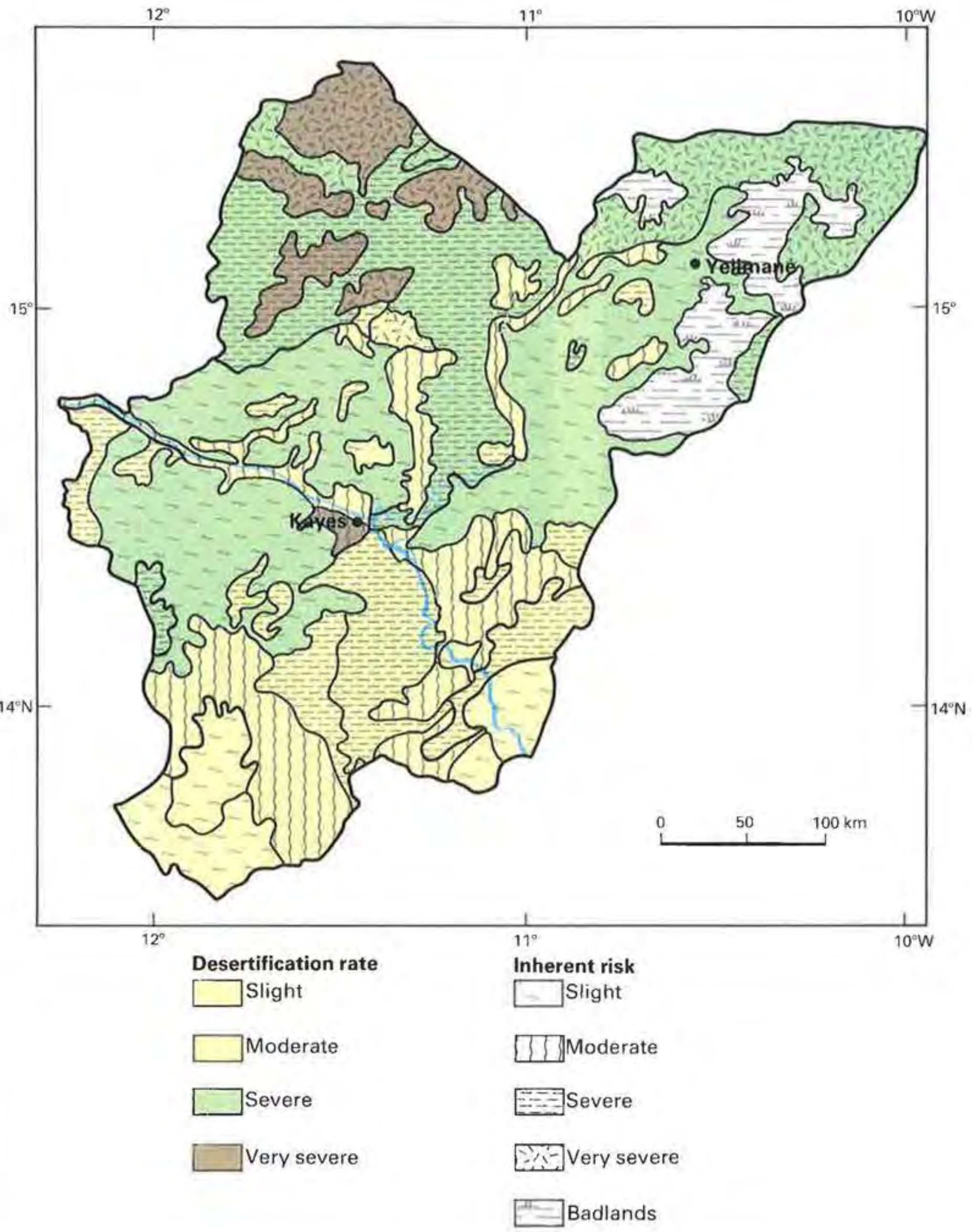
Map 1 Desertification status 1980



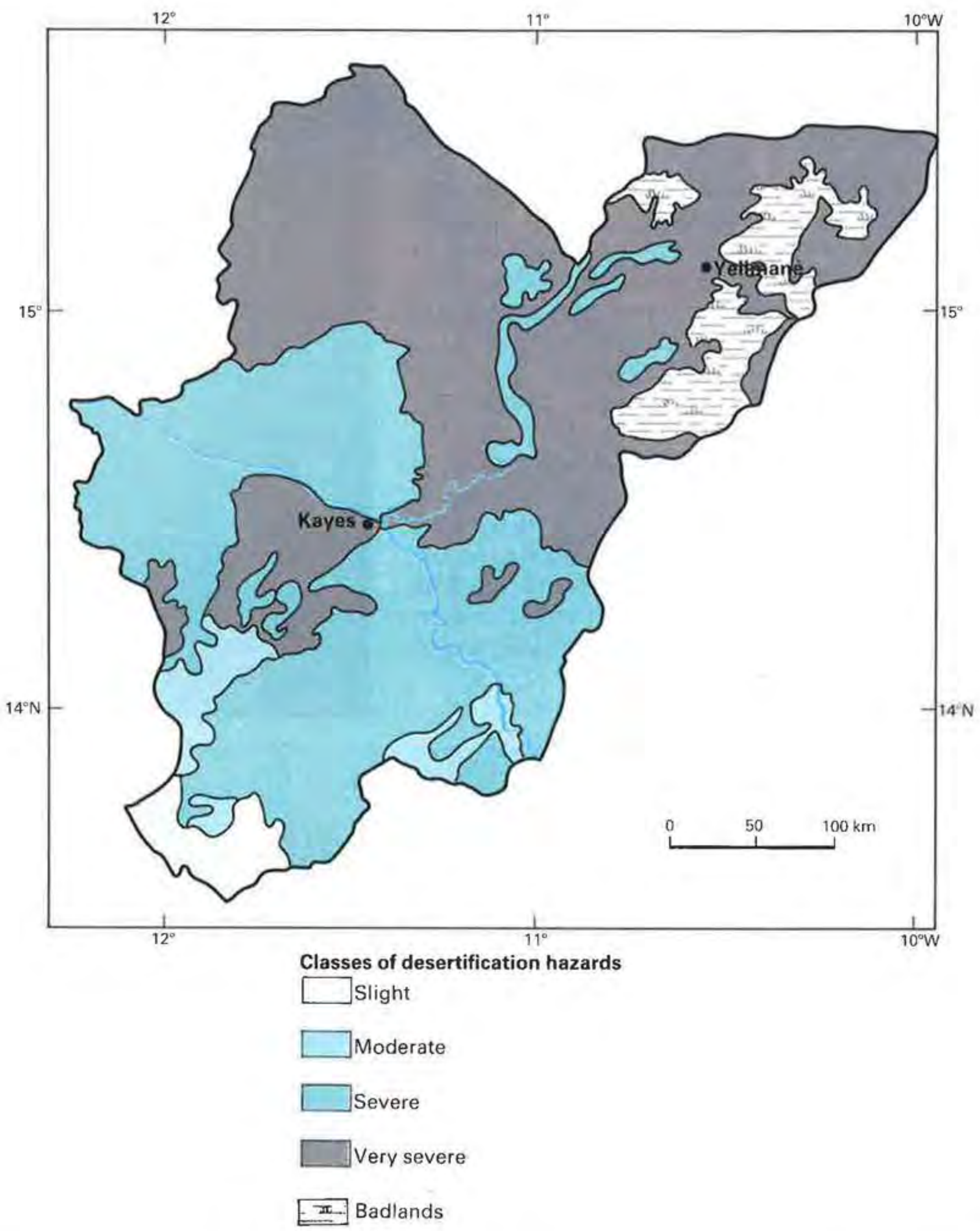
Map 2 Desertification status 1989

Table 2 Size of the areas subject to desertification in km² (and percent)

	Desertification Years	CLASSES Slight	Moderate	Severe	Very Severe	Total
Degradation of the vegetative cover	1980	499(1.8)	8049(28.9)	9243(33.1)	623 (2.2)	18414 (66.0)
	1989	499(1.8)	3411(12.2)	10245(36.7)	2922(10.5)	17077 (61.2)
Wind erosion	1980	–	–	115 (0.4)	–	115 (0.4)
	1989	–	–	169 (0.6)	780 (2.8)	949 (3.4)
Water erosion	1980	–	1581 (5.6)	404 (1.5)	–	1985 (7.1)
	1989	–	1627 (5.8)	810 (2.9)	51 (0.2)	2488 (8.9)
	1980	–	520 (1.9)	4378(15.7)	533 (1.9)	5431 (19.5)
	1989	–	520 (1.9)	4378(15.7)	533 (1.9)	5431 (19.5)
Badlands	1980					1945 (7.0)
	1989					1945 (7.0)
Total	1980	499(1.8)	10150(36.4)	14140(50.7)	1156 (4.1)	27890(100.0)
	1989	499(1.8)	5558(19.9)	15602(55.9)	4286(15.4)	27890(100.0)



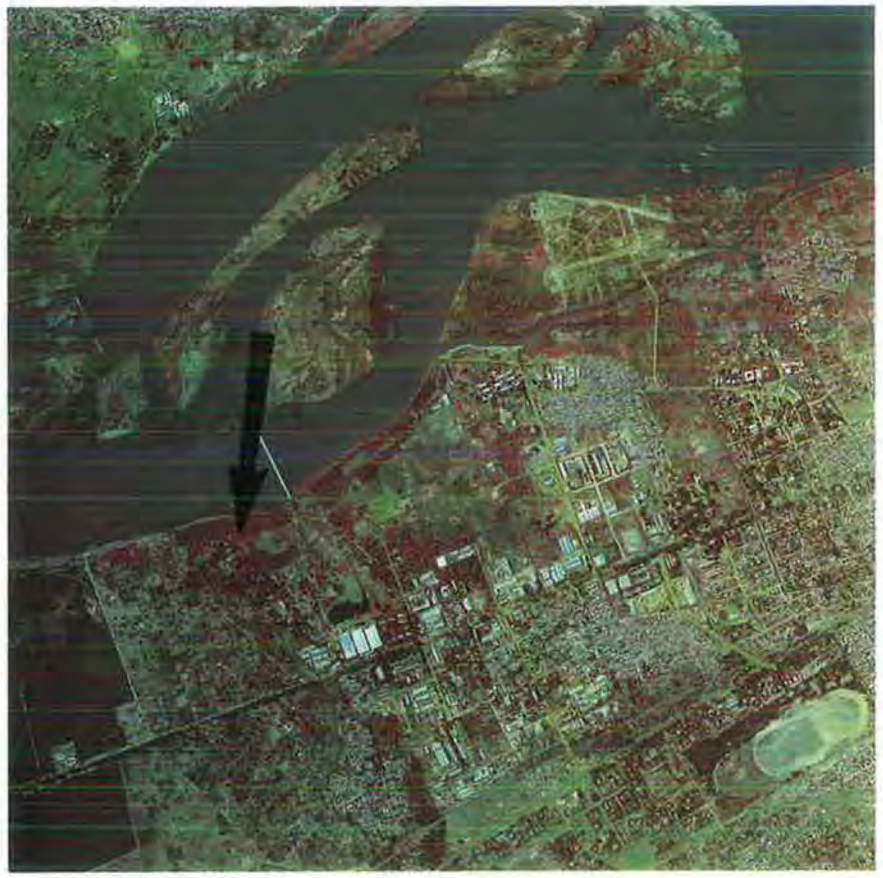
Map 3 Desertification rate and inherent risk



Map 4 Desertification hazards

MALI: Transect Methodology to Assess Ecosystem Change

Study directed by IGN France International with participation by ORSTOM and the University of Reims



Introduction

The French National Geographic Institute (IGN) are co-operating with UNEP-DC/PAC to develop a cost-efficient methodology for the assessment of desertification, to be used as a conceptual basis for desertification control activities. The methodology aims to identify and classify the environmental and ecosystem changes discernible from remote sensing, as a basis for subsequent more detailed investigations that will interpret the changes in terms of their significance, cause, and control.

1952 and 1957 1:50,000 scale air photographs covering an area south of the Sahara in West Africa and held by IGN were utilized for terrain mapping in the 1950s. These have been used as the basis for comparison with modern aerial photography covering part of the same area, high resolution SPOT satellite imagery and ground survey in order to identify ecosystem changes in arid, semiarid and dry subhumid bioclimatic zones in the Sahel region.

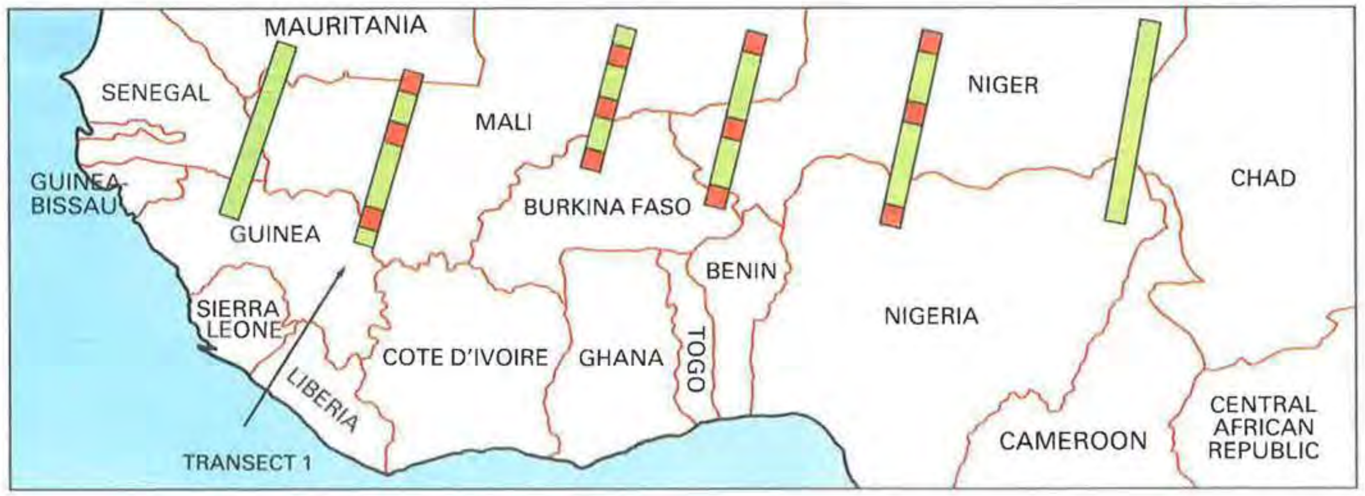
Figure 1 Example of aerial photography used over a built-up area, showing irrigated agricultural plot ground-truthed from field surveys (Lower photograph taken in area indicated by arrow)

Figure 2 Example of aerial photography used over a rural area, showing savanna landscape ground-truthed from field surveys (Lower photograph taken in area indicated by arrow)

Data and approach

Six north–south transects, each approximately 500 km apart, were selected. They cover part of the Sahel extending from Mauritania, Mali and Burkina Faso in the west, through Niger and Nigeria to Chad in the east (see Map 1). Each transect shown in Map 1 is 60 km in width, corresponding to the scale of individual SPOT images, and covered by 1:50,000 aerial photography from the 1950s. Cost constraints have restricted the use of new 1:50,000 scale aerial photography, produced in 1987, to 10 km wide north–south transects within these 60 km swaths. The aerial photographs, supplemented by ground data and satellite imagery, have been used in the following stages to map information relevant to determining the location and status of desertification.

1. Comparison of land use and terrain types in the 1950s and 1987, using a system of "terrain classes", based on the two air photograph sets, mapped at a scale of 1:100,000 onto a geometrically-corrected base map derived from SPOT imagery. Interpretation of the 1987 aerial photographs has been verified using field data collected in the weeks following the aerial photography flights.The use of a digital-editing computer cartographic technique has allowed high-precision measurements to be made, the creation of a GIS, and has led to the preparation of temporal land use change maps.



Map 1 Location of IGN transects. Squares marked within the transects represent areas covered by individual SPOT images

2. Comparison of visual and digital interpretations of areas common to the SPOT imagery and the 1987 air photographs. This stage warrants further investigation as it suggests that visual interpretations of satellite images tend to underestimate terrain classes that are either poorly represented or are widely dispersed over an area. Conversely, classes that are well represented or massed together, such as agricultural land, are accurately assessed.

A further stage is planned for the future:

3. Following resolution of the problems indicated in stage 2 above there will be an attempted interpolation of areas covering entire 60 × 60 km SPOT images straight from satellite images themselves. Ultimately, the same automatic interpretation procedures using image-processing software may be used for larger areas covered by NOAA satellite imagery.

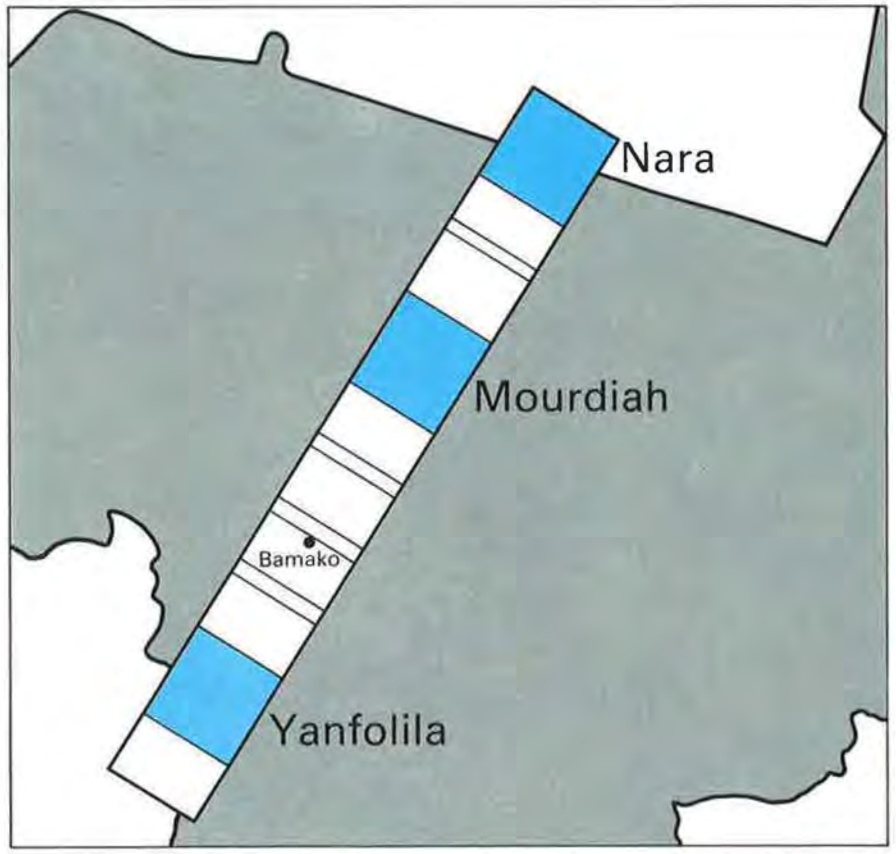
Examples of land use change

Three simple examples of the temporal land use change maps are presented. These belong to Transect 1 (see Map 1) and represent changes in the period from 1952-1957 to 1987 and are taken from the westernmost aerial photograph transect as follows:

1. Nara, in the Mauritania-Mali border area;
2. Mourdiah, in central Mali; and
3. Yanfolila, in the Mali-Guinea border area.

These examples therefore represent a north to south progression in increased humidity, but all fall within the susceptible drylands as defined in the global section of this atlas.

On the temporal land use change maps, areas that remained unchanged between 1952/1957 and 1987 (or which may have experienced change but had reverted to the 1952/1957 situation by 1987) appear in black and white. All the coloured areas have experienced change, as per the scheme shown in the key to the maps. It is important to reiterate here that causes of changes (e.g. human-induced or climatic fluctuations) cannot be established from the maps alone; rather, the maps represent an appropriate methodology for assessing changes and can be utilized as part of a wider land degradation study, including ground survey, in order to explain the observed patterns of change.



Map 2 First transect studied, with location of three SPOT images

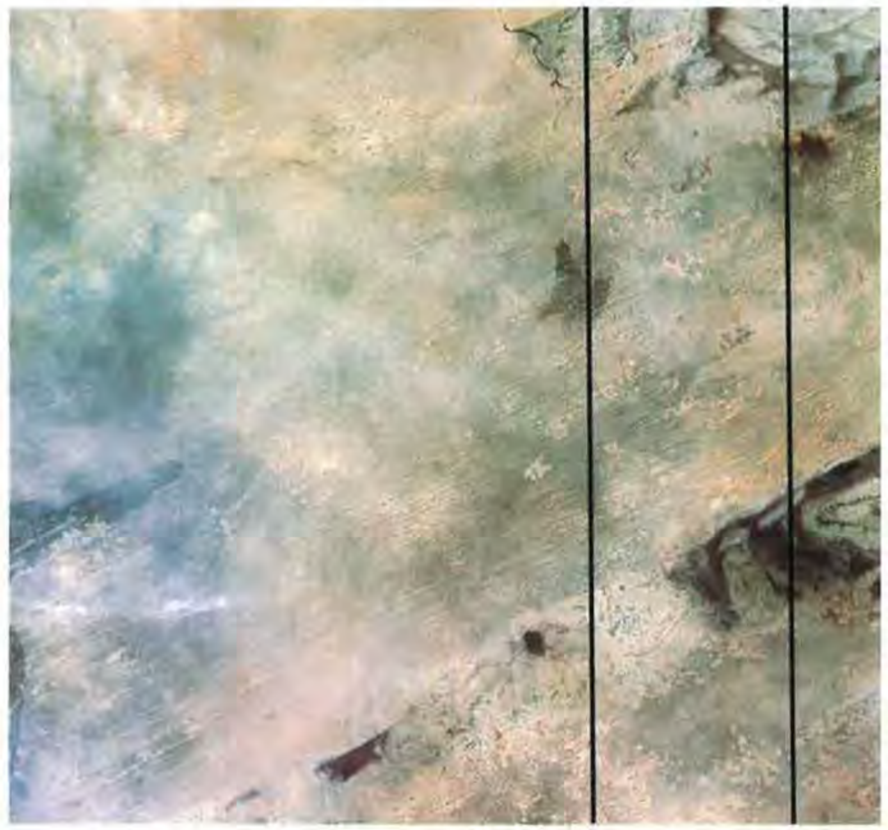


Figure 3 SPOT image 40–319 of Nara, also showing 1987 aerial photography track. Map 3, (land use change) is located within the aerial photography track

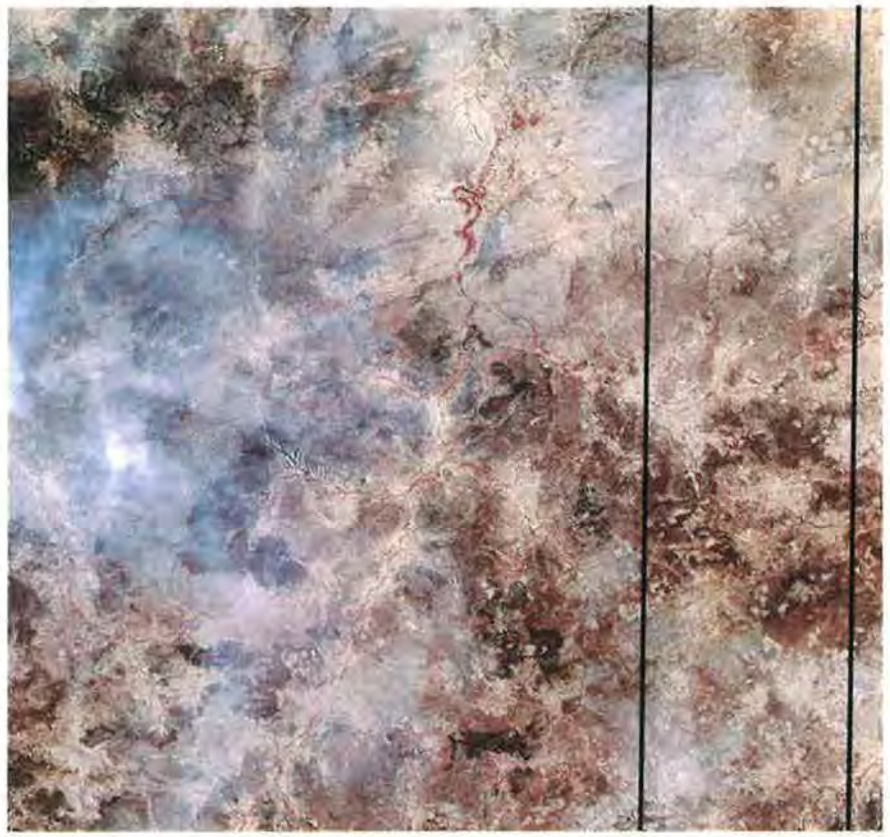


Figure 4 SPOT image 40–322 of Mourdiah, also showing 1987 aerial photography track. Map 4, (land use change) is located within the aerial photography track

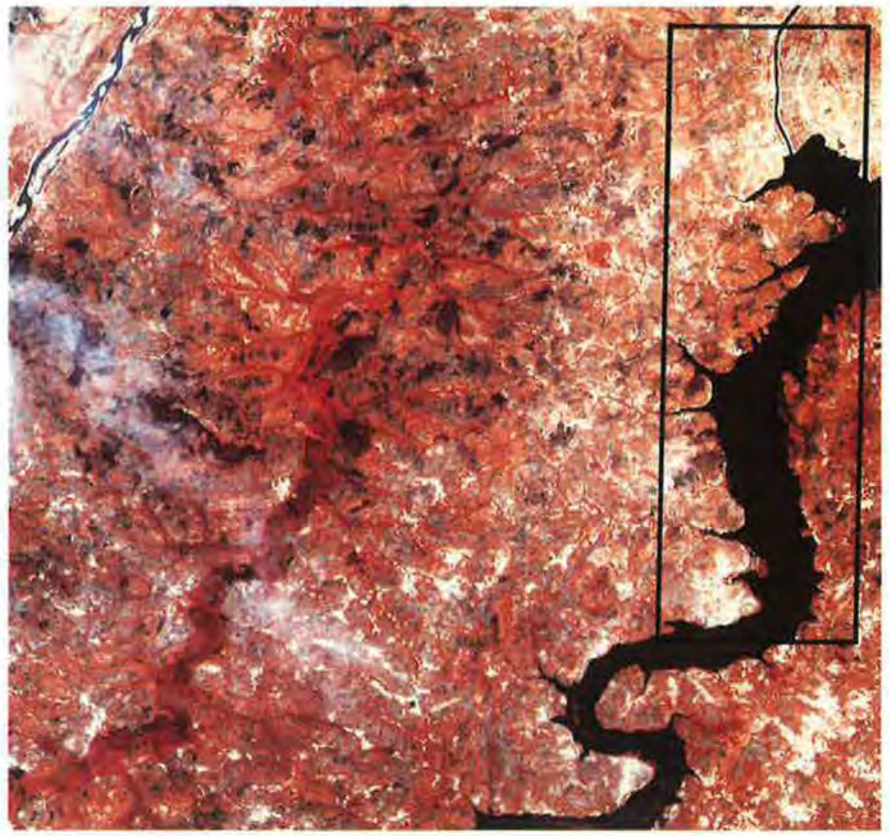
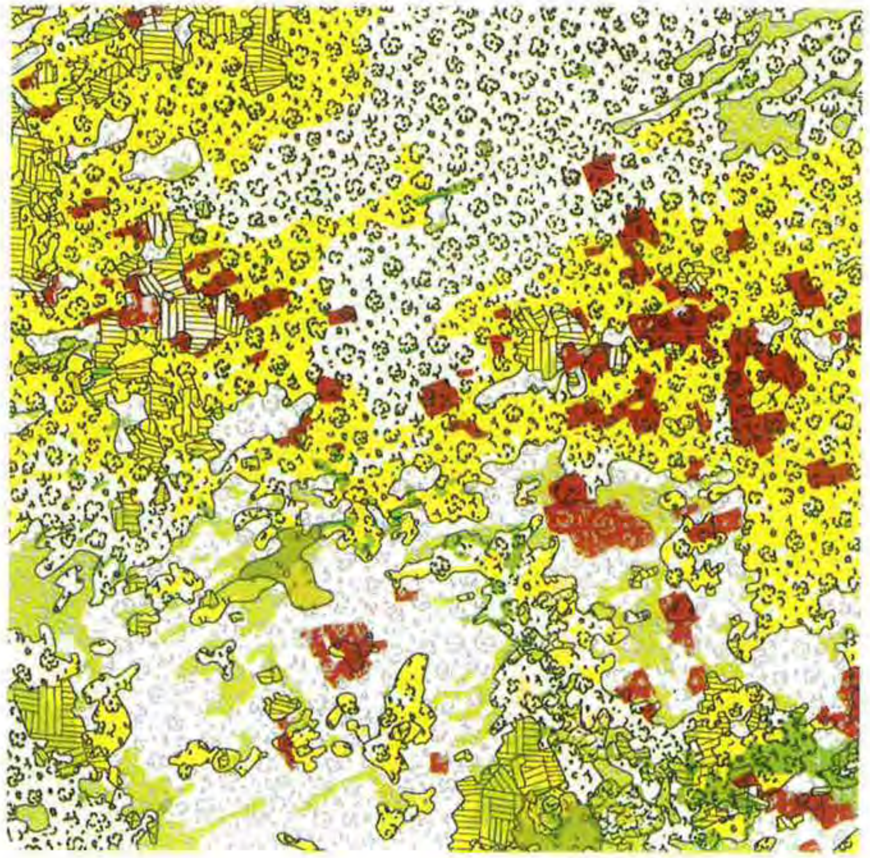
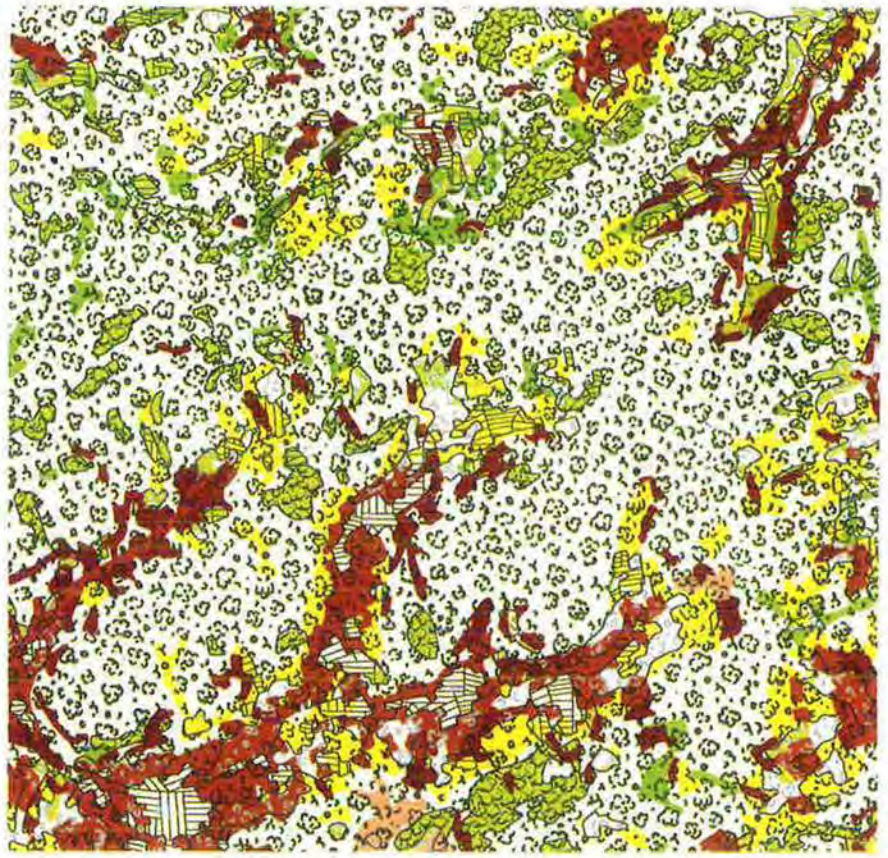


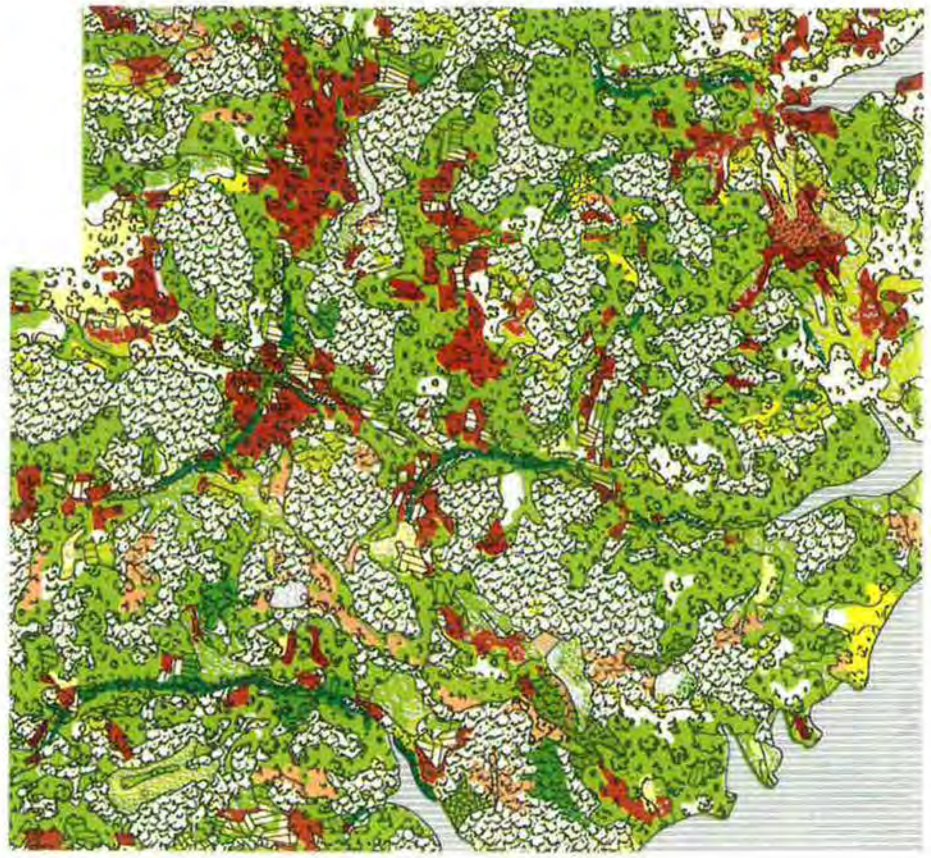
Figure 5 SPOT image 40–327 of Yanfolila, also showing 1987 aerial photography track. Map 5, (land use change) is located within the aerial photography track



Map 3 Land use change, Nara, 1957–1987



Map 4 Land use change, Mourdiah, 1952–1987



Map 5 Land use change, Yanfolila, 1952–1987

Nara

This map shows two main trends. First, the plant cover was mainly tree savanna in 1957, but by 1987 this had both broken up in extent and largely become lower biomass shrub savanna. Second, some areas that were shrub savanna in 1957 were, in 1987, tree savanna. Overall, these two seemingly opposing trends highlight the dynamism of savanna ecosystems. Shrub savanna has in many instances been interpreted as a degraded form of tree savanna. If this is correct, this map therefore suggests that such vegetation systems, though experiencing degradation in the Nara area, display a marked ability to recover and to behave in a dynamic manner.

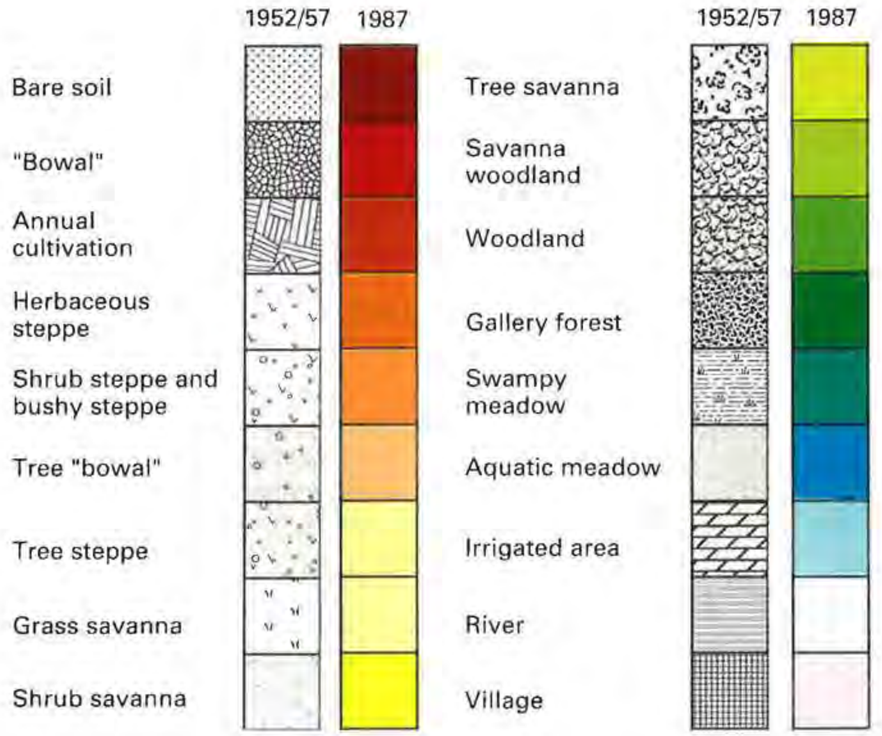
The main locations experiencing changes in vegetation during the period concerned are located on the fringes of areas that were cultivated in 1957 and include an expansion of the area under cultivation. In general, wholesale changes in vegetation communities have not taken place; rather, changes have often radiated out from the areas of most intensive human activity.

Mourdiah

A marked degradation of tree and shrub savanna units has taken place in the 1952–1987 period, coinciding with the expansion of the area under crops. Agriculture has expanded from a series of nuclei in 1952 to extensively occupy the bottoms of valleys. It has also expanded to valley sides, where the larger area of bare ground by 1987 can be attributed to soil degradation by water erosion.

Yanfolila

The dynamism of vegetation communities and the absence of a simple trend in vegetation system changes are also illustrated in this map extract. The area used for cultivation has increased considerably in low-lying areas, doubling in three decades. In other locations however, natural vegetation communities have evolved to higher biomass types. On the interfluves, which are unaffected by cultivation, much of the tree savanna area of 1952 has developed to open forest in 1987. This provides a good example of the need to consider a range of natural and human phenomena when considering changes in land degradation status. This development of plant communities in interfluve areas is probably a consequence of changes in the spatial distribution of the population of the area, with a move towards concentration around developments associated with the construction of the Selingue Dam as well as out migration from the area due to an upsurge in sleeping sickness.



Legend for Maps 3–5

Initial results

Some basic generalizations concerning the agricultural land use changes between the 1950s and 1987 in the three areas can be made from the data stored in the GIS and shown in Table 1:
1. The proportion of land used for growing crops has increased considerably in all three areas, with the proportion having more than doubled in Mourdiah and Yanfolila.
2. A comparable extension of all agricultural land (including crop land and fallow) has occurred only in Nara, while in Mourdiah and Yanfolila it has remained fairly stable at around 70% of the total area.
3. A shortening by half of the fallow period in Mourdiah and Yanfolila, while in Nara it has remained more-or-less the same.

The investigation of the first transect as a whole allows a number of provisional assessments to be made. The most arid areas, as exemplified by the Nara map, where mean annual rainfall is about 400 mm, are not necessarily those most threatened by degradation because agricultural land use, is to date, limited in many places. The dominant land use here is pastoral, but cereal production continues to extend.

The most humid areas, in the south of the study area which receive up to 1300 mm mean annual rainfall, have experienced an intensification of agriculture by shortening fallow periods. Intensification has not spread to intervening areas such as interfluves, however, suggesting that the threat from overall degradation is not at its greatest in such areas.

The intermediate semiarid area, by contrast, represented by Mourdiah in the examples above, appears to have the greatest risk of degradation. The area under cultivation had expanded by 1987 to cover over 21% of the agricultural land, while a further risk comes from being a refuge zone for populations from the north during times of drought. The Mourdiah region receives a mean annual rainfall of about 700 mm. As well as degradation of vegetation communities, soil degradation is indicated where cultivation has expanded on to steeper slopes such as valley sides.

These initial findings suggest that a more detailed appraisal of the Sahelian "buffer zone" is needed, involving full use of existing aerial survey and satellite images of the area, plus additional present-day aerial surveys roughly between the 600 mm and 900 mm annual average isohyets.

Table 1 Data on agricultural land use in Nara, Mourdiah and Yanfolila as a percentage of area in the interpreted zone

		Nara %	Mourdiah %	Yanfolila %
Crops of 1950s	C1	4.1	6.4	4.3
Crops of 1987	C2	7.3	15.2	10.6
Agricultural land including the crops for the 1950s	T1	28	65	73
Agricultural land including the 1987 crops	T2	55	71	72
Proportion of crops for the year in relation to agricultural land	C_1/T_1	14.7	9.9	5.9
	C_2/T_2	13.3	21.4	14.8

Methodological Prospects

The study briefly described above provides a methodology for land degradation assessment which is applicable to susceptible dryland areas where relatively good quality old air photograph coverage is available. This can be used as a baseline input to a detailed comparison of the past and present status of ecosystems, allowing an objective assessment and measurement of the degradation and rehabilitation that has occurred during the period covered by two or more air photograph sets. In this case, the comparative study spans more than thirty years of change in the western Sahel.

One of the most useful features of this method is that it provides the countries concerned with a databank, linked to a GIS, that can be supplemented in the future from new aerial photograph or satellite imagery. This can be used to monitor ecosystem changes, to identify the locations and rates of land degradation, and to aid planning of rural land use and desertification control. The transects that have been established can also act as baselines for more detailed ground monitoring of specific environmental components. Overall, therefore, this method offers a framework for degradation monitoring that can be adapted to a variety of scales, to a range of uses and to a multitude of future time spans.

Technical Feasibility

The development of this methodology has been undertaken with the practical national considerations of developing countries firmly borne in mind. The future use of remote sensing tools for land use change and desertification monitoring should increasingly be carried out by national bodies. Training of technicians in remote sensing interpretation, use of GISs and data management will have to be undertaken, possibly as part of a larger scale pilot project in a single West African state. The multiple uses of aerial photography and satellite imagery, particularly for cartographic and surveying purposes, means that investments in human and technical resources can be spread across several disciplines and departments in both national and supranational organizations. Furthermore, the advances in microcomputing have made the acquisition and maintenance of image-processing equipment and GIS much more feasible financially.

TUNISIA: Present Status of Landscapes in the Central Northern Region

A joint collaboration between Moscow State University, Moscow Centre for International Projects, Ministry of Environmental Protection (former USSR), E.V. Milanova, A.V. Medvedev, A.K. Posypkin, I.N. Maslennikova
Agence Nationale de Protection de l'Environnement (Tunisia),
Direction des Sols, Ministry of Agriculture (Tunisia)
Institut Nationale des Recherches Forestières (Tunisia)
Centre Nationale de Télédétection (Tunisia)
Institute des Régions Arides (Tunisia)

Introduction

Deserts occupy about 30% of Tunisia's land area, including 15,000 km^2 recently desertified. An additional 20,000 km^2 are considered to be at high risk from desertification. Since the semiarid and dry subhumid regions of the country are inherently dynamic environments, in which processes of ecological change are continually active, it is important to be able to distinguish between natural processes leading to more desert-like conditions and those instigated by human activities. Hence the study of dryland landscapes is important from both a methodological and practical viewpoint.

The Present-day Landscape Concept

The study and assessment of desertification requires a complex approach to the environment, which is here viewed as a combination of hierarchically subordinated geosystems called "present-day landscapes". Each present-day landscape is a distinct unit of land surface characterized by a combination of natural and anthropogenic forces which have together moulded a spatially distinct and temporally stable territorial system. Hence the present-day character of any landscape unit can be seen as the result of anthropogenic transformation of its natural basis. The notion of present-day landscapes used in Map 1 and the map of the Aral Sea on page 69 corresponds to the concept of "land" used throughout the global and continental Africa sections of this atlas.

By stressing the natural foundation of particular landscapes, the present-day landscape concept encourages the researcher to be aware continually of the fact that in order to achieve optimal environmental management, all economic structures and processes must be compatible with the dynamic equilibrium of natural structures. Ignoring this principle is often the major cause of most environmental problems, including desertification.

Present-day Landscape Methodology

Present-day landscape maps are compiled using existing maps, remote sensing imagery and field observations. An initial categoric division is made between landscape units deemed to be "modal", (natural landscapes that have not been affected by human modification) and "natural-anthropogenic" (landscapes thought to have been significantly affected by human action). Factors indicative of a landscape unit's natural character include characteristics such as relief, soils, and climax vegetation communities. The degree of landscape transformation is determined by changes of vegetation cover and actual land use. Three classes of natural-anthropogenic landscape are recognised, according to the degree of effect (See Figure 1 and Table 1).

The derivative, or secondary landscapes, (D) are those that have resulted from some previous human activity but which do not currently experience any sensible controlling human influence. Hence these derivative landscapes are all characterized by the predominance of natural processes working in a context set by human action. The context includes elements such as vegetation, landforms and soils that have been modified by human activities at some time in the distant past.

Landscape anthropogenic modifications (A) can be defined as transformed landscapes whose natural components have been more or less changed through conscious human impact. Importantly, in this type of landscape, modal components may typically constitute up to half of the unit.

Landscape technogenous complexes (T) embrace areas where anthropogenic structures almost totally replace the natural vegetation cover. Examples include urban areas, industrial and mining zones.

Using this system, therefore, every mapping unit can be considered as a stable and objective inventory data cell, furnished with data on the state of the natural and socio-economic landscape.

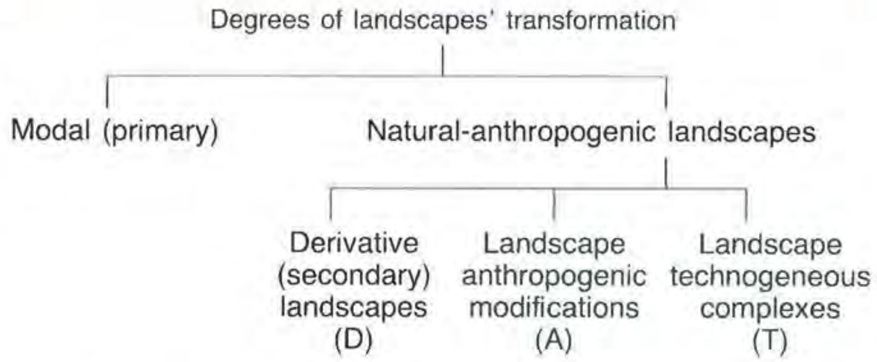


Figure 1 Major categories of present-day landscapes

Table 1 Degree of landscapes' transformation

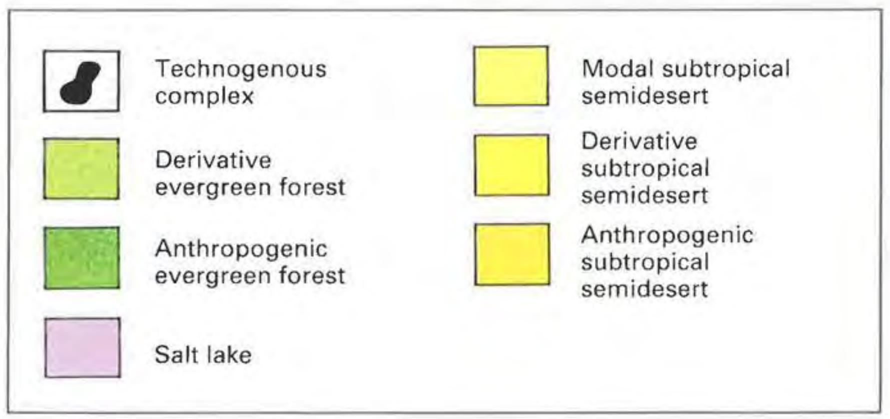
Present-day landscapes' categories	Vegetation cover transformation	Intensity of present-day human impact
Modal landscapes (M)	Light (practically no transformation)	Low (low-intensive or virtually absent)
Derivative landscapes (D)	Moderate (secondary biotic successions)	Medium (medium-intensive or territorially limited)
Landscape anthropogenic modifications (A)	Strong (cultural vegetation cover)	High (dominantly high-intensive on over 50% of area)
Landscape technogeneous complexes (T)	Extremely strong (replacement by technogeneous structures)	Very high (dominantly very high-intensive and technogeneous on over 50% of area)

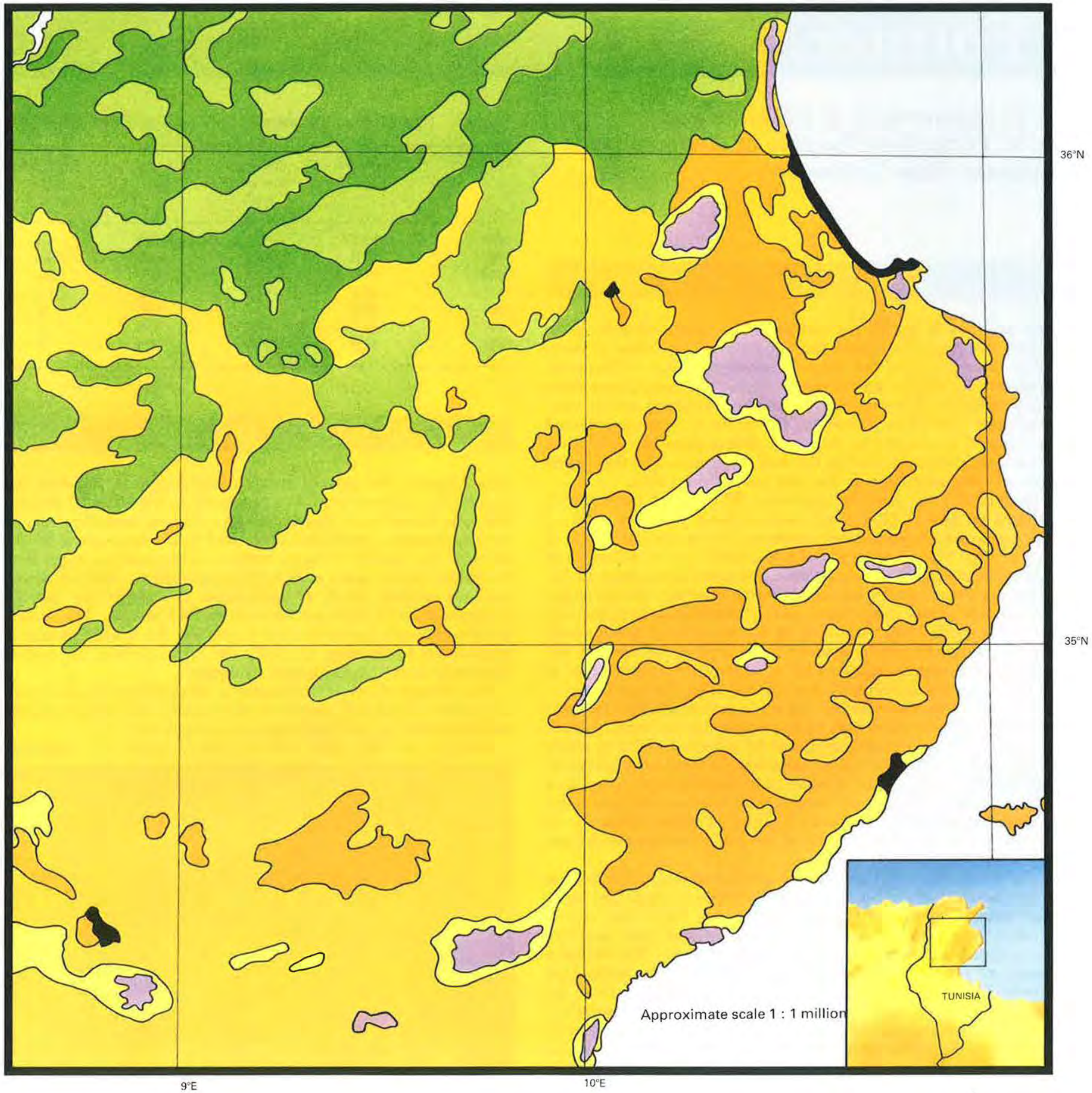
The Map

Map 1 is the result of intensive study by Soviet and Tunisian experts using more detailed and relevant maps, remote sensing imagery and field observations. The region mapped lies in the subtropics and is made up of two natural zones: evergreen sclerophyllous forests and subtropical semideserts.

The state of the environment in Tunisia, as shown in the map, reflects the deep and large scale transformations of natural landscapes, virtually all components of which have been significantly transformed as a result of centuries of exploitation, especially for agriculture. In Tunisia's central Mediterranean region (the northern parts of the map), the result is a widespread loss of the former forest cover and replacement with modern cereal cultivation or traditional cereal cultivation with pastures. In the southern, subtropical semidesert region, the natural vegetation characterized by grasses and shrubs has been widely replaced with non-irrigated fruit plantations and pastures with modern cereal crop rotation.

Overall, the map suggests that the landscapes of the Mediterranean zone do not reveal evident desertification features, despite the high degree of anthropogenic transformation. In the semidesert zone, however, even relatively low-intensity human impact has lead to widespread desertification, the degree and form of which depends primarily on the type of economic activity and not on the properties of the primary landscape.





Map 1 Present status of landscape in the central northern region of Tunisia

Former USSR: Present Status of Landscapes in the Aral Sea Region

E.V. Milanova, E.V. Glushko and A.V. Ptichnikov (Faculty of Geography, Moscow State University)

Introduction

The Aral Sea is fed by the waters of the largest Middle Asian rivers, the Amu-Darya and the Syr-Darya. The deltas of these rivers have provided the focus for several ancient civilizations, most notably that of the Khorezm. Today the Amu-Darya delta is a densely inhabited agricultural region producing cotton, rice, grain and vegetables. However, the drive to increase irrigated agricultural production in this area, dating from the 1950s, has been instrumental in turning the Aral Sea region into the largest zone of ecological crisis in the arid part of the USSR.

In the 1957, the Aral Sea contained 1075 km^3 of water which covered an area of 66,085 km^2, with a mean sea level of 53 m. The sea's water balance was maintained by an annual inflow of 56 km^3 from the Amu-Darya, with another 5 km^3 of atmospheric precipitation. Rapid development of irrigated agriculture in the following three decades has resulted in a dramatic decline in the annual flow of the Amu-Darya and Syr-Darya reaching the sea, so that in some years the waters of the Amu-Darya barely reach the sea shore. In 1990 a total of seven million hectares in the Aral region were irrigated, with annual water withdrawals of 60 km^3 from the Amu-Darya and 45 km^3 from the Syr-Darya.

Consequently, the Aral Sea has shrunk dramatically. Its water level has fallen by more than 14 m, its area has declined by more than 40% and its volume decreased by more than 60% in about thirty years. In 1989 the sea had receded into two separate parts. The level of the southern "Greater Sea" stood at 38.6 m and that of the northern "Lesser Sea" was 39.5 m. Together the two water bodies covered 36,500 km^2 with 330 km^3 of water (Table 1). At the same time the mean salinity of the water has increased from 9% in 1957 to 30% in 1989.

The economic, social and environmental effects of the decline in the Aral Sea are numerous. The sea formerly contained more than twenty species of fish, most of which have died out as shallow spawning grounds have dried up and food reserves disappeared in the increasingly saline waters. The exposed seabed of the Aral has become the source of large scale dust storms, blowing up to 75,000 tonnes of dust annually from the saline "solonchak" soils. Much of this salty material is deposited on the irrigated cropland of the delta, adversely affecting soils and crop yields. The heavy use of toxic chemical pesticides in irrigation areas has influenced local drinking water supplies which have also deteriorated through inadequate purification and sewage treatment plants. The incidence of typhoid and hepatitus in the region has risen over the thirty-year period of intensive irrigation development.

Table 1 Hydrological parameters of the Aral Sea, 1957–1989

Year	Sea level (m)	Sea area (thousand km^2)	Sea volume (km^3)	Total river runoff into sea (km^3)
1957	53.3	66.1	1075	—
1965	52.5	63.9	1030	31
1970	51.6	60.4	970	33
1975	49.4	57.2	840	11
1980	46.2	52.4	670	0
1985	42.0	44.4	470	0
1989	39.0	36.5	330	5

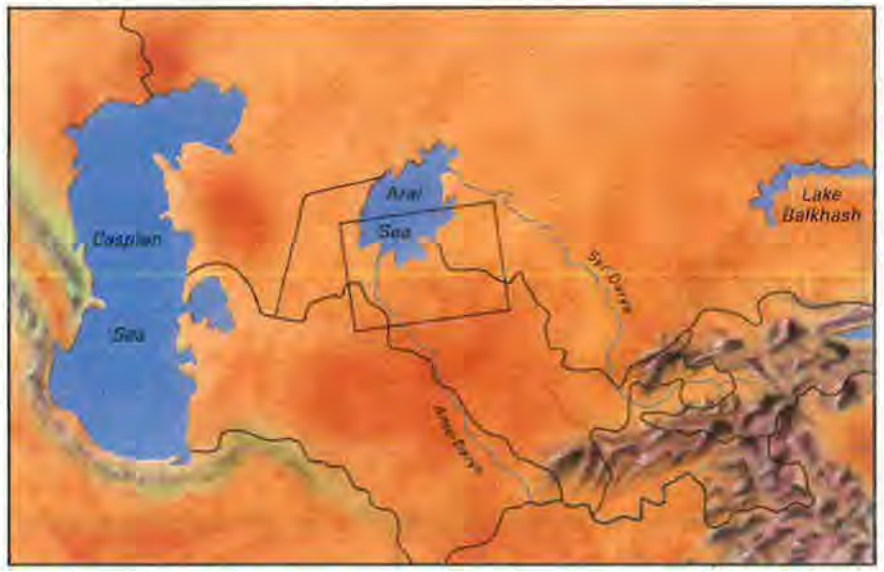
Methodology and Map

Map 2 shows the present status of landscape in the Aral Sea region. The original map was produced to the scale 1:1,000,000 and was based on a variety of data sources including remote sensing imagery, published data, and field observations by the authors. The satellite imagery comprised composite images from the Salyut orbital space station (70 m resolution) and the Meteor resource satellite (10–30 m resolution). The shore line and the contours of delta lakes are taken from 1969 images. The remote sensing imagery has been used to identify the spatial pattern of present-day landscapes, to verify the types of land use and to determine trends in landscape evolution.

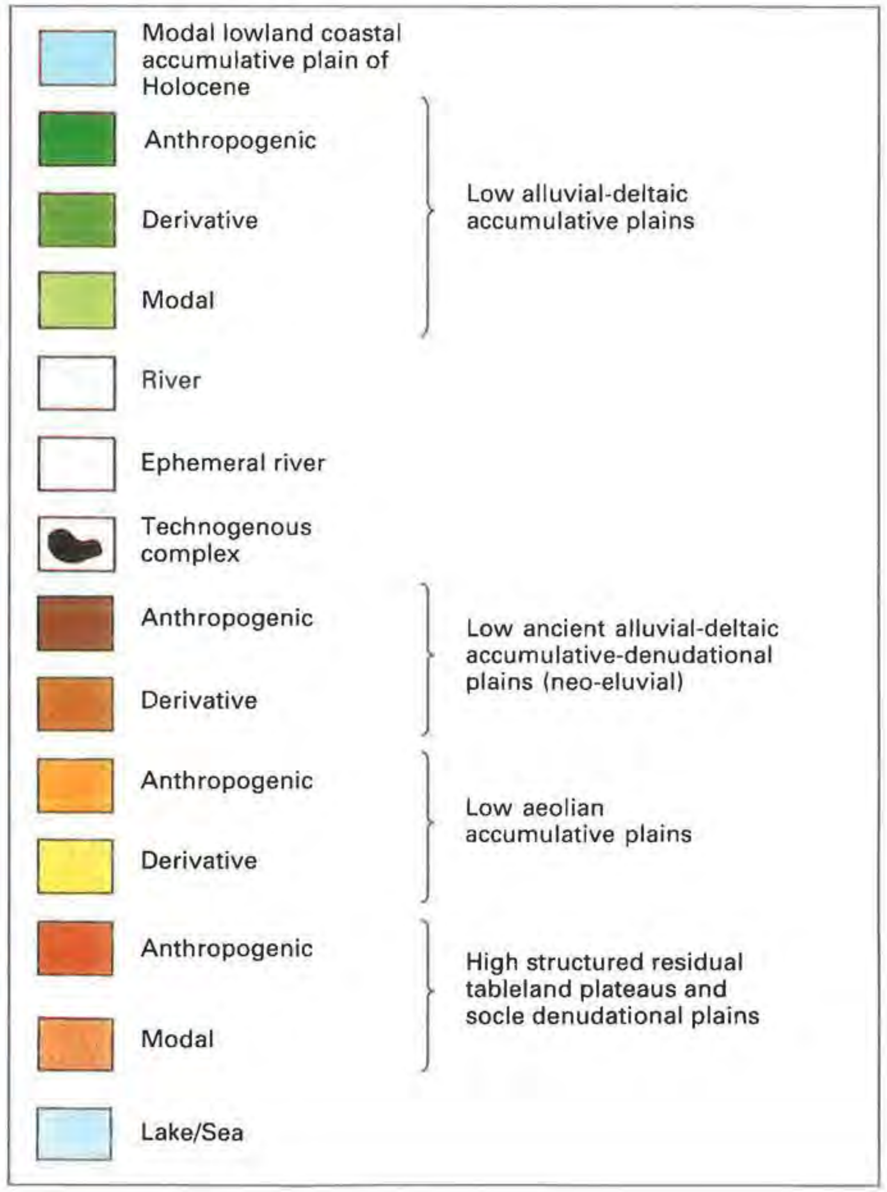
The present status of landscapes is characterised by four main categories: Modal (M), derivative (secondary) (D), anthropogenic modifications (A) and technogenous complexes (T).

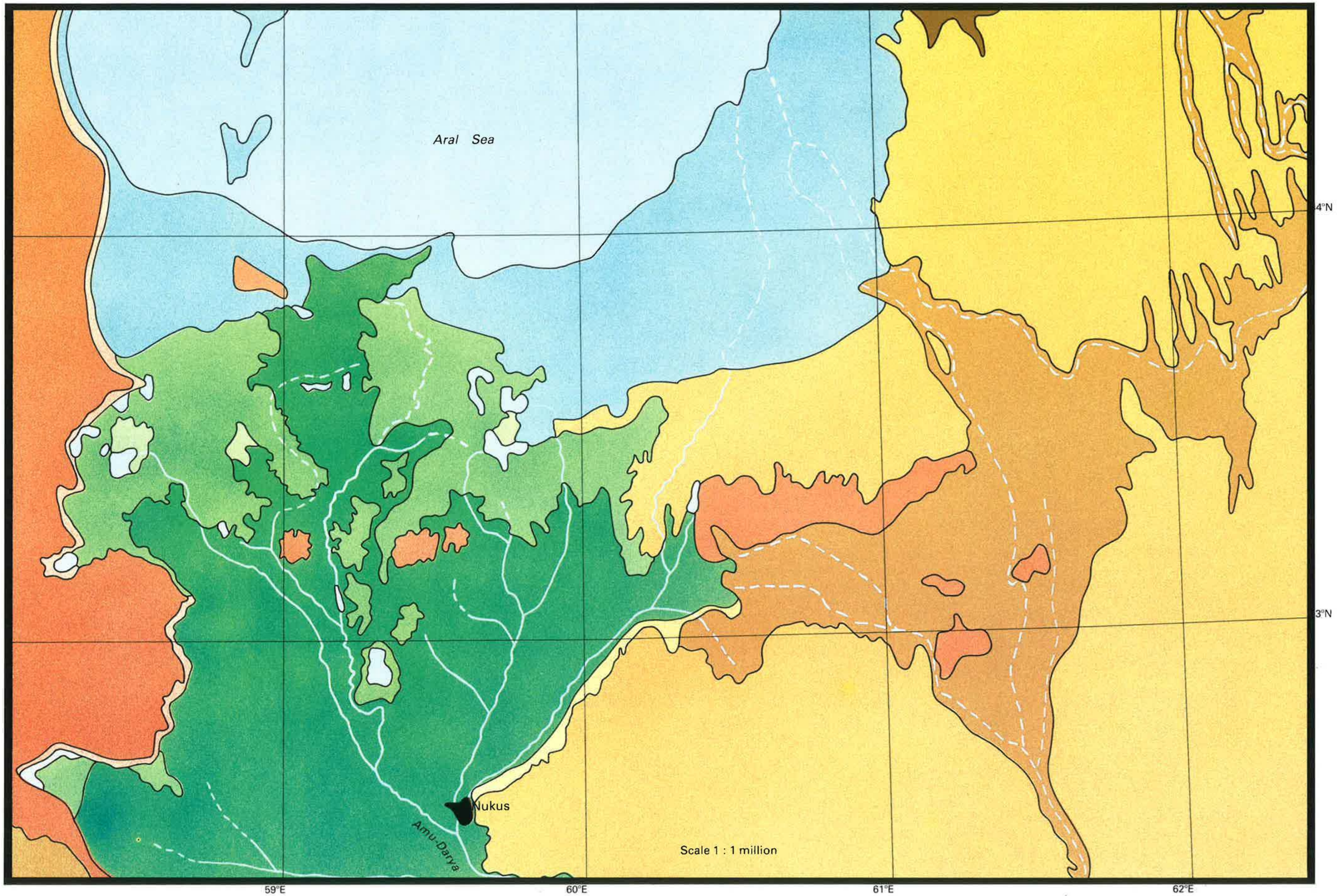
Analysis of the map allows identification of landscape transformations in the process of their utilization and the tracing of landscape evolution under the influence of desertification processes. The map forms a necessary basis for the objective assessment of desertification factors in the Aral Sea region, as well as enabling an evaluation to be made of the nature and degree of desertification processes in arid landscapes.

The low alluvial-deltaic accumulative plains represent the desertification "hot spot" of the Aral Sea region. They have experienced radical changes, especially in their non-irrigated areas, where flooding has ceased since the 1960s due to regulation of river flow by reservoirs. Widespread desiccation of the delta lakes and reed beds has been the result. Secondary salinization and waterlogging plague the irrigated areas, while saline water flowing back into the Amu-Dayra from irrigated fields causes serious problems as water quality has declined.



Map 1 Location of Aral Sea case study.





Map 2 Present status of landscape in the Aral Sea region.