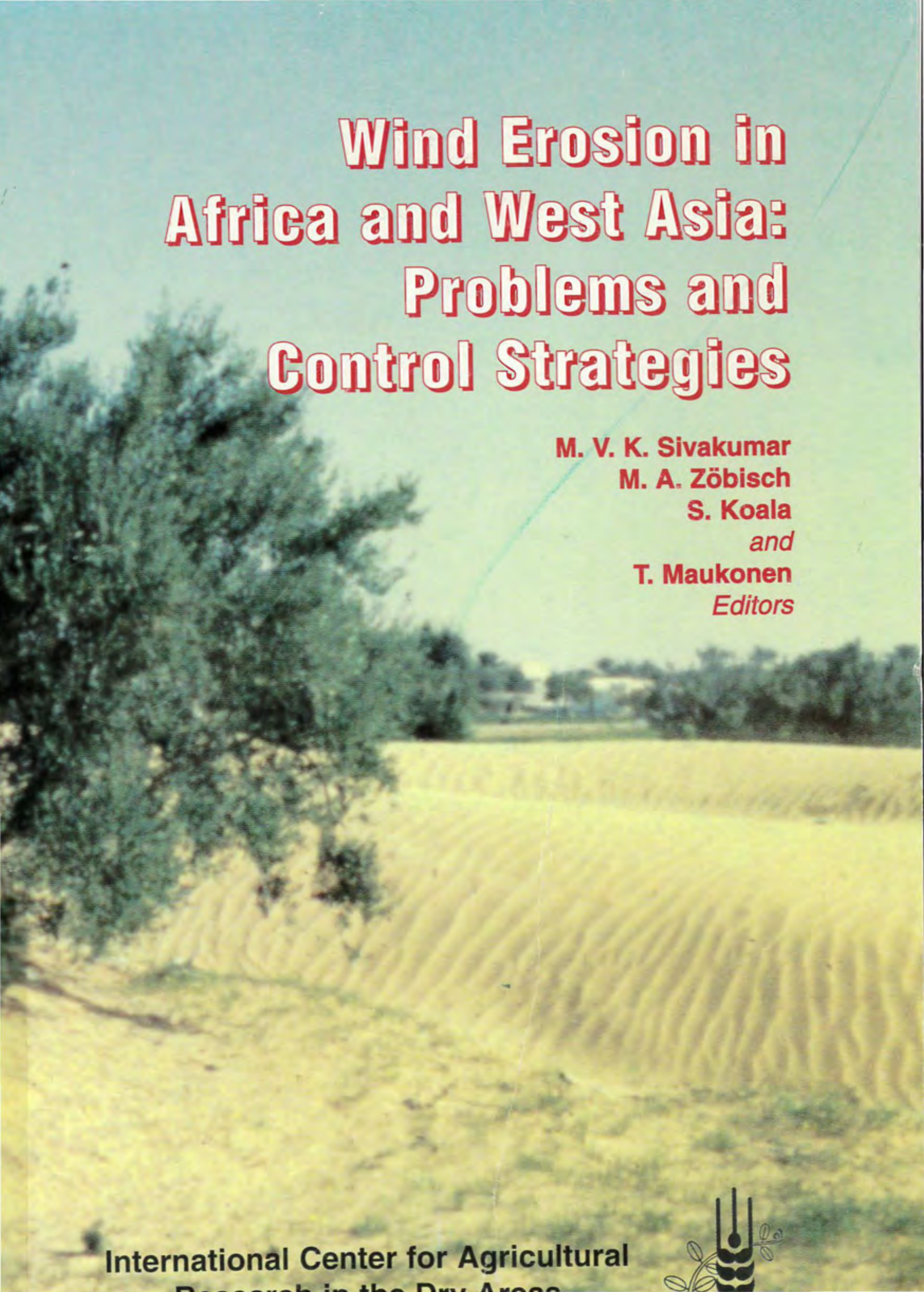

# Wind Erosion in Africa and West Asia: Problems and Control Strategies

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*Editors*

International Center for Agricultural

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# Wind Erosion in Africa and West Asia: Problems and Control Strategies

*Proceedings of the Expert Group Meeting*
*22–25 April 1997, Cairo, Egypt*

*Editors*

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World Meteorological Organization (WMO)

**International Center for Agricultural Research in the Dry Areas (ICARDA)**

**1998**

**Citation:** Sivakumar, M.V.K., M.A. Zöbisch, S. Koala and T. Maukonen (Ed.). 1998. Wind Erosion in Africa and West Asia: Problems and Control Strategies. Proceedings of the ICARDA/ICRISAT/UNEP/WMO Expert Group Meeting, 22–25 April 1997, Cairo, Egypt. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria. v + 198 pp.

ISBN: 92-9127-077-6

**Production supervisor**: Guy R. Manners

**Language editor**: Ellen Larson

**Typesetting**: Savvy Press

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**Acknowledgement**: Financial support provided by the Royal Ministry of Foreign Affairs, Government of Norway, to organize the Expert Group Meeting is gratefully acknowledged.

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# Contents

# Foreword

The dry parts of Africa and West Asia experience tremendous pressures on their land resources. Population increases in these regions are some of the highest in the world. At the same time, signs of serious land degradation are apparent everywhere in the region. Without appropriate land management practices, these lands will deteriorate beyond the state of useful rehabilitation.

In many areas, traditional land management practices can no longer cope with the pressure exerted on the land. Land-users need to adopt more appropriate ways of management of the land. However, despite advanced scientific knowledge and the availability of land-use technologies suited to many different circumstances, adoption by the land-users is often low. The reasons for non-adoption are many-fold. For example, proposed new technologies may not be suited to the particular farmer's circumstances, they may be too complicated or too expensive, or the general policy environment may not encourage the adoption of improved land-use technologies.

This poses a great challenge to the international community of researchers and development workers. However, we do not need to re-invent the wheel to help the land-users. Existing traditional and modern technologies need to be examined more closely within their local contexts. Building on this existing knowledge, new and better approaches and technologies may be derived, developed and adapted to local situations. In doing so, however, there should be concern for the environment. Not everything that is good for the land-user is good for the environment. Balancing the needs and requirements of the land-users with the need for protecting the environment is probably the most delicate task facing research and development organizations in these areas.

International, regional and local research and development organizations have to work closer with the local communities to achieve this. Land-user participation will ensure that research and development activities do not lose sight of reality.

During the Expert Meeting on Wind Erosion in Africa and West Asia held in Cairo from 22 to 25 April 1997, the causes, effects and impacts of wind erosion in the region were analyzed and evaluated. Alternative strategies and general approaches to fight wind erosion were proposed. This book presents the experiences of professionals of different disciplines and from different organizations who have a common interest in halting land degradation and contributing to a sustainable utilization of the land resources in the region.

I sincerely hope that this book will help to initiate more concrete action and collaboration between all parties concerned with the protection of the land against wind erosion and other forms of degradation.

Prof. Dr Adel El-Beltagy
Director General, ICARDA

# Introduction

Drylands are important sources of aeolian particles (dust and other particulates) associated with a variety of human activities, including vegetation removal and biomass burning. A wide range of empirical and numerical modeling studies, which relate climatic variation in drylands to a variety of forcing mechanisms, has established the strength of the link between the global climate system and specific climate patterns in the dryland areas.

Wind erosion, the removal of soil by wind, is one of the most damaging effects of wind in many parts of the world. As a rule, it only assumes the status of a major problem in regions with a strongly-marked annual dry season, and hence is a potential hazard in all dry environments. Much of the early work on wind erosion was carried out in the great plains of the United States, the wheat fields of the Canadian prairies, and the south of the former USSR. The problem has also been studied in Europe, Asia, and Australia.

The occurrence of wind erosion is a function of weather events interacting with soil (intrinsic properties) and land management (past and present practices) through its effect on soil structure, tilth, and vegetation cover. As with water erosion, most wind erosion damage comes from relatively rare, severe events. Increased availability of simple and inexpensive "sand catchers" and automatic weather stations over the past 5–10 years makes the task of monitoring sand flux and weather data easier.

Wind erosion presents multiple challenges: identifying where wind erosion is most threatening to sustainable agricultural productivity; what practicable farmer-friendly measures can be devised to contain it; and how these measures can be transferred (for instance, through extension services) and implemented within agricultural land-use systems.

According to previous studies, wind erosion in the semi-arid regions of America, North and South Africa, Australia, the Near East, and many parts of Central Asia only reached threatening proportions when man disturbed the ecosystem balance. This is true for West and Central Africa (WCA), and West Asia and North Africa (WANA), where growing population pressures have led to the replacement of the traditional practice of fallowing with slash and burn practices and continuous cultivation. In regions (WCA and some parts of WANA) where little or no nutrient amendments are made to replace the rapidly declining soil nutrient pool, soil cover is declining rapidly, leading to wind erosion and land degradation. In WCA, where wind erosion is usually severe during the beginning of the growing season, young crops are damaged by wind-blown sand, leading to problems of poor crop stand and yield decline. Wind erosion in arable fields and rangeland causes various losses of soil depth, organic matter, clay content, nutrients, and indigenous seed. Downstream effects, e.g., effects, e.g., increased atmospheric dust, reduced visibility, blockage of roads, railway lines, problems of health, etc., are also causing considerable concern.

In Morocco, seasonal hot winds not only carry away soil but also affect crop performance through excessive evapotranspiration and direct wind effects. In the oases, sand encroachment affects wells, palm tree plantations, and traditional irrigation systems. In the southern and southwestern parts of Tunisia, the movement of sand dunes poses a major threat to farmlands. In much of West Asia and North Africa, large areas of the traditional semi-nomadic rangeland, the steppe, are being opened for barley cultivation. The consequent removal of the natural vegetation cover has exposed the soil surface, leading to the loss of the fertile fine fraction of the shallow soils through wind erosion. This has led to a tremendous decline in soil productivity and quality of life. Hence, the Government of Syria, for example, has forbidden the conversion of steppe for barley cultivation.

## Objectives and Format of the Meeting

Despite the growing realization of the problems of wind erosion in WCA and WANA, there is little qualitative or quantitative information on their seriousness or the location of problem areas. As a consequence, there are no long-term strategic plans to counter wind erosion and reduce the resulting damage. Hence, the International Center for Agricultural Research in the Dry Areas (ICARDA), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the United Nations Environment Programme (UNEP), and the World Meteorological Organization (WMO) organized this Expert Group Meeting to:

- Review the occurrence and form of wind erosion in the dry areas of WCA and West Asia North Africa (WANA).
- Discuss available control measures, both indigenous and improved, and assess the extent and potential of application in different regions.
- Define appropriate methodologies for identifying hot spots (on different scales), quantifying erosion and risk of erosion, and developing simple control measures.

The Meeting was designed to allow time for:

- Presentations on the main issues and identification of priority areas for further discussion.
- Brainstorming and analysis of priority areas for identification of future research needs and development applications.

The presentations allowed the Group to comprehend the major issues involved and identify priority areas for the discussion session. A keynote address delivered by Prof. Monique Mainguet, University of Reims, France, entitled "Wind Erosion in Africa, a Neglected, Creeping, or Catastrophic Process of Land Degradation: Suggestions for Control," outlined the major issues of wind-erosion control in Africa. Following two major overviews, one on WCA by ICRISAT and the other on WANA by ICARDA, presentations were made by scientists from Niger, Egypt, Tunisia, and Syria describing the research work carried out in their countries. These were followed by presentations from the USDA–ARS in Kansas, USA, the USDA–ARS in Big Spring, Texas, USA, the University of Wageningen, Netherlands, and the University of Hohenheim, Germany on understanding the major processes, modeling, farmer perceptions, local practices, and socioeconomic constraints to the adoption of wind-erosion control techniques.

Brainstorming and analysis of priority areas was a major activity of the meeting and covered two days. This session sought divergent views from the Group, engaged the Group in discussion, and arrived at a consensus on the research needs and development applications for each of the priority areas identified.

# Opening Address

**T. Maukonen**
*United Nations Environment Programme*

It gives me great pleasure to welcome you on behalf of UNEP and the other organizers, ICARDA, ICRISAT, and WMO, and to make this statement to this Expert Group Meeting on Wind Erosion.

I also want to express my appreciation to ICARDA for making the arrangements to host this workshop here in Cairo, a city which, for several reasons, provides a unique backdrop for a regional meeting for Africa and the Near East. First, it is located at the crossroads between Africa and the Near East. Second, Cairo is an important place for the desertification issue. The leadership of desertification control for the first two decades has rested on the shoulders of two famous personalities: Dr. Mostafa Tolba (the former Executive Director of UNEP and the man in charge of the 1977 Desertification Conference) and Professor Mohamed Kassas. They, true sons of Africa, both from Cairo, were instrumental in the organization of the United Nations Conference on Desertification (UNCOD) in 1977 and in maintaining the momentum for the decade and half until the UNCED in Rio and the ensuing negotiations on the United Nations Convention to Combat Desertification (UNCCD). Third, Cairo is a living example of a capital city which has to regularly face and taste the consequences of wind erosion, where people other than the natural resource users see the result of wind erosion every year. Maybe the timing was not correct for this meeting, as the visibility is good and no sand is blowing into our eyes and mouths.

There is also a fourth reason for holding this Meeting here, having to do with making this workshop financially possible. In this connection, I want to express our sincerest appreciation and thanks to the Norwegian Government, which provided us with the funds to hold this Meeting for Africa and the Near East in Cairo. Special thanks are also due to you, the experts, who have found the time to come and contribute to this undertaking.

Wind erosion is an important part of the desertification process, causing the devegetated land to lose its topsoil and productivity. This Expert Group Meeting will attempt to quantify the seriousness of the problem and identify a price tag (in economic terms) and solutions to the losses wind erosion brings about. This will strengthen the appeal of technical specialists and rural people made to the authorities in charge of development funding. The slow degradation of the resource base by wind erosion often remains unnoticed in the short term. Considered annually, it may not attract enough attention to activate counter measures. In addition, the regions where this phenomenon/process take place are more often than not outside the immediate interest of the decision makers (both national and international).

Once the dust storms affect cities, roads, and railway lines, the problem receives attention, but the rural dweller in remote areas, who is first affected by this menace and whose well-being may be endangered, may not benefit from this attention.

Can the loss for the entire national or international community be calculated? Is there a prudent, robust, and yet scientifically acceptable way to measure and quantify the consequences of wind erosion or of land degradation in general?

UNEP prepared, for the 1992 Rio Conference, a report on the global cost of desertification, including the income foregone, and ended up with figures running in billions of dollars annually. These were the best guess estimates at that time and were based on expert opinions and extrapolation of case studies etc. We at UNEP have been in search of better figures based on quantified data ever since (and even before Rio).

Thus there has been a need to improve the basis for quantification. Desertification, as a global environmental problem, is almost on equal footing with other global issues such as climate change, biodiversity, ozone depletion etc. It is a concrete problem and carries implications for socioeconomic development. Hence the need for quantification, especially at the national level, to raise the issue to the level of national priority and for the distribution of development funds.

In the new philosophy of the UNCCD, the National Action Programs (NAPs) will play the most prominent role. Progress at the national level (how things have been organized nationally to combat desertification) must be achieved in order to convince external funding agencies for help in the battle. Thus, the national treasurers need to be convinced, and they require strong economic data and reliable assessment of quantified losses.

The vast areas in the Near East and North and West Africa, which for thousands of years lived with wind erosion, are now under threat of widespread desertification. We must realize that food production potential is at stake, and that silt disappears forever from the land where it is needed and does not melt into the ground like snow for the benefit of the new crop in the spring.

Ladies and gentlemen, in an attempt to visualize the problem we are here to deal with, please allow me the above allegories and this bit of melodrama for the start of this workshop. I trust that you have amongst you a wealth of scientific expertise and knowledge, which we hope to bring together to establish the state of the art, identify knowledge gaps, develop and improve tools for quantification, and plan procedures and programs to fill gaps in research and development for wind-erosion control.

Ladies and gentlemen, I hope that during the next three and half days we will have a frank exchange of information and an active group effort to bring to wind-erosion control the attention it deserves. Thank you.

# Welcome Address

**M.V.K. Sivakumar**
*World Meteorological Organization*

On behalf of the Secretary General of WMO, Prof. G.O.P. Obasi, I extend to you all a warm welcome to this Expert Group Meeting on Wind Erosion in Africa and West Asia.

The topic of Wind Erosion is of particular interest to WMO, as it is an extreme meteorological hazard that carries implications for food security. As a rule, it assumes the status of a major problem in regions with a strongly-marked annual dry season, and hence is a potential hazard in all dry environments. As with water erosion, most wind erosion damage comes from relatively rare events, when thresholds for surface particle movement are exceeded, and only reaches threatening proportions when man has disturbed the original balance of soil, climate, and vegetation by his interference. This has been very much in evidence over the past three decades in the dryland regions of West and Central Africa, West Asia, and North Africa where increasing rates of deforestation and overgrazing, and declining soil fallow periods, have resulted in increased problems of wind erosion.

To develop appropriate strategies to cope with wind erosion and arrest land degradation, it is imperative that we build a sound base of scientific knowledge of the processes of wind erosion, quantify the extent of wind erosion under natural conditions, study control measures, evaluate farmer acceptance of such measures, preferably through a farmer participatory approach, and address the institutional and policy issues that need to be put in place for a wide adoption of wind-erosion control strategies.

WMO is very pleased to cosponsor this Expert Group Meeting. The Commission for Agricultural Meteorology (CAgM) of WMO recognizes the importance of the study and application of agrometeorological information to better cope with extreme events such as wind erosion, and has initiated a major project on agrometeorology for extreme events. WMO has close collaborative linkages with UNEP and the CGIAR Centers such as ICARDA, ICRISAT, and IRRI. Together we have demonstrated that the judicious application of meteorological and hydrological knowledge and information greatly assists the agricultural community to develop and operate sustainable agricultural systems and increase production in an environmentally sustainable manner. UNEP and WMO, through our Dryland Ecosystems and World Climate Program, respectively, and through our joint undertakings, continue to take active global roles in providing substantive scientific knowledge and information for decision makers so that they may understand the important interaction of climate and drought with the processes of land degradation and desertification, including wind erosion. The UNEP/WMO publication, "Interactions of Desertification and Climate," a substantive scientific document for understanding these interactions, also identifies wind erosion as a major problem in the dryland areas.

Along with a letter of invitation, all of you have received an introductory note that describes the objectives and format of this meeting. Let me recapitulate briefly what we want to achieve over the next four days:

- First, we would like to review the occurrence and form of wind erosion in the dry areas of West and Central Africa, West Asia, and North Africa.
- Second, we will discuss available control measures, both indigenous and improved, and assess the extant and potential applications in different regions.
- Finally, we will try to define appropriate methodologies for identifying hot spots (on different scales), quantifying erosion and risk of erosion, and developing simple control measures.

We have designed the meeting in such a way as to allow time for presentations on the main issues and identification of priority areas for discussion. Following two major overviews, one for WCA by ICRISAT and the other for WANA by ICARDA, presentations will be made by national scientists from each region covering the research work carried out in their countries. These will be followed by presentations from centers of excellence of wind erosion research in Europe and North America covering ongoing research on understanding the major processes, modeling, farmer perceptions, and socioeconomic constraints to wind-erosion control.

In planning for this Expert Group Meeting, we have deliberately designed brainstorming and analysis sessions, extending over two days. These sessions will seek divergent views, engage the group in discussion, and arrive at a consensus on the research needs and development applications for each of the priority areas. Your full participation and considered views are crucial for the success of these sessions. I am most pleased to note the presence of Dr. F. Abdalla, who will act as moderator to assist us in these sessions.

The presentations, discussions, and final recommendations of this expert group meeting are expected to contribute towards the preparation of a concept note for a project on wind-erosion control for sustainable land management in the dry areas of West and Central Africa, West Asia, and North Africa.

As you may be aware, the first Conference of Parties, or COP-1 of the United Nations Convention to Combat Desertification, will be held September–October this year in Rome. The Committee on Science and Technology for the UNCCD will hold its first meeting at this Conference, and invites input from all concerned parties in dealing with scientific and technological issues concerned with desertification.

Once again, on behalf of the Organizing Committee for this Meeting, I would like to thank all of you for attending this meeting and contributing to our efforts to combat wind erosion in Africa and West Asia. Thank you.

# Keynote Address

# Wind Erosion in Africa, a Neglected Creeping or Catastrophic Process of Land Degradation: Suggestions for Control

**Monique Mainguet**
*Laboratoire de Géographie Zonale pour le Développement, University of Reims Champagne-Ardenne, Reims, France*

## Abstract

Wind erosion is one of the worst environmental and human disasters in the drylands that cover 33–37% of the continental area of the planet. Yet this mechanism has not received the international attention it deserves. The reason for this is the difficulty of perception: wind erosion is a low-grade, insidious-onset, long-term, cumulative process.

Many assertions concerning aeolian sand deposit need revision: the relationships among sand deposit, climate, and vegetation cover; the relationships among regional changes in the atmospheric pressure fields, aeolian erosion, aeolian transport, and aeolian sand deposit; the development of sand seas in relation with topography; and the concept of sediment balance.

One of the most common errors is to consider dunes as resulting from accumulation alone; many of the dune fields or sand seas are residual edifices.

The control strategies for wind erosion must take into account the global wind action system. This includes the combination of areas of sand deflation, sand transport, and sand accumulation on scales including the local, regional, and synoptic, as well the analysis of phenomena that define the solutions.

## Introduction

The title of this paper reminds us that wind erosion, one of the worst environmental and human disasters in the drylands (which cover 33–37% of the continental areas of the planet), is a mechanism that has not received the international attention it deserves. Increasing human and livestock populations in most parts of the arid lands have led to an increasing use of sand and loess areas and areas of high wind-erosion risk for grazing, agriculture, and urban and industrial development. All these activities accelerate wind erosion.

The sandy areas—mainly those of the drylands—are probably the most vulnerable *vis-à-vis* wind erosion. Aeolian sands cover 6% of the global land surface. About 97% of aeolian sands have accumulated in the drylands (defined as receiving annual rainfall <600 mm). On average, about 20% of the world's arid zones are covered by aeolian sand: 20% of North America, 20% of the Sahara, >30% of Australia, and >45% of Central Asia. The semi-arid zones can be as rich and even richer in sand than the arid areas themselves, as has been found in the Sahara–Sahel region.

The first part of this paper aims to show that wind erosion is a deleterious chain of cumulative processes, which is yet to find its rightful place in the fight against land degradation. The second part will try to take stock of the numerous questions which still remain unanswered in the areas of sand deposit, dune genesis, and wind action. Finally, a summary will be presented of what should be done for better control of sandy areas and dunes within the framework of what we propose to call the "Global Wind Action System."

## Deleterious Effects of Wind Erosion

Wind erosion is a low-grade, long-term cumulative process with an insidious onset and several overlapping evolutionary steps:

### Step 1

Incremental, insidious environmental changes occur during an undetected incubation period (Table 1). Wind erosion, in the form of winnowing or deflation, introduces a very slow rate of change, which is difficult to detect. Most of society does not recognize the changes. The major symptoms of this adverse environmental process are not very well known. This explains the lack of perception of the damages caused by wind erosion at this step among policy makers.

**Table 1. Evolution of the Taokest area (Mauritania): surprising case of severe land degradation in the mid 1950s in Aoukar.**

*1. Observations of the oldest aerial documents*

Observations are required to determine the date desertification was triggered.

In aerial photographs of Mauritania NE 29-XV Nos. 79-80, 1:50,000 scale, Dec 1956 to Jan 1957 (early dry season), the sand deposits around the Taokest were organized in a slightly fixed dune field of transverse dunes of 400 $km^2$ (from 17° 30' to 18° 30' N and 8° to 12° 30' W), indicating a positive sediment balance.

After the accumulation phase responsible for the Taokest dune field (main wind direction 19° 5' ENE) the dunes were vegetated, creating relative stability of the field (lower reflectance in the south) because of a slightly denser vegetation cover. The interdunal depressions also have lower reflectance. To the north of the photographs (18° 12' N), the dunes are already active, with some vegetation at their feet.

To the south of the same photographs the barchanic edifices are vegetated with some bushes in the interdunal spaces.

*2. Prodromes to desertification in 1956*

Even if the dune field in 1956 seems fixed by open vegetation cover, symptoms of land degradation can already be observed, indicating prodromes to desertification:

- Omnipresent grooves of deflation, responsible for the transverse dunes of the first longitudinal patterns.
- Elongation of the dextrial barchanic wings in the majority.
- Appearance of small depressions on the flat back of the barchanic edifices, initiating a parabolic pattern.
- North of the photographs, the crest of the barchanic dunes is abraded, reactivated, and rounded. The reactivation proceeds from the foot of the back of the dune to the summit, which is reached by shallow furrows.
- Appearance of a new family of small barchans at the crest of the primary ones.
- Genesis of seifs (linear dunes) on the dextrial wing of the original barchans.

These figures are all preambles of longitudinal patterns, revealing an export of sand and the transition from a positive to a negative sediment balance. At the end of 1956, indicators of erosion, sand movement and severe land degradation were already visible, 12 years before the discontinuous drought of 1968–1985.

This reorganization of dune fields from a positive sediment balance (a general trend in the Sahel) to a negative sediment balance is an objective indicator of land degradation by aeolian escape of soils occurring before the 1968–1985 drought.

This important result shows that just after independence, signs of land degradation can be observed, probably human-induced, because the 1950s was a decade of good rainfall. This demonstrates that drought alone doesn't trigger land degradation, but probably reinforces pre-existing land degradation.

For a long time, the Sahel was a huge vegetated accumulation area, south of the Saharan active sand-exporting wind-action system. In the 1950s, with increasing population and overgrazing, the area was reactivated and the sandy topsoil reworked.

## Step 2

This is marked by awareness of a transformation in the environment involving a slowly changing geomorphic system associated with three sets of difficulties:

- Wind, which is only moving air, is not visible. It becomes traceable when it moves particles. This raises a question: should wind loaded with particles be considered as a specific fluid, different from empty wind?
- It is harder to develop a worldwide awareness of the associated risks of gradually occurring adverse environmental changes, such as those induced by wind erosion, than for "rapid-onset hazards" such as earthquakes and flash floods.
- One additional difficulty lies in the difference of scale. Wind erosion cannot be understood without an approach that embodies synoptic, local, and regional scales, as well as time scales, to integrate all the climatic changes.

## Step 3

Transformation in the environment is progressively viewed as environment degradation.

## Step 4

Change in the kind of difficulty, from local erosion to local catastrophe, due to encroaching sand, dust, and disturbance of everyday life, is recognized. This includes air traffic disturbed by aerosols (almost each year in Niamey) and reduction of visibility, and sand encroachment on roads, railways (the Zouérate–Nouakchott line), and urban structures (Brava in Somalia). It is mainly at this step, which is the step of sand deposition and dune initiation near or on human infrastructures, that awareness of risk occurs.

## Step 5

Change in the degree of evolution from soil degradation to regional production damage, socioeconomic disaster, and eventually famine (this year in Mali) is observed.

These five steps, from a non-perceived environmental change to a perceptible environmental degradation and finally to socioeconomic crisis, correspond to acceleration from a geologic to a human scale. On the of scale of time, wind erosion induces incremental changes in environmental conditions which accumulate imperceptibly over time until they are suddenly revealed or accelerated with the appearance of new data such as inundation, flood, and drought. Then a change of rhythm occurs, resulting in an environmental crisis or emerging as a full disaster. Wind erosion is neglected because the rhythm of its adverse consequences results in a long lead time before becoming apparent, and is taken into account only when its rhythm accelerates and develops over a short time frame. In the case of wind action, the indicators are first vegetation cover degradation and then deflation and winnowing with soil degradation. They also include lowered agricultural production, health problems due to dust, sandstorms, and air pollution.

## Scientific Uncertainties

Wind erosion is a complete science (Table 2). Among the factors which control major dune-building episodes, some are confirmed but others seem to be incorrect or unverified. Many assertions concerning aeolian sand deposit need revision. We shall examine those which are the most doubtful.

**Table 2. Combating wind erosion.**

| |
|---|
| Combating wind erosion is a complete science, including field observation and measurement, and laboratory and field experimentation. |
| *1. Field observations sustained by air photography and satellite imagery:*<br>• According to precise indicators, satellite imagery allows us to detect and delimit the sandy areas and the areas of erosion (source), transport, and accumulation.<br>• Relationship between topography (obstacles, wind/sand currents) and GWAS.<br>• The relationship between vegetation cover and aeolian dynamics.<br>Thanks to field investigations the following can be determined:<br>• Wind direction by indicators such as strikes in sand, corrasion grooves, and nebkas (sand arrows).<br>• Patterns of local erosion.<br>• Patterns of local accumulation: inventory of the type of dunes.<br>• Analysis of initiation, development, and morphology of the dunes.<br>• Investigation of interdunal spaces. |
| *2. Field measures and laboratory measures:*<br>• Measurement of wind speed at different locations (surface, crest line, and slope).<br>• Sedimentologic analysis: granulometry, morphoscopy, and heavy minerals. |
| *3. Aeolian processes experiment:*<br>The objective is to simulate, on a smaller scale, selected geomorphic features.<br>Laboratory tunnel studies provide:<br>• Understanding of the physics of sand movement.<br>• Relation between surface characteristics: roughness, particle size, slope, moisture content, and cohesion.<br>• Wind shear velocity, flux rates. |

## Sand Deposits, Climate, and Vegetation Cover

Dune building episodes are considered most likely to take place during dry periods. The statement that in arid lands peak dune formation corresponds to drought should be submitted to scientific verification. Periods of increasing aridity and drought are in fact accompanied by increasing wind speeds, as proved by wind measurements in Niger during the 1968–1975 drought, and thus increasing wind activity, meaning export and not accumulation of particles in the arid zone. Therefore, one of the main difficulties is to admit that the periods of dominant aeolian deposition do not correspond to the most arid periods (less prone to accumulation because of decreasing roughness due to the disappearance of the vegetation cover), but to semi-arid environments.

Moreover, only one fifth of the Sahara desert is covered by sand, the deepest and most continuous sand cover being in the Sahel south of the Sahara. The presence of a thick continuous sand sheet can be explained by an increase in the density of the vegetative cover in the semi-arid Sahel south of the wind action system of the Sahara, and by the increase of roughness, which leads to a decrease in the boundary-layer winds. These questions should be analyzed on the synoptic scale and in terms of a geologic time scale.

## Regional Changes in the Atmospheric Pressure Fields, Aeolian Erosion, Aeolian Transport, and Aeolian Sand Deposit

These relationships are almost unknown and should be investigated using scientific measurement, as should the view that the frequency, magnitude, and persistence of high winds and aeolian deposits are simultaneous. The lack of significant data to quantify the effects of atmospheric conditions on air flow profiles, from which sand transport rates are calculated, is widespread.

## Development of Sand Seas in Relation to Topography

Why accumulation results in a sand veneer, a sand sheet, isolated dunes, or a dune field is still not adequately understood. Many uncertainties still exist concerning the mechanisms of dune and dune field initiation, the rate of sediment transport over dunes, dune fields, and sand seas, and the influence of wind regime and topography. We have observed that on a flat surface the dominant trend is to form barchans. Natural and artificial obstacles tend to disturb the shape and conservation of dunes, but as soon as the dunes cross the obstacle, barchans reappear.

According to the general opinion, the location of the largest sand seas is in basins. This opinion is verified for the intramountainous basins in Asia, especially Taklamakan, which is the most convincing example, but is not verified for the Aral basin sand seas Kara Kum and Kyzyl Kum to the east and south of the Aral lake, which are on a gently climbing slope, as are the Grand

Erg Occidental and the Grand Erg Oriental in the north of Sahara. The sand seas in the Chad basin are at a higher altitude than the Bodele depression NE of lake Chad, itself the second lowest point of the Chad basin.

## Sediment Balance for Revision of Diachrony

Different dune-building episodes have been identified, related to different dune orientations. This identification has lead to erroneous results because the concept of sediment balance is not taken into account. In fact, an area which has a positive sediment balance (SB+) is a system receiving more sand than it can export. It represents a phase of sand accumulation where the dunes are, in general, oriented at right angles to the main wind direction. If the export of sand is higher than the import in the wind action system (WAS) then there is a negative sediment balance (SB-) and the orientation of the dunes is mainly parallel to the main wind direction. Both can coexist in one sand sea, as in the Grand Erg Oriental (south Tunisia).

The diagnosis of the sediment balance is obtained by genetic analysis of the sandy edifices of the area:

- Transverse dunes and barchans are the indicators of SB+. Linear dunes (seifs), oblique to the dominant wind, are also an indicator of SB+. In areas with SB+, the risk of sand accumulation is severe as soon as human activities (buildings, roads, railways) create obstacles or increase the roughness (agriculture, lines of communication). All new management practices must foresee a free circulation of the sand, avoiding the blocking of particles. To check sand accumulation in the existing human infrastructures two strategies are possible: to stimulate accumulations upwind but at a considerable distance from the human settlements, or to induce dispersion of the deposits.

- Erosion dunes, such as parabolic and longitudinal dunes, are indicators of SB-. In the areas with SB-, export is dominant and the rule should be to avoid building human settlements on the leeward side. The SB- areas should be protected from soil erosion through any kind of existing system.

A specific strategy to combat degradation due to aeolian actions corresponds to each sediment balance.

## Residual Dunes

Aeolian bedforms have a complex genesis, but the most common error is to consider them as resulting from accumulation alone. Many aeolian bedforms are residual and must be considered forms of erosion. Dunes can be classified as accumulation bedforms or erosion edifices.

**Table 3. Dune classification combining different dune types with wind regime and sediment balance.**

| Sediment balance | 1. Positive<br>Deposition > deflation<br>*Dominant accumulation* | 2. Negative<br>Deposition < deflation<br>*Dominant deflation* |
|---|---|---|
| Aeolian regime | Dune type | |
| One dominant wind | Barchanic edifice:<br>• Barchan<br>• Barchanic chain<br>• Transverse dune<br>• Climbing dune<br>• Falling dune | Longitudinal sand ridge (with a reg. type desert pavement)<br>Parabolic edifice (genesis in a fixed sandy cover) |
| Two dominant winds | Linear dune (seif)<br>Climbing dune<br>Falling dune | |
| Multidirectional winds | Star dune (ghourd) | |

## Accumulation bedforms

The dunes developed by accumulation are crescentic (barchans), the most difficult to control. When barchans are coalescent and aligned at right angles to the wind, they are called transverse chains or transverse dunes. Linear dunes (also called seif) are another type of accumulation bedform.

Wind is also responsible for the wholesale movement of dunes. The most mobile dunes are barchans, which can move in isolation or in formation like the flight of ducks, or in dune-flows. The best examples are in Mauritania.

Both dunes, barchans and seifs, are edifices where the sand arrives and from which the sand departs. The whole body of a barchan moves forward as one unit and can invade all human settlements; the seif evolves by elongation and can threaten human structures in that manner.

Other initial accumulations may occur:

- Falling dunes are found in the lee of an obstacle, echo and climbing dunes are found upwards of the obstacle. The obstacle can be a rock or a stone or a plant, giving a coppice dune (nebka, rebdou).
- Areas of reduced wind speed, where the roughness of the surface is increased by vegetation cover or reliefs, initiate accumulations.

## Deflation bedforms

- Sand ripples, visible on the back of dunes or on sand sheets, and easily reproducible in a wind tunnel, are the smallest aeolian bedforms. Contrary to general opinion, they should be considered residual, formed as lag deposits of coarser grains when winnowing has swept away the finer particles.

- Parabolic dunes, known as deflation dunes, are also erosion edifices. The most complex and typical are found in the Thar desert where the compound parabolic dunes form the major component of the 800 km Thar dune field. This desert should be considered an area of sand export with a negative sediment balance.

- Too often confused with linear dunes (seif dunes, which are oblique to the main wind direction), sand ridges are erosional aeolian bedforms. The most impressive are located in the central Sahara in the Erg Chech, Iguidi, and the Tenere, where we have described and measured them. The ridges are aligned parallel to each other and to the main wind direction, which justifies their description of longitudinal.

The term "interdunal corridor" is proposed for the space which separates two sand ridges. The genesis of longitudinal corridors separating longitudinal sand ridges is deflation in a sand sheet. The sand ridges are residual dunes between two deflation corridors, where wind erosion is active.

The width of the interdunal corridors is at a maximum in the central Sahara sand seas. Measurements from Landsat images in the Erg Chech and the Erg Iguidi show a sand ridge width reaching 3 km, and 5–6 km for the corridors between 26° and 29° North.

In Egypt, between 25–28° N and 24–27° E, the sand ridges reach a maximum of 1,500 m, and the corridors 4,000 m (Skharet al Amud dunes). Further east, at the Abu Mingar sand ridges (27–30° N, 28–30° E), the maximum width is 2,500 m, with corridors 2,000 m wide.

Approaching the Sahel, south of the Saharan–Sahelian strip of ergs, the corridors become narrower, showing either the still positive sediment balance or a less advanced negative one. In Ouarane Erg (22° N), Spacelab images show widths of 1,000 m for the sand ridges and 250–1,500 m for the corridors. North of Timbuktu (17° N and 13° W) in the Azaouad, and in Niger, south of the Erg de Fachi Bilma, the sand ridges are 750–1,000 m wide and the corridors 250–1,500 m wide.

All these longitudinal edifices correspond to a negative sediment balance, meaning that they are in areas of previous deposition with a positive sediment balance, but are now in a phase of deflation. In these areas, the danger due to aeolian degradation lies in the export of the finest particles and the loss of soil and soil structure. This fundamental difference, between aeolian bedforms resulting from accumulation and others resulting from deflation, explains the existence of two schools of thought. The first school believes that the shifting of dunes and the shifting over time of the dune fields and the sand seas are the main effects of wind erosion triggered by droughts and man-induced land degradation. The second school is convinced that the concept of progressing dunes is more or less a legend. This difference lies in the fact that the former have made their observations in barchan-infested areas with a positive sediment balance where the dunes are all mobile, whereas the latter have worked in areas of negative sediment balance in longitudinal dune fields where the dunes are not mobile but nevertheless dangerous because they are sand reservoirs where sand particles can be set in motion. These two situations and diagnoses lead to two different strategies to combat wind erosion: the first must avoid encroaching sand, the second must avoid soil loss.

## Global Wind Action System and Aeolian Flows as Criteria for Wind-erosion Control

### Global Wind Action Systems

A combination of sand deflation, sand transport, and sand deposits detectable on satellite imagery is defined as a Global Wind Action System (GWAS). A GWAS is a dynamic aeolian system where, in a definite area, particles are exported (source area), transported (sand shifting area), and accumulated (sand deposition area), or re-exported in consequence of wind activity. A GWAS can be an open or a closed system.

A closed GWAS is an area where particles are imported and accumulated, but where outflux is negligible. The Taklamakan sand sea, because of its location in a deep basin between high mountains (Tien Chan to the north and Kuen Lun to the south), is the best example of a closed GWAS.

An open GWAS is defined as a system where, after import and accumulation, particles can be re-exported out of the system. The Sahara, which exports its aerosols to the north as far as Greenland, to the east as far as Khazakstan, to the south as far as the tropical forest of the Gulf of Guinea, and to the west across the Atlantic Ocean as far as the Bermudas and the Nordeste (Brazil), is the best example of an open GWAS. The correlation between Sahara and Sahel, and the way Sahara exports its sand particles towards the Sahel, has been demonstrated (Mainguet et al. 1992). The active Tenere sand sea in Niger, for example, is continued without interruption by the fixed Hausa sand sea, which also receives a part of its sand from a branch of a sand current running west of Aïr Massif and has loaded sand from the alluvium accumulated by the dallols (dry wadis).

In a GWAS, there is no simple juxtaposition of the three units—erosion, transport, and deposit—but rather a juxtaposition of multi-scale units: in areas of dominant erosion, units of deposition can be found at the local scale, and in areas of transport, figures of deposits can be seen. This multi-scale organization should be studied using a multi-scale approach:

- At the synoptic level of the global wind action system.
- At the regional level of a major sand sea.
- At the local level of villages and other human settlements, roads, railways, plantations, and projects.

## Aeolian flows or sand currents in the Saharo–Sahelian GWAS

- The Saharo–Sahelian GWAS is formed of currents of sand, a kind of aeolian sand "river," conforming to harmattan. By analyzing Meteosat Images from 20 May 1978 to 25 January 1979, a map was drawn (Mainguet 1984) showing that, in the absence of topographical mega-obstacles, the currents of sand that cross the desert follow the northeast–southwest trade winds in the hyper-arid and arid desert, curving at the Tropic of Cancer across the Sahel (Fig. 1). These trade winds change from a northeast–southwest direction to an east northeast–west southwest direction, then to an east–west direction in north Chad, north Niger, north Burkina Faso, and Mauritania. A Meteosat image from 3 January 1992 confirms these wind flows (Fig. 2).
- The most western current of sand flows, from southeast Cap Juby, near Tarfaya, to southeast Cap Blanc, are induced by constant winds—coastal trade winds—blowing from north northeast to south southwest along the Atlantic coast of the Sahara. The current, 800 km long, is composed of individual barchans, barchans grouped in dune fields, and moving sand veils. The barchans reach a height of 15 m with an average of 6–10 m, a maximum width of 75 m, and an average of 15–35 m from the end of one wing to the end of the other. The rocky surface is favorable to saltation. The barchans reach an average speed of 25 m/y. The size of the grains has a median of 220 µm.
- Along the currents of sand, different dynamics can be identified, according to alternating sectors: those where transport is dominant and those where deposition dominates. Rocky pointed landscapes—the linear rock yardang landscape between the Tibesti and Ennedi mountains—and saltation are characteristic of the first, sand seas of the second. The large saltation currents, which cross the desert, are subdivided into several branches according to highland patterns.
- The sand flows link the sand seas in chains. A comprehensive analysis of the sand seas of the Sahara shows that they are open regional deposition centers that receive the sand at their north or northeastern edge and lose their particles at their south or southwestern edge. The open sand seas are more or less dependent on one another and communicate along the chains. The sand seas are connected along these synoptic flows of sand, where the sand is submitted to a general long-distance drift—discontinuous in time and space—from north to south of the desert and even out of the desert towards the Sahel. They are more or less rich in sand (Figs. 3 and 4).

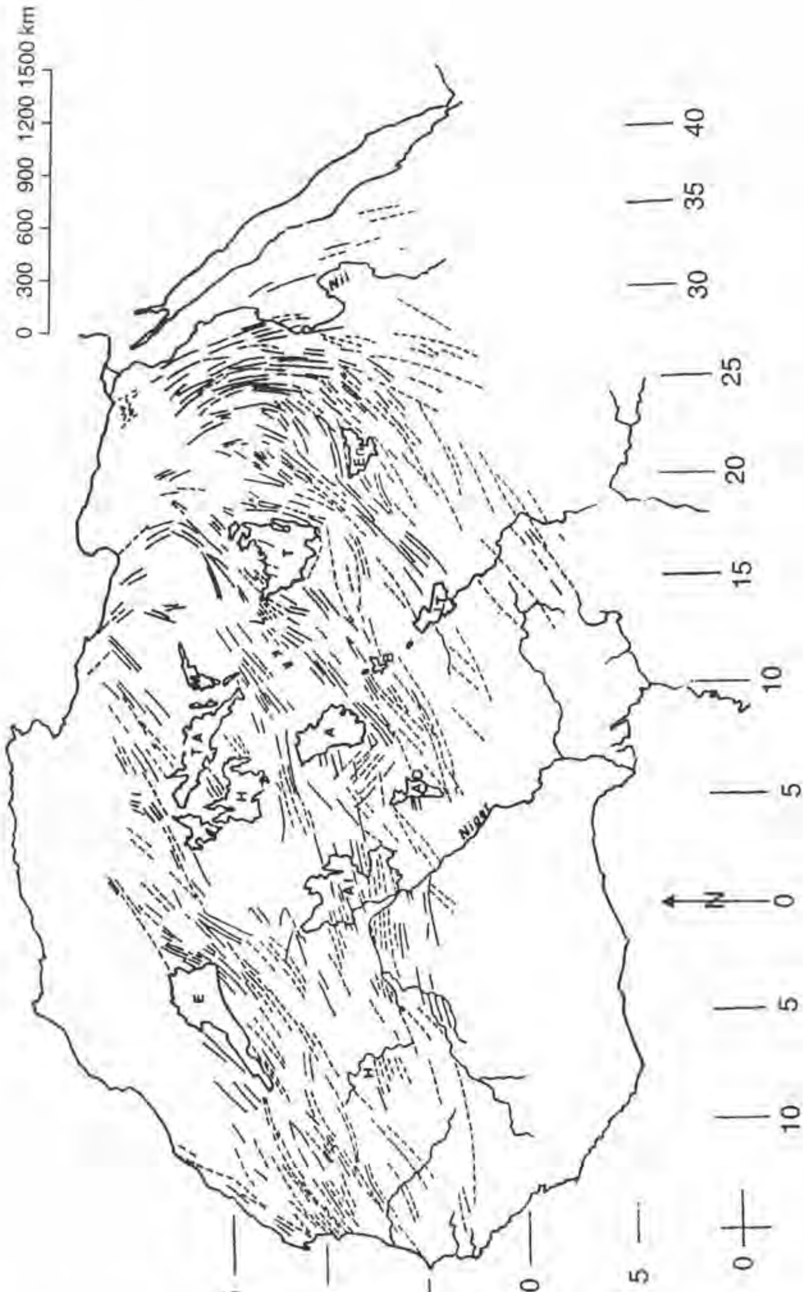


**Figure 1. Trans-Saharian and Sahelian wind flows according to Meteosat images (30 May 1978 to 25 January 1979). A=Aïr; AD=Ader Doutchi; AI=Adrar Des Ifoghas, B=Bilma, E=Eglab, En=Ennedi, H=Hoggar; H=Hodh; LT=Lac Tchad; M=Messak; TA=Tassili N'Ajjer; T=Tibesti. Solid lines indicate lines of sand deposit or corrasion with high reflectance on Meteosat. Dashed lines indicate lines of deflation with low reflectance on Meteosat.**

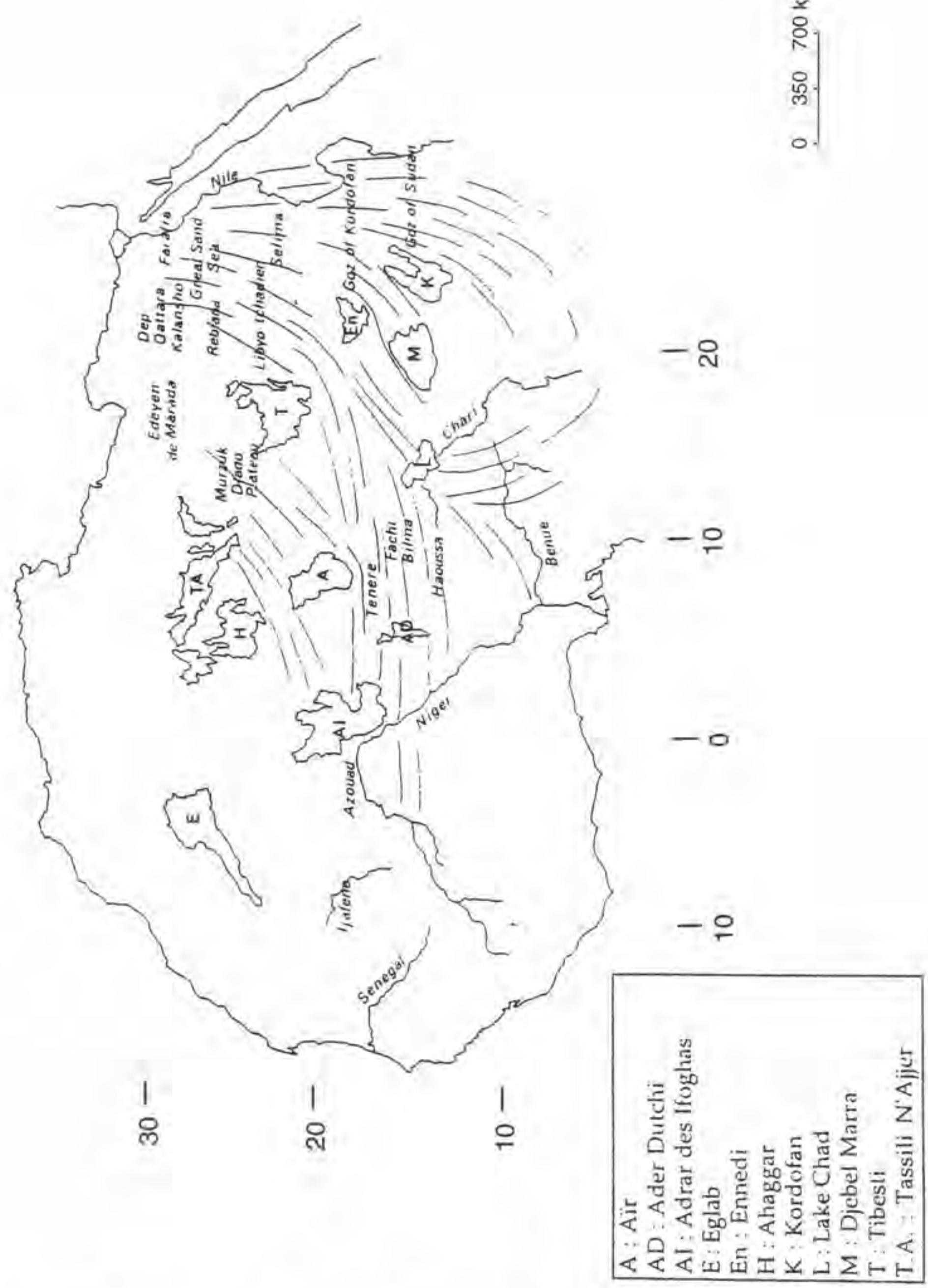


**Figure 2. Main wind flows though the Global Wind Action System, Sahara–Sahel, interpreted with Meteosat Infrared (3 January 1992).**

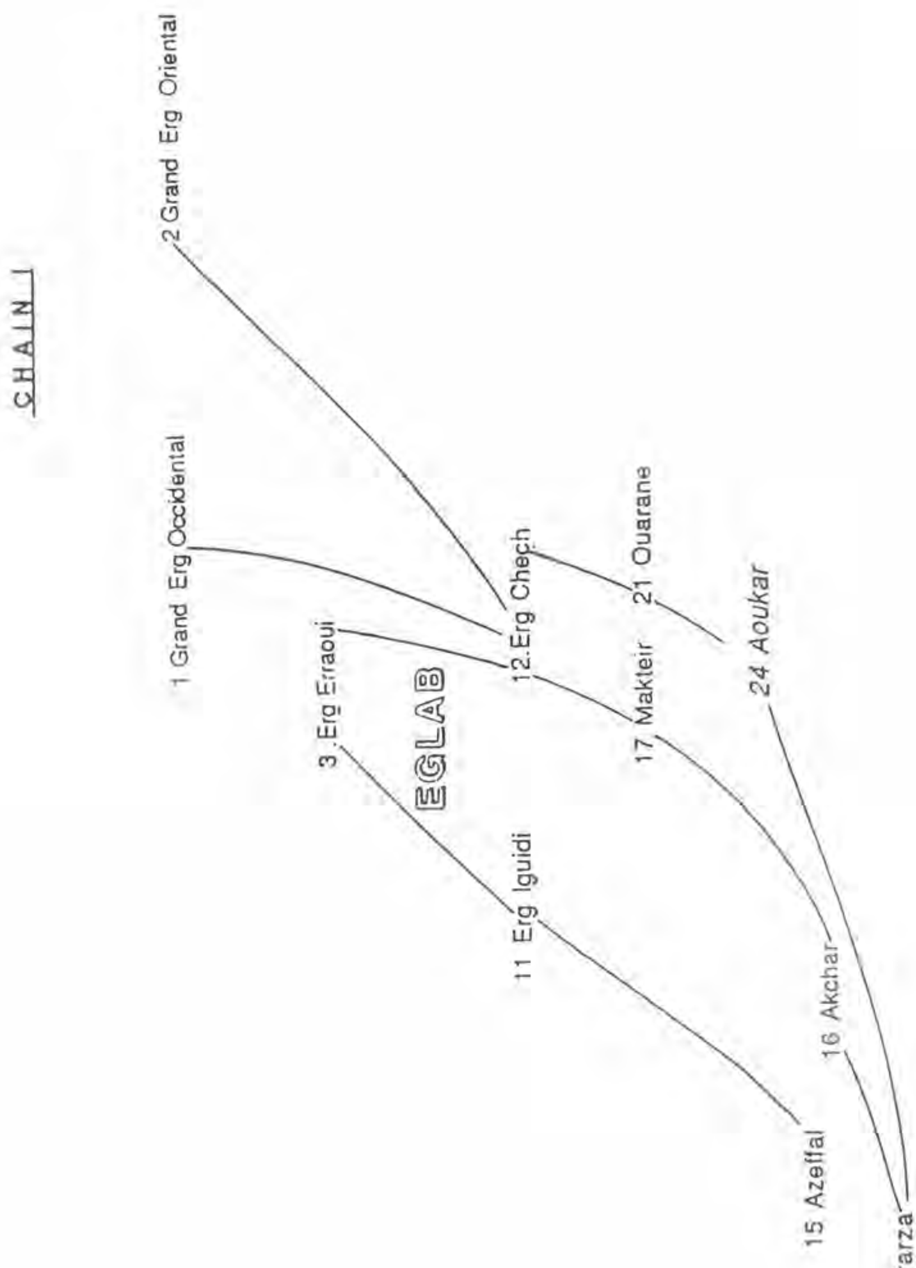


**Figure 3. Western Sahara-Sahel chain of sand seas (deposition centers) connecting the North Sahara with the Sahel.**

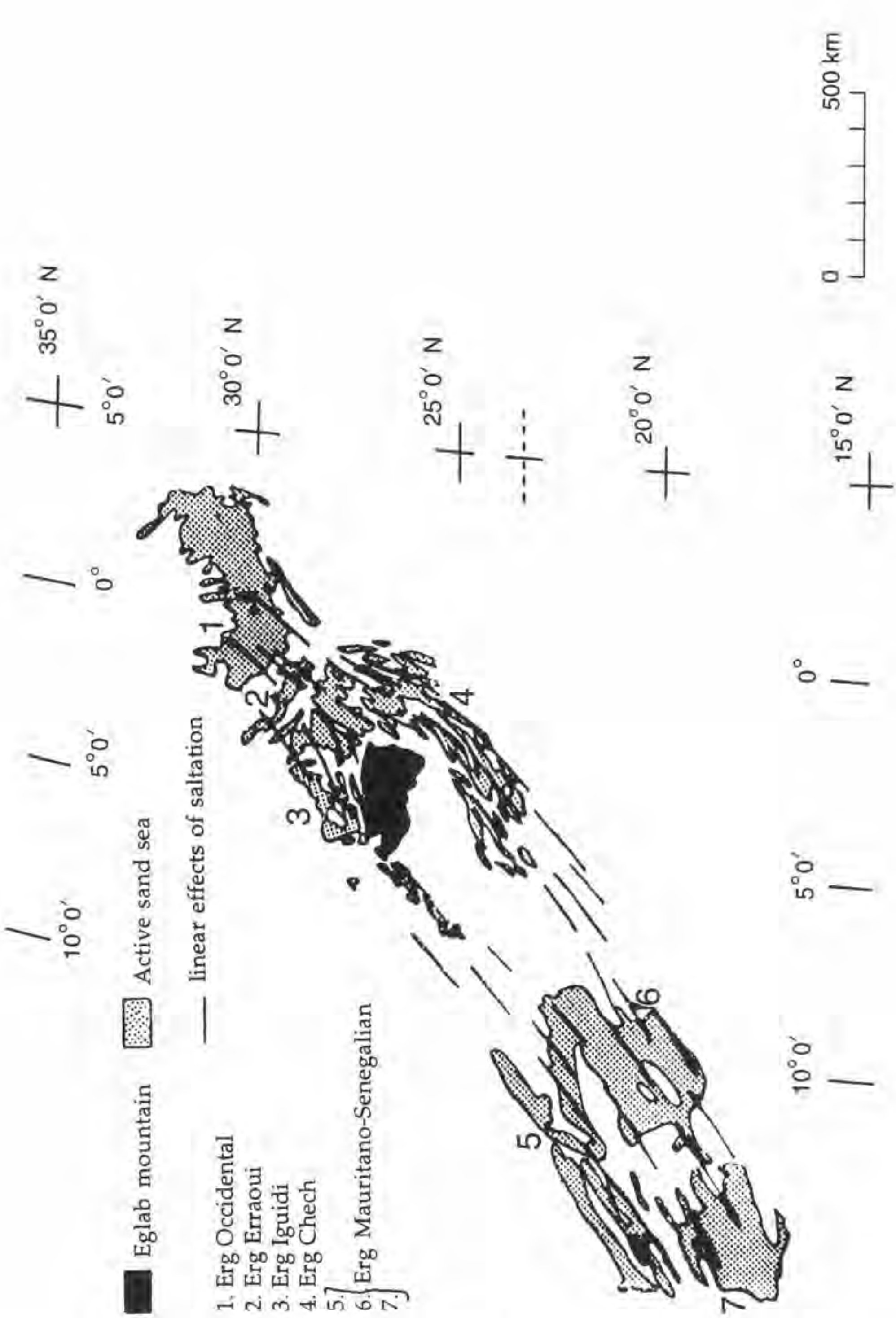


**Figure 4. Wind flows in the Sahara Occidental from Algeria to Mauritania according to Meteosat (November 1978).**

All these sand movements correspond to the displacement of particles one by one during sand storms that follow the sand currents previously described. These currents can climb small topographic obstacles and reach, for example, 600 m along the Tibesti slopes. They also cross the Adrar of Iforas from east to west. Sand transport can also be collected as barchanic edifices.

Selecting techniques to control mobile sand and moving dunes requires knowledge of the whole system, as well as an appreciation of the dynamics of the problem area.

## Strategies for Control of Wind Erosion

Controlling wind erosion, often considered as dune stabilization in its restricted sense, should also mean controlling the movement of particles in the different parts of a GWAS, from the source area towards the areas of transport and accumulation. Strategies to combat wind-blown sand and migrating or encroaching dunes are different. The effects of dune disturbance are not the same as for the disturbance of migrating sand. Control of wind-blown sand may have no effect on the rate of dune movement.

### Stabilization of Mobile Sand through Physical Methods

In hyper-arid and arid ecosystems, with an almost limitless supply of sand and frequent and strong winds, managers face the double danger of mobile dunes and drifting sand. Mauritania, where the sand flows are simultaneously organized in saltating sand and barchans threatening human settlements (roads and railways), is the most significant example and probably the most difficult to control.

#### Blocking the sand in the source and transfer areas

This action requires knowledge of the location, nature, and extent of both the erosion area and the sand migration area. The size and distance of the source can make the solution impossible or impractical. In the Egyptian desert, for example, the wind flow bringing the encroaching sand to the Kharga oasis originates in the Qattara depression 700 km to the north northwest. The transporting fluid takes its load of grains, which can be a mixture of more or less autochthonous and/or allochthonous particles, along its fluxes.

If the source area is too wide or too far from areas that require protection against encroaching sand, or are located in an arid ecosystem that does not allow the establishment of a vegetative cover, an economically reasonable solution cannot be proposed. In more favorable cases, palisades or mechanical barriers should allow the creation of an artificial dune, but this requires a constant strategy of sand trapping until continuous vegetative cover is obtained upwind of the edifice.

It is often cheaper and more effective to take measures that will prevent the sand from being picked up in the source area than to fix the dunes formed in the accumulation area. In the source areas, the objective is to protect the soil particles from entrainment by:

- Reducing wind speed through windbreaks of dry or preferably live vegetation, if rainfall or available water permit; strategies differ according to the degree of aridity.
- Increasing the cohesion of soil particles by planting vegetation; here the efficiency of tree plantation or rehabilitation of a grass cover should be considered.
- Fixing the soil using chemical adhesives, or covering the loose particles with plastic sheets, nets, or dead vegetation.

The strategies to control aeolian damage linked to drifting sand and mobile dunes can be divided into two sets of actions:

- Blocking the shifting sand in the source area or at any step of transport by palisades or barriers made of artificial material (plastic or organic), creating an artificial dune, or fixing the loose sand by chemical measures. When the source area does not allow biological rehabilitation, blocking the sand may require repeated or permanent action.
- Stabilizing the loose sand by biological measures.

In the transport area, the objective is to bring about a reduction in wind speed by increasing the roughness of the land; the resulting turbulence causes the airborne particles to settle. Deposition of sand in pre-selected areas will reduce the threat to human settlements.

The approaches employed to reduce drifting sand are:

- Promotion of the deposition of drifting sand by ditches and barriers.
- Plantation of vegetation belts to trap sand moving away from source areas.
- Enhancement of sand transportation by shaping the land surface and treating the surface.
- Deflection of the sand stream.

The objective is to minimize the volume of particles transported to encourage accumulation upwind of the area requiring protection. Nevertheless, to trap moving sand is a solution which requires indefinite maintenance. The excavation of deep ditches upwind of human installations is based on sand entrapment and can bring temporary protection against encroaching sand. To be effective, ditches built at right angles to the main wind direction must be wider than the length of the jump of saltating grains (3–4 m). The ditch must have a depth which prevents aeolian deflation from the floor and must be regularly cleared of entrapped sand or doubled by parallel ditches.

When the area of transport is underlain by unconsolidated material, techniques to reduce deflation should be applied, such as:

- Spreading coarse-grained material over the surface to obtain a kind of desert pavement. Protection must be continuous to reduce the scouring of underlying material.
- Mulching, to prevent excessive movement of particles. This involves the even covering of the sand, sand sheet, or dune with natural or man-made materials. The objective of mulching is to break up the smooth surface of a bare field into a rough surface which slows down the speed and stabilizes the surface against wind erosion. Chemical mulching can be used, and combined with biological methods if rainfall is sufficient. The sand-fixing layer formed by chemicals should be maintained in good condition until the vegetation is well enough established to control wind erosion.

The accumulation area is characterized by sand sheets, transverse dunes or dune fields, and sand seas. The different shapes of dunes are related to sand supply, wind speed, the duration of the wind, wind regime, and local topography.

Mechanical stabilization is based on the use of non-living, organic, or inorganic material to construct sand-binding barriers. This method is not ideal, because the effective life span of these structures is limited: three to five years for the checkerboards in the Tengger desert in China. Sustainable stabilization of dunes can only be achieved by the development of a vegetation cover. Mechanical techniques used for sand stabilization are essentially designed for the protection of human settlements and villages, communication lines, transportation routes, and precious agricultural land. Sand-blocking measures must be considered to assist sand stabilization measures.

The aims of sand and sand-sheet mechanical or chemical stabilization are to fix the sand long enough to enable natural regeneration of the vegetation cover (or planted vegetation), which then establishes itself without watering. This will nullify the abrasive action of blowing sand upon young seedlings that have germinated during the rainy season, the burying of seedlings by drifting sand, deflation, and exposure of the root system.

### Biological Stabilization of Sand, Sand Sheets, and Dunes

In areas where rainfall reaches 300 mm/y, biological stabilization is favored, following two steps:

1. A checkerboard pattern of low fences (25–30 cm high) spaced 1 m apart. Various materials can be used to construct fences with the checkerboard

pattern: bundles of millet stalks and other crop residues, plastic sheets, and even cardboard.

2. Development of a natural or planted vegetation cover, the only sustainable solution to permanently immobilize any dune. This method was initiated by the Institute of Desert Research Academia Sinica (IDRAS) in Shapotu, South Tengger desert, China.

Biological methods are difficult to use when rainfall is lower than 300 mm/year. In areas of recent revegetation, fencing is necessary to prevent animals from accessing these areas. Animals participate in the scattering of seed, but avoiding overgrazing is a basic requirement. Fencing where sand has been reactivated can also allow natural rehabilitation to occur. In areas of continuous sand deposition, such as the Chinese basin sand seas, the solutions are more difficult—and more expensive—because they are linked to a mountainous geomorphology and a continuous sand supply.

Stabilization of sand, sand sheets, and dunes requires development of a permanent vegetation cover. There are three possibilities for rehabilitating the dry areas:

- Natural regeneration of the vegetation cover if rainfall is sufficient.
- Semi-natural regeneration of the vegetation cover.
- Creation of a vegetation cover.

To these methods can be added biological shelter belts, windbreaks, and wind barriers. Ideally, a wind barrier made of trees must consist of at least three rows:

- The central row contains the tallest trees, preferably a fast-growing species.
- The second row, upwind, is made up of a shorter species.
- The auxiliary rows, downwind, contain short trees or bushes.

Greenbelts, formed of several rows of trees or bushes, are a classic technique in China. The species are locally adapted, and selected for their drought resistance, speed of growth, and suitability to water potential and depth of underground water. In the Chinese oases, fruit trees planted are nut, apricot, and mulberry. In the oasis of Turfan (South Taklimakan), 16,000 ha of vineyard are surrounded and subdivided by greenbelts: 1,130 ha have been planted since 1964. Similar greenbelts have been planted in Hetian to avoid a bi-directional wind regime.

To obtain the maximum decrease in wind speed, the ideal porosity is 50%. The ideal spacing of barriers is five times the height of the wind barrier. However, this optimum spacing may not be compatible with agriculture or land tenure in the area. There is no general rule to calculate the most efficient spacing. According to wind speed and topography, the recommended spacing is 5–25 times the height of the wind barrier. If the wind is very turbulent (for example, in areas with varying topography, in valleys swept by local winds, or in corridor-cutting escarpments) the spacing must be reduced to 5 times the height of the barrier. The spacing of wind barriers depends on the topography of the windward slope, where the wind streams are compressed and the wind speed accelerated. When the belts are aligned at 45 degrees to the eroding wind, or are on slopes exposed to the wind, the distance between the shelter belts should be reduced. On the leeward slope, where the wind streams are expanded and the wind speed is slower, the density of the wind barrier can be decreased.

Other biological techniques include intercropping or micro-crop shelter belts. For example, three rows of tall-growing pearl millet planted across the prevailing wind direction by the Central Arid Zone Research Institute (CAZRI 1984), were found to be instrumental in increasing the water-use efficiency and productivity of summer grown vegetables such as lady's finger and cowpea. Pearl millet as a micro-crop shelter belt must be sown about a fortnight earlier than the vegetable crop to provide a shelter effect.

## Control of Mobile Dunes

The problem of moving dunes can be tackled in three ways: removal, dissipation, and immobilization. However, all three techniques have their negative aspects. Removal of the dunes is very expensive. Dissipation of a mobile dune by trenching, surface treatment (complete or strips), and transformation of the dune in shifting sand is feasible only in areas were shifting sand is not a disturbance for human activities. Reshaping of mobile dunes into mobile sand mounds is temporary; the sand mounds will evolve very quickly toward the optimum aerodynamic form; to be permanent the surface of the reshaped dune must be vegetated.

Digging ditches to the leeward of the edifices is useless to stop the dunes; physical barriers leeward of the edifices are also useless. Vegetative stabilization requires rainfall or irrigation, and the question of cost becomes a priority. Techniques of reshaping dunes (reducing height or volume) can aggravate the problem by increasing the speed of the dunes.

Free movement of sand is a basic rule; the presence of human installations disrupting the sand flow should be avoided since these stimulate sand accumulation. If obstructions are unavoidable they should be aerodynamically streamlined. A fundamental obligation is that all linear installations (roads, railways, pipelines, etc.) should run parallel to the direction of the dominant sand flow. The facilities should be located in areas where the dominant sand-moving winds blow over gently rising ground. On a windward rising slope the ground-level wind speed is increased and results in sand transport rather than in accumulation.

## Conclusions

*Vis-à-vis* aeolian action, there is no example of a reasonable preventive strategy. Prevention is often undertaken when therapy is what is needed. Because of increasing population and the need to use more and more marginal land north and south of the Sahara and in the Middle East, sustainable management requires a good knowledge of the aeolian dynamic and the laws that rule sand accumulation, sand exportation, fluctuations of the limits of the sand sheets, and the direction of sand transport to or from the sand seas.

# West Asia and North Africa

# The West Asia and North Africa Region: Some Underlying Factors of Wind Erosion and Perspectives for Research and Technology Development

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## Abstract

Vast areas of West Asia and North Africa (WANA) are marginal, with fragile ecosystems. High populations exert pressures on the land, which paves the way for serious land degradation, such as soil erosion caused by wind. The scarcity of arable land in the region is a major cause of poverty. Rural poverty inhibits investment into more sustainable land use, and promotes exploitative use of limited land resources. Sustainable resource use is not only dependent on agricultural development but also on policy frameworks that are conducive to judicial land use, and on the development of alternative non-agricultural sources of income for the growing population. Research in sustainable land use must be solution-oriented and focused on technology improvements that are directly beneficial to the land users. Therefore, research needs to be people-centered. Participatory approaches to research involving all stakeholders—farmers, researchers, extensionists, and other people and institutions directly or indirectly involved in rural development—are promising alternatives to conventional mono-directional researcher–farmer links.

## Introduction

The occurrence and severity of wind erosion in drylands is basically governed by the interaction of the prevailing climatic conditions and land-use practices. Where long dry periods, associated with strong seasonal winds, occur regularly, where the vegetative cover of the land does not sufficiently protect the soil, and the soil surface is disturbed due to inappropriate management practices, wind erosion is usually a serious problem (Hudson 1986; Nir 1974). These conditions are typical for large parts of WANA. Wind erosion is one of the major threats to the land in the region (FAO 1986).

Traditionally, land use in the region has been balanced with the environment. Therefore, civilizations in these dry areas survived over long periods. However, with increasing pressure on the land, the equilibrium between utilization and regeneration has been disturbed. The limits of the system's resilience have been exceeded and the natural mechanisms of regeneration are failing (Greenland et al. 1994). As a consequence, degradation processes dominate, leading to soil exhaustion, reduced biomass production, and increased susceptibility of soil to wind erosion (Ryan 1982; Sperber 1994).

In the drier arable areas of the region, large tracts of land are being cultivated without any wind protection measures such as windbreaks or vegetated buffer strips. During the hot and windy summers, this land is particularly vulnerable to wind erosion. Stubble or other crop residue could give some protection and also contribute to the maintenance of soil structure. But it is removed for fodder or grazed by the animals (Jones 1991). In addition, the trampling of the grazing animals destroys the structure of the topsoil. This leads to pulverization and compaction, and thus contributes to the susceptibility of the surface soil to wind erosion (Mulholland and Fullen 1991).

Similar conditions prevail in the rangelands. Due to persistent overgrazing and firewood collection, the perennial natural vegetation has been almost totally destroyed, leaving the soil exposed and unprotected (Williams and Bolling 1996). The decreasing availability of range vegetation for the animals forces the land users in many places to plow large areas of the land and plant barley for grazing (Jones 1991; Nordblom et al. 1997). This, however, directly destroys the dry season cover provided by the natural perennial rangeland vegetation that protects against the eroding forces of the wind.

## Pressure on the Region's Land Resources

WANA is the mandate area of the International Center for Agricultural Research in the Dry Areas (ICARDA). The region is vast and very diverse, extending to Morocco in the west, Ethiopia, Sudan and Somalia in the south, the Arabian Peninsula in the southeast, Pakistan and Afghanistan in the east, and Turkey in the north. The newly independent Central Asian Republics were recently added (Fig. 1).

After a long history of food self-sufficiency, WANA can no longer feed itself. Food imports per capita are among the highest in the world (Nordblom and Shomo 1995). The pressure on the land is ever-increasing, and with currently practiced technologies, the soils are being exhausted at alarming rates. This applies to arable land as well as to grazing areas. Severe soil erosion and degradation are widespread. Limited water resources are being depleted rapidly by expanding and intensified irrigation of the drylands (Rodríguez 1996).

Population growth in the region is significant, and it is expected that the population will more than double by the year 2020. The pressure on the land is already high, and only a few areas permit a substantial increase in productivity. Only where the limited rainfall is supplemented with suitable irrigation water, and nutrients are replenished with commercial fertilizer in an economic environment attractive to the land user, can productivity be increased significantly. However, the productivity of the land cannot be "squeezed" indefinitely beyond its natural productive capacity. The balance between the available resources and their use must be maintained. The sustainability of land use and the concern for its efficient functioning far into the future should be the overriding criteria for future land-resource planning and land use.


**Figure 1. The West Asia and North Africa region (El-Beltagy 1996).**

In order to raise the living standard of the rural population while using the available agricultural resources, the dimension of quality—and value—of agricultural products must be recognized as more important than the conventional production goal of quantity. Given the limited agricultural resources and their state of exhaustion, more efficient and sustainable ways to use them must be found. These must first address the degradation and conservation of land resources.

## Economic Diversity and Disparity

WANA is extremely diverse. In statistical studies, poverty in the region is frequently masked by averaging rich and poor countries. Wealthy countries, such as Libya and the Gulf States, should not be directly compared with the poorer countries of the region. The wealthy states of the region are the oil-exporting countries with low populations. The agricultural sectors in these countries cannot feed their populations, but the oil income permits the import of food and investment in agriculture and land-resource conservation (El-Beltagy 1996). These countries only have 7% of the region's population, but their average per capita income of US$ 9,417 is the highest in the region (Table 1). The remaining 93% of the WANA population is much poorer. The four most disadvantaged countries of the region, Sudan, Ethiopia, Eritrea, and Somalia, have an average per capita income of only US$ 88, which is less than

1.2% of that of the oil-exporting countries. Seventy five percent of the region's population (421 million people) has a per capita income of less than US$ 2 per day; and 235 million people in the region have a per capita income of less than US$ 1 per day. These people are on the bottom rung of the poverty ladder and thus have little or no means or opportunity to invest in the improvement of their lives and their environment.

**Table 1. Income and population of seven groups of WANA countries.**

| | Average per capita GNP (1992) | Population (millions) | |
|---|---|---|---|
| | US $ | 1994 | 2020 |
| Oil exporters with small populations (Libya, Kuwait, Oman, Qatar, Saudi Arabia, Unites Arab Emirates) | 9,417 | 29 | 58 |
| Oil-exporters with large populations (Algeria, Iran, Iraq) | 1,929 | 113 | 222 |
| Fast population growth (Syria, Jordan) | 1,000 | 20 | 41 |
| Transitional population growth I (Lebanon, Morocco, Tunisia, Turkey) | 1,520 | 99 | 150 |
| Transitional population growth II (Egypt) | 586 | 62 | 89 |
| East WANA (Afghanistan, Pakistan, Yemen) | 379 | 146 | 313 |
| South WANA (Ethiopia, Eritrea, Somalia, Sudan) | 88 | 93 | 19 |
| Total population | | 562 | 1,071 |

Source: El-Beltagy (1996).

Table 2. Population and available per capita cropland in WANA.

| Region | Country | Total Arable Land (× 1000 ha) | 1960/1961 Total Population (1,000) | 1960/1961 Per Capita Cropland (ha) | 1990 Total Population (1000) | 1990 Per Capita Cropland ha | 2025 (UN Estimate) Total Population (× 1000) | 2025 (UN Estimate) Per Capita Cropland (ha) |
|---|---|---|---|---|---|---|---|---|
| North Africa | Mauritania | 205 | 991 | 0.27 | 2,003 | 0.10 | 4,239 | 0.05 |
| | Morocco | 9,327 | 11,626 | 0.60 | 24,334 | 0.38 | 36,342 | 0.26 |
| | Algeria | 7,644 | 10,800 | 0.65 | 24,935 | 0.31 | 40,347 | 0.19 |
| | Tunisia | 4,851 | 4,221 | 1.01 | 8,080 | 0.60 | 11,802 | 0.41 |
| | Libya | 2,155 | 1,349 | 1.46 | 4,545 | 0.47 | 12,406 | 0.17 |
| | Egypt | 2,648 | 27,840 | 0.09 | 56,312 | 0.05 | 87,080 | 0.03 |
| | Sudan | 12,900 | 11,165 | 0.97 | 24,585 | 0.52 | 56,365 | 0.23 |
| Middle East | Syria | 5,626 | 4,561 | 1.40 | 12,348 | 0.46 | 30,871 | 0.18 |
| | Lebanon | 298 | 1,857 | 0.14 | 2,555 | 0.12 | 3,991 | 0.07 |
| | Jordan | 607 | 1,695 | 0.28 | 4,259 | 0.14 | 11,496 | 0.05 |
| | Israel | 436 | 2,114 | 0.19 | 4,660 | 0.09 | 7,088 | 0.06 |
| Arabian Penn. | Iraq | 5,450 | 6,847 | 0.69 | 18,078 | 0.30 | 40,631 | 0.13 |
| | Kuwait | 5 | 278 | 0.00 | 2,143 | 0.00 | 2,550 | 0 |
| | Saudi Arabia | 2,365 | 4,075 | 0.29 | 16,048 | 0.15 | 41,251 | 0.06 |
| | Oman | 61 | 558 | 0.04 | 1,751 | 0.03 | 5,580 | 0.01 |
| | UAE | 39 | 90 | 0.09 | 1,671 | 0.02 | 2,787 | 0.01 |
| | Yemen | 1,609 | 5,247 | 0.25 | 11,311 | 0.14 | 30,922 | 0.05 |
| West Asia | Turkey | 27,677 | 27,509 | 0.91 | 56,098 | 0.49 | 82,583 | 0.34 |
| | Iran | 15,050 | 21,552 | 0.71 | 58,946 | 0.26 | 112,672 | 0.13 |
| | Pakistan | 21,100 | 49,955 | 0.34 | 121,933 | 0.17 | 270,915 | 0.08 |
| WANA Ave. | | | | 0.52 | | 0.24 | | 0.13 |

Availability of croplands for food production is seriously limited (Table 2). The average per capita area of available cropland in the region dropped from 0.52 ha in 1961 to 0.24 ha in 1990. Estimates predict a further reduction to 0.13 ha by 2025 (FAO 1995). With these limited land resources, the pressure on the soil is not likely to decrease without alternative developments of non-agricultural enterprises and income generation for the growing rural population.

Poverty in rural areas is more prevalent and more pronounced than in urban areas. Rural infrastructure and access to services has improved considerably over the past two to three decades, but this has not resulted in sufficient employment creation and poverty alleviation within the affected countries (El-Beltagy 1996). Large numbers of people (approximately 9 million) are employed in the wealthy oil-exporting countries of the Gulf and in Europe. Private investment in agriculture is largely financed by the earnings sent home by these overseas workers. However, this is only a small fraction of the unemployed population in WANA (Rodríguez 1995). Large numbers of the population are still employed in agriculture, and the increase in rural population will further fuel migration from rural to urban areas.

## The Region's Grain Gap

The diet of the WANA population is based on cereals and pulses. Although the food supply has improved over the past 20 years, the supply of adequate amounts of protein is still deficient. A considerable proportion of food grain is still being imported, and current trends show an ever-widening gap between production and consumption of grain in the region (El-Beltagy 1996; Nordblom and Shomo 1995).

Using FAO data from 1970 to 1990, future trends in the production and consumption of all grains in 15 countries of the region can be projected (Fig. 2). Assuming an annual increase in production of 2%, the gap between production and consumption (the grain gap) will continue to widen. If grain production does not drastically rise, increasing amounts of grain will have to be imported. This imminent pressure to increase production, however, may lead to further over-exploitation of the natural resources, further accelerating degradation of the land. Increasing demand on grains will continue to force states to generate non-agricultural revenue (income) for the purchase of grain on the world market to feed their growing populations.

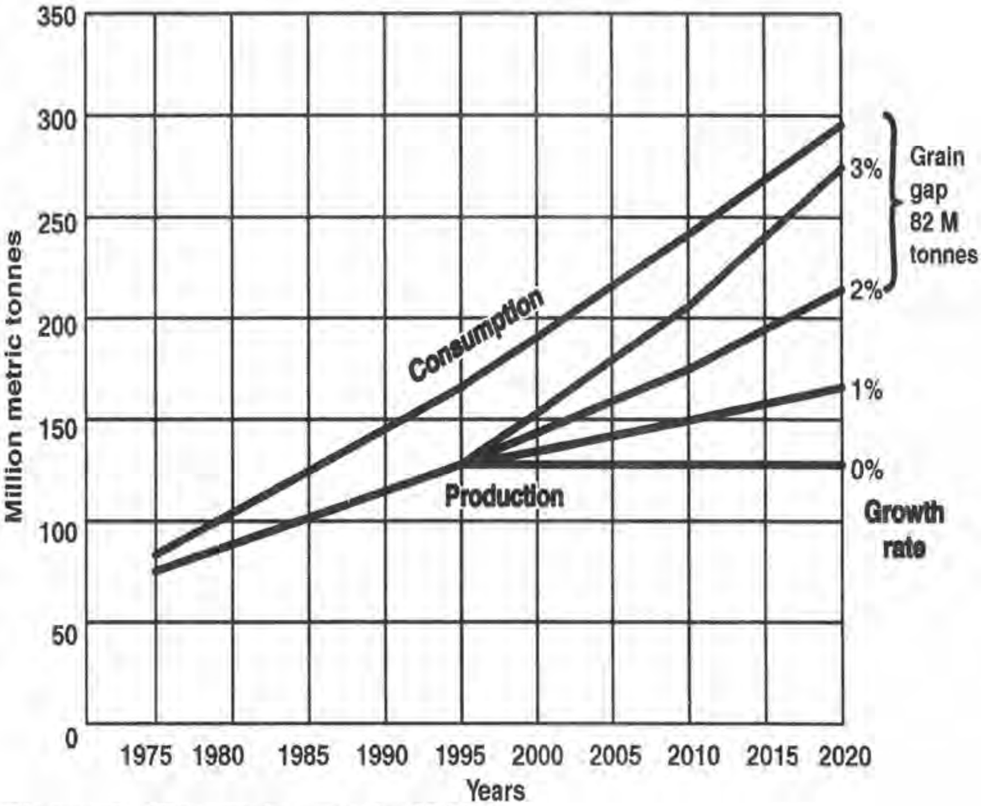


**Figure 2. The grain gap in WANA.**

## Research and Technology Development

The causes and effects of land degradation are complex. The fight against land degradation cannot be won at the land-user level alone. Holistic approaches will have to be developed that, besides implementing direct biophysical measures on the land, take into consideration the living conditions (the socioeconomic setting) of the rural areas and all the external forces and constraints directly and indirectly linked to the pressure on the land and its use. Solutions do not lie in the direct influence of the land user alone, but to a large extent in the general framework within which rural people live and have to produce to survive. This framework is largely determined by the state and its policies. General policy frameworks should emphasize and favor environmental conservation, encourage good stewardship of the land, and provide scope and opportunities for agricultural development.

Research into degradation processes, their underlying causes and their long-term effects (consequences) on the land and the environment should be solution-oriented. The study of the processes of degradation (e.g. wind erosion) should not be a purpose unto itself, masking the need to develop solutions that will lead to a resource-protecting and sustainable land utilization. Therefore, within the context of the land-use system, the term "research" is more appropriately replaced with the term "technology development." Technology development encompasses packages of measures within the context of the land-use system, and has a spatial dimension. It involves components of traditional research, exchange of knowledge, and testing under "real-world" conditions, and implies the involvement of all stakeholders crucial for the appropriate management of the natural resources (in this case, soil).

## Approaches to Technology Development

Traditionally, land management skills in WANA were developed through a system of trial and error. Only systems which were compatible with the environment survived. As populations increased, the need for increased agricultural production placed growing pressure on the land. This has resulted in a more intensive use of land and the expansion of agriculture into marginal areas. With today's rapid population increases, time does not permit the development and adaptation of land-use and conservation practices in the traditional trial-and-error method of the past. Modern scientific methods have to be used to speed up the process of developing and implementing new and more sustainable soil and land management practices. However, experience has shown that many science-based and government-promoted improved technologies for land management and soil conservation have failed to be adopted by the land users (Zöbisch 1996).

### Conventional Approach

In the conventional approach to technology development, it is the role of the researcher to identify and analyze the land users' problems. Solutions are then developed on research stations and transferred to the farmers via the extension service. In this way, the extension service forms the link between the researcher and the farmer, and helps the farmer put the new technologies into practice, usually with the aid of incentives in cash or kind. This conventional approach clearly separates the three actors in the technology development process—researcher, extensionist, and land user—and puts them into a hierarchical relationship. The information flow is in one direction, from researcher to extensionist to farmer. Researchers tend to work in isolation and extensionists seldom have a good understanding of the land users' environment or constraints to changing conditions. Extension is often fragmented into separate specializations, and, consequently, each specialization depicts only a narrow section of the overall situation. Moreover, different specializations may be attached to different institutions, with little or no interaction.

### People-centered Approach

If the concept becomes people-centered, traditional vertical hierarchies are eliminated. Information flow is free and poly-directional. Farmers become equal partners and have the opportunity to participate in technology development, from problem identification to implementation. Consequently, they are considered not only recipients, but are expected to play a part in initiating and evaluating technology development.

Land users do not subdivide or segment their farming activities as researchers traditionally do. The whole farm enterprise dictates their thinking. Linkages within the farming system are understood. With a wealth of traditional knowledge, this can be used in the development and implementation of improved or new technologies.

An important outcome of the people-centered approach is that, as pressure on the land increases, farmers recognize the limitations of their knowledge, and of the traditional technologies to sustain production. Present conditions call for participatory research and development, with a changed and closer relationship between the traditional institutions of research, extension, and farming. The concept of people-centered technology development also recognizes that there are other stakeholders in the process of rural development, such as local leaders, schoolteachers, religious leaders, rural business people, and government officials.

These groups are vital for rural development in general because they have their own interests and the means to influence opinions and decisions (Group for Development and Environment 1995; Zöbisch 1996). It is these groups that may be instrumental in promoting or hindering the development and implementation of important aspects of technology, such as creating the right social environment, providing credit facilities, and land-use rights.

## A Perspective on People-participation in Technology Development

Modern soil conservation does not highlight soil conservation as a separate activity, but as a part of good land husbandry from which the land user will benefit directly. The need for conservation and appropriate management of land resources are of concern all over the region. It is also clear that there are no universal solutions. Technologies have to be appropriate to local conditions, and these can be very specific. Recent experience has shown that technology development does not seem to work effectively anywhere without the involvement of the land user, from the initial stage of identifying problems to implementation and adoption by the land user.

Many important aspects of rural life crucial for the adoption of technologies are either hidden from the outsider or are not comprehensible to the modern scientific worker. Through farmer participation, these circumstances are automatically considered and can be incorporated into land conservation strategies and technologies. Farmer participation has proven to be a key to success. Practices and technologies can be developed which find general acceptance and sustainable use (Zöbisch 1996).

In people-centered approaches to technology development, researchers, extensionists, and land users are equally important. The extension worker occupies a central role in technology development. He is the carrier of messages and feed-back in all directions, a center of information exchange, and a mediator between the stakeholders in the development process. There has to be a general understanding that a focus on the biophysical environment—such as the soil—alone, does not explain and solve soil-erosion problems (Group for Development and Environment 1995). The wider context, including the social and economic frame within which the farmers operate and on which they are largely dependent, must be considered. Only then will an understanding of the land users' behavior be developed. From this perspective, more realistic development options and avenues will be developed.

Researchers have to be made aware of these circumstances. The translation into "researcher language" is equally important. People-centered approaches are neither top–down nor bottom–up approaches. They are ways to improve the understanding of all the stakeholders' interests within the context of technology development, with the aim of reaching solutions that are acceptable and sustainable.

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# Review of Major Research on Wind Erosion in Arid and Desert Tunisia

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## Abstract

Large parts of Tunisia are arid, with soil and climatic conditions allowing only a sparse natural vegetation. Overuse, due to high population pressures, of these fragile areas has led to severe land degradation. Lands formerly used only for seasonal and nomadic grazing have been converted to arable use. The use of heavy machinery permits the clearing and clean-tillage of large tracts of land. This gives way to severe wind erosion. The loss of grazing reserves through expanding arable land, in connection with the settling of formerly nomadic people, leads to serious overgrazing of the remaining rangeland, and hence denudation and wind erosion.

Research on soil protection against wind erosion in Tunisia focuses on preventive and curative measures. Generally, good ground cover has been shown to be the most effective measure against wind erosion. Strip cropping has proven to be very efficient in cereal cropping on sandy soils. Mulching is very effective, but mulching materials cannot usually be produced locally in sufficient quantity. More realistic are natural vegetation strips across the main wind direction. Good wind protection has been achieved with strip widths of 10–20 m. The strips take up a lot of land but they can also be utilized as a source of feed for animals.

Appropriate soil tillage can also protect the soil, but although narrow tines and sweeps were very effective in reducing wind erosion, yield under the disk harrow was higher.

In olive plantations vulnerable to sand encroachment by small sand dunes, the flattening of the dunes and mulching of the ground surface with shrub and palm leaves proved to be effective.

Mechanical fixation of sand dunes is an effective but expensive measure. Local materials for dune fixation are being tested. First results show that dune fixation also encourages the re-establishment of natural vegetation on the stabilized lands.

## Geography of Tunisia Adjacent to the Sahara

The zone adjacent to the Sahara in Tunisia covers approximately 30,000 $km^2$. The annual rainfall ranges between 100 and 200 mm (Fig. 1). This rainfall, which is accentuated by dry winds and is highly variable, prevails mainly between May and September, during the cold period and the drought. The thermal regime is quite variable. The average maximum temperature of the hottest month (July) varies from 32 to 36 °C. According to the classification of Emberger, a major part of the region is located at the lower end of the Mediterranean arid climate.

Because of different soil types, the redistribution of rainfall through runoff, and the more or less strong demographic pressure (cultivation, overgrazing, etc.) a very limited steppe vegetation prevails.

Since the beginning of this century and in particular during the last few decades, rapid changes of the landscape in southern Tunisia have been observed, due mainly to population growth and human settling. Changing styles of living and rural development are accompanied by changes in the land tenure system and the quantitative and qualitative use of natural resources (Floret and Pontanier 1982; Le Houerou 1969 and 1990; Talbi 1993).

In the past, this area was used for extensive grazing (by sheep, goat, and camel) on communal rangelands, and for traditional systems of cereal cultivation, mainly in the higher rainfall zones. Due to the rapid settlement of nomadic populations and the ownership of collective lands, new forms of natural resource management have been developed. This is illustrated by the gradual abandonment of transhumance systems, establishment of home gardens, and the rapid extension of tree- and cereal-crop cultivation at the expense of pasture lands. This is due mainly to the introduction and general use of mechanization (disking), which permits the rapid and less expensive clearing of large areas in the steppe (Khatteli 1981, 1984).

Adoption of this aggressive technology for cultivating the sandy steppe lands, which are the most attractive for cereal- and tree-culture, promotes accelerated wind erosion. This rapid extension of cultivation at the expense of pasture land has led to a decrease in the traditional pasture zone. Sheep, still found in significant numbers, are progressively pushed to graze on lands with reduced numbers of living species and low biomass, which also leads to land degradation. This process is of serious concern, as the lands are particularly prone to wind erosion, which removes the thin topsoil and leads to the formation of dunes (Ben Dali 1987; Akrimi et al. 1988; Akrimi and Abaab 1991).

Settlement is leading to the loss or dispersal of huge flocks, which are replaced by smaller units that graze year-round close to inhabited areas. This also provokes localized overgrazing and an accelerated degradation of the environment in the vicinity (Floret and Pontanier 1982).

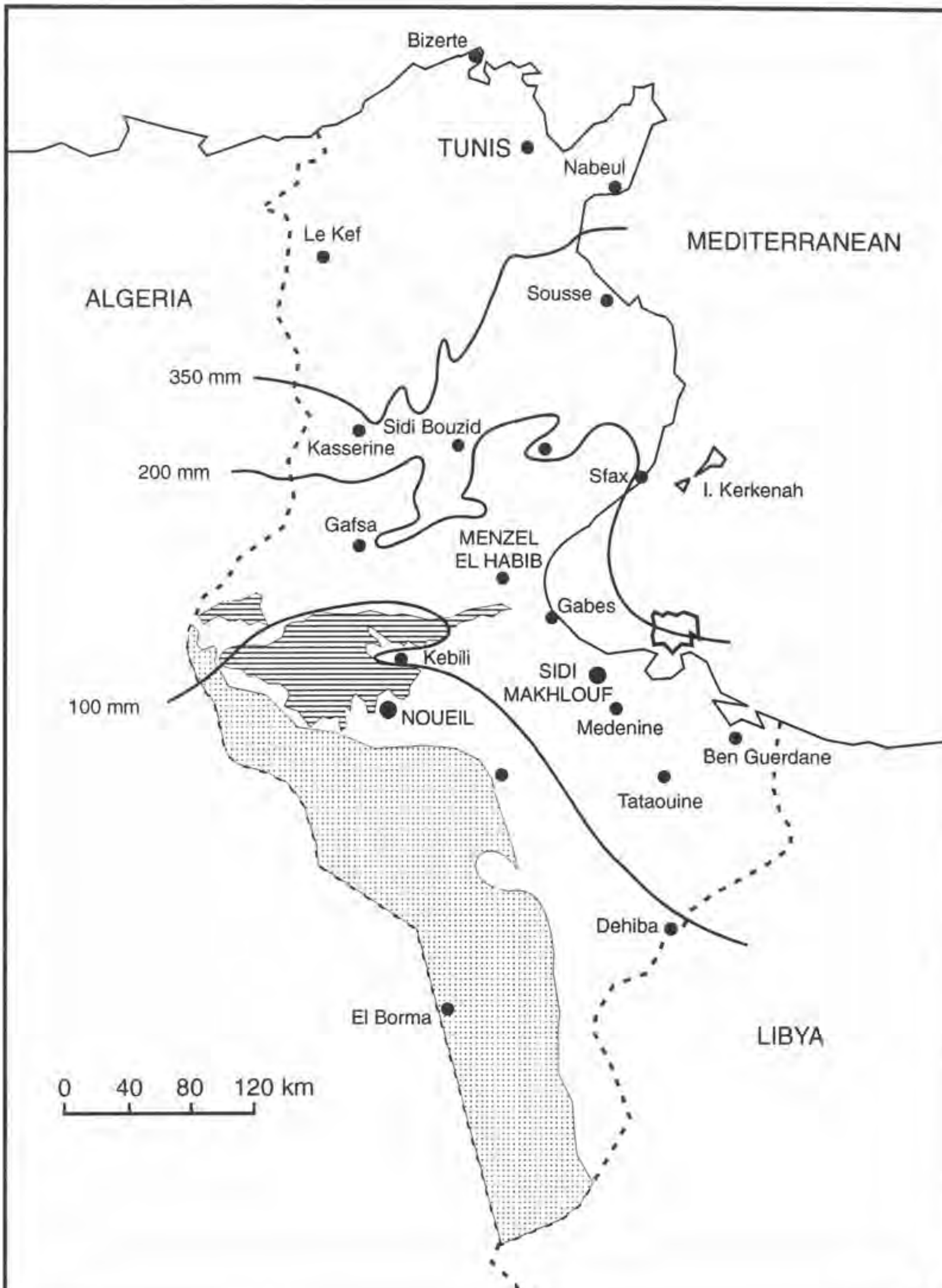


**Figure 1. Location of experimental stations.**

Sheep grazing is more or less a semi-nomadic practice, easily adapted to a spatial and temporal variability of rainfall and grazing resources. Thus, the deterioration of the ancient system of management of rural areas is leading to changes, sometimes irreversible, in the ecological equilibrium that existed in the traditional management systems of land and vegetation. Natural resource management is thus disturbed, and the degradation process increased. This is demonstrated by the decreased biological productivity of ecosystems, resulting in a lower standard of living for the inhabitants (Floret et al. 1976). Floret et al. have shown that if the current systems of exploitation of marginal lands continue until the year 2000, degraded lands will increase from 35 to 65% and the productivity of the ecosystems will decrease by 35%.

## Fundamental Knowledge of Wind Erosion Processes

The research that we have undertaken has provided several useful results concerning the fundamental processes of wind erosion and the implementation of practical solutions, both curative and preventive, to counter wind erosion.

Studies carried out at different research stations (Ben Gardane, Dar Dhaoui, Sidi Makhlouf, Menzel El Habib, and Noueil) demonstrate that desertification, where sand encroachment poses the most serious problem, should not be considered as an unstoppable progression of sand masses from the Sahara. In fact, this is a local phenomenon—discontinuous, diffuse, and non-generalized—that occurs at all places in a vulnerable and marginal environment where the delicate equilibrium is disturbed by excessive and indiscriminate use by human populations (Khatteli 1981, 1982).

In fact, the movable sand dunes that are encountered frequently near oases, cultivated lands, and villages are formed following the destruction of vegetative cover due to multiple anthropogenic effects (eradication of woody species, overgrazing, crop cultivation, etc.). Their progression in the direction of the Sahara in general, and the Erg Oriental in particular (and not the other way as we previously believed), is due to the dominance of active winds that blow from the east, southeast, and the north over the winds that originate from the west and the south (Khatteli 1981; Khatteli and Bel Haj 1993).

At the planning level, the results of our study on wind dynamics and sand movement can provide practical solutions for efficient control of movement of sand dunes on the local scale, or even in terms of movement of the dunes. Mechanical windbreaks can be oriented perpendicular to the axis of sand displacement, and the implementation of mechanical stabilization of sand dunes can be undertaken when winds are relatively quiet. However, maintenance operations and the re-erection of the fences installed should be done during the windy periods in order to avoid their burial under the mobile sands (Khatteli 1996).

Low wind breaks (maximum height of 1 m) with a homogeneous permeability and without an opening at the base, are highly recommended to combat moving sand dunes.

# Combating Wind Erosion

In our research, we wanted to demonstrate that the wind erosion in our zone is an anthropological phenomenon which, once initiated, tends to become more extensive and even encroach on the more stable environmental zones. The experiments carried out at the research stations have demonstrated that it is possible to combat this degradation, at the curative as well as the preventive level.

## The Curative Control of Wind Erosion

### Olive crops affected by sands

The sand encroachment of olive crops results from excessive cultivation of soil with a disk harrow, which pulverizes the soil and renders it more vulnerable to wind erosion. This is manifested by the disappearance of olive crops where the deflation and formation of movable sand dunes occurs, or where sand deposition occurs. To combat this phenomenon, mulching was employed, consisting of spreading plant residue over the soil surface after leveling the dunes (Khatteli 1984). The erosion process has slowed down markedly, and no new dune formation has since occurred at this site.

Three types of plant residue were tested. The twigs of *Artemisia campestris* were found to be more suitable for the fixation of the mobile dunes than the other two (*Rhanterium suaveolens* and palm leaves). This was due to their application efficiency, pastoral and economic value, and availability in sufficient quantities on the degraded lands and fallows in the study zone.

It is strongly recommended that the disk harrow be replaced by a tooth-harrow, plowshare, or blade-harrow, all of which provoke less degradation. The maintenance of natural plant strips between the olive trees and their utilization as wind breaks is also highly recommended.

### Land covered by degradation

The research done at Menzel Al Habib on a degraded steppe covered by *Rhanterium suaveolens* under multiple anthropogenic effects (overgrazing and removal of woody species) illustrates the positive impact of measures taken to combat wind erosion. The ecological evolution of the study zone under the effect of the protective measures is demonstrated from a geomorphological stand point in terms of:

- A spatial extension of nebkas at the expense of mobile dunes and the denuded zone.
- A decrease in the susceptibility of the land to wind erosion.
- A general tendency towards the establishment of an eco-pedomorphological equilibrium.

The protection of degraded land subjected to intense wind erosion processes can be envisaged as an efficient and less expensive method to combat wind erosion, provided the limit of its irreversibility has not yet been reached.

## Mechanical fixation of mobile dunes

A trial at the Sidi Makhlouf station examined the use of dry wattling (living brushwood) for rapid and effective stabilization of mobile dunes. Five treatments (including a control) were studied, and the following conclusions drawn:

- Wattling arranged either in 20 m squares (continuous pattern) or in rows spaced 20 m apart (across the main wind direction) were the most effective treatments in terms of the quantity of sand trapped and the stability of soil surface inside each plot. The 40 m squares were less effective, but still resulted in improvement. Wattling rows planted 40 m apart were the least efficient, although they were significantly superior to the control (no intervention).
- In terms of cost/benefit, the 20 m parallel rows were better than the 20 m squares because they were only half as expensive. This allows us to evaluate the actual cost of mechanical stabilization of dunes carried out by the regional technical services of the General Directorate of Forestry.
- The first six months of the trial were characterized by instability inside the different plots, which damaged the fixed plants. It is thus advisable not to begin tree planting during this period to avoid the burial of young plants due to sand deposit, or their removal due to deflation. Work during this period should be oriented towards the cleaning and care of the fence. Replanting should not be started until after the second year, or, at a minimum, six months after the installation of the plot.
- The dune soil, especially when it is a little mobile, generally constitutes a favorable atmosphere for the development of natural vegetation, thanks to its capacity to retain soil moisture at shallow depths. It responds well to protective measures and may be sufficient for soil-surface fixation. This procedure will prevent re-afforestation, resulting in reduced expenses for the fixation of the mobile dunes and the restoration of the degraded lands.

## Preventive Measures

The results of the experiments carried out in Dar Dhaoui on the tools for soil cultivation, as well as natural plant strips for the prevention of wind erosion on lands cropped to cereals, clearly point out the extreme fragility of arid ecosystems, notably those on sandy soils. Inappropriate exploitation of the natural resources in this zone (water, soil, vegetation) provokes wind erosion, which, once initiated, feeds on itself and intensifies due to anthropogenic as well as climatic factors.

Crop cultivation can be regarded as a factor of soil degradation in south Tunisia because wind erosion is provoked on soils that are cultivated. This erosion is at its highest when the land is cultivated by disk harrow. Utilization of the disk harrow on sandy soils cannot be tolerated unless the soil roughness is improved by the addition of plant residues or by keeping uncultivated natural vegetation strips between the cultivated strips. If the first solution cannot be achieved, because it requires an investment to provide plant residue (hay, straw, or any other natural residue available locally), the second solution of natural vegetation strips is attractive to the farmers because it does not require any investment. It can be easily implemented on a large scale. Strips 10–20 m wide are more efficient than strips 5 m wide, because they are more effective in decreasing wind erosion, and also help achieve a small increase in barley yield. In addition to the ecological benefits (conservation of natural vegetation which is nearing extinction because of land clearing), the uncultivated strips also provide livestock feed, thanks to the pasture potentiality.

The tooth harrow (tiller) and the blade (sweep), even though they significantly reduce wind erosion in comparison to the disc harrow, cannot substitute for the latter in the cereal zone because of the low yield of barley obtained in fields where they were used. Therefore, their utilization is recommended in horticultural fields (i.e., for olive cultivation). The plowshare is *a priori* the most appropriate tool because it results, on average, in a three-fold reduction in soil loss compared to the disk harrow, while producing an annual harvest closer to the mean yield.

Research results achieved on wind erosion in the arid and desertic Tunisia have been utilized at several locations:

- The Regional Technical Services of the Directorate General of Forestry made use of our results to select the most permeable mechanical windbreaks and their orientation relative to the dominant active winds. These are being implemented at Medenine, Gabes, and Kebili.
- The farmers at Ben Gardane and at Zarzis used our results regarding the maintenance of uncultivated strips between cultivated lands and the progressive replacement of the disk harrow by the tooth harrow, particularly in olive fields.

- Dune fixation in olive fields encroached by sand using the mulching technique has started to interest some olive farmers in the Zarzis region.

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# Some Observations on Wind Erosion in Egypt

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## Abstract

Egypt lies in an arid region, where the problems of wind erosion are considered a real threat. The current research was conducted under field conditions to measure the quantity and properties of soil loss due to wind erosion during certain periods in the Northwest Coast (NWC) and North Sinai. Laboratory study using a wind tunnel was also carried out at the Desert Research Center to evaluate the relation between wind velocity and soil loss.

Three sites were selected for field study, the first in the NWC and the others in North Sinai. Airborne material was collected from eroding soil with a BSNE dust sampler. The quantity of airborne material varied according to sampling period, location, sampler height, and soil-surface conditions. At each site the amount of soil collected decreased with increased height and the percent of particles <0.1 mm increased with height. The relation between the quantity of soil collected and sampler height is best described with logarithmic or power equations. The amount of airborne material expressed as t/100 m width was 0.783, 3.161, and 86.192 for the bare soil of South Abou Lahu (NWC), El Shiekh Zowaied, and El Maghara (North Sinai), over 93, 193, and 340 days, respectively. Vegetative cover reduced the wind erosion rate in North Sinai. In most cases, concentrations of N, P, K, and organic matter in airborne material were greater than that of the parent soil, and the enrichment ratios were greater than 1.

Laboratory study using a wind tunnel indicated that the quantity of soil loss increased with increasing wind velocity. The threshold velocity of Abou Lahu soil was 5 m/s. Future research is needed for the successful planning of soil conservation measures to control wind erosion in Egypt.

## Introduction

Egypt lies in an arid region, where the problems of wind erosion are considered a real threat for arable lands. Wind erosion also causes severe losses to human habitation, communication, and transportation, and imperils human health. This is especially true for the newly reclaimed areas in the vicinity of the Nile Delta and Valley, as well as the arable lands of the desert areas, which are characterized by unprotected erodible soils, low variable precipitation, and erosive wind especially during the spring and summer.

The Economic and Social Committee of Western Asia (ESCWA 1993) showed that about 18 million ha in Egypt are affected by different levels of wind erosion. Arroug (1995) used the wind prediction equation of Woodruff and Siddaway (1965) to estimate soil loss by wind erosion in El-Omayed, Northwest Coast. He showed that soil loss by wind erosion reached 100 t/ha per year. In South Sinai, Wassif et al. (1997) used the Big Spring Number Eight (BSNE) dust sampler to measure soil loss by wind erosion during 83 days beginning in March, 1994. They found that the quantity lost was 3.07 t/100 m width. El Maghraby et al. (1994) studied the effect of sand dune stabilization on the amount of shifting sands in Siwa Oasis. They found that the daily amount of shifting sand reached 28.5 g/m width in the stabilized area, and 856.5 g/m width in the unstabilized area. However, quantitative information about soil loss and nutrient loss due to wind erosion under various conditions in Egypt is still lacking. Therefore, the purpose of this study was to measure the quantity and properties of soil loss by wind erosion during certain periods in the Northwest Coast and North Sinai. Moreover, the relation between wind velocity and soil loss was determined using the wind tunnel at the DRC.

## Materials and Methods

The study was performed under field and laboratory conditions. Field studies were carried out in two regions (the NWC and North Sinai). Both regions represent the main areas of rainfed agriculture in Egypt. Figure 1 shows the location of the sites.

In the NWC, the field work was conducted in South Abou Lahu (Site 1), located 40 km west of Marsa Matruh. The mean annual precipitation varies from 100 to 150 mm. The dry season lasts 6–7 months. Mean annual maximum and minimum air temperatures are 25 °C and 15 °C, respectively. Relative humidity varies from 50 to 70%. Winds blow strongly during winter, early spring, and certain summer months. The average wind speed is 5.5–7.0 m/s. FAO/UNDP (1970) estimate that velocities of more than 60 km/hr occur 58 times in ten years. The site was cultivated with barley on rainfall in the winter season, and left fallow during summer. The dominant soil is Lithic Torripsamments, mixed, Hyperthermic. The field was nearly flat. Table 1 shows some physical and chemical properties of the upper 5 cm of the soil surface.

**Table 1. Physical and chemical properties of surface soil (0–5 cm) at Abou Lahu.**

| Particle size distribution (%) | | | | Texture class | $CaCO_3$ (%) | Bulk density ($g/cm^3$) | Roughness coefficient | pH of soil paste | Total N (%) | OM (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Coarse sand | Fine sand | Silt | Clay | | | | | | | |
| 2.37 | 77.65 | 19.95 | 0.03 | Loamy sand | 16.32 | 1.36 | 3.33 | 7.9 | 0.031 | 0.38 |


**Figure 1. Field study locations.**

Samples of soil material from eroding soil were collected three times between 8 April and 10 July 1994, at heights of 0.05, 0.2, 0.5, and 1 m using the BSNE dust sampler, as described by Fryrear (1986). Three samplers were located in a 150 × 30 m field, placed 50 m apart in a line parallel to the direction of the dominant wind. The field was surrounded by a non-erodible area covered with natural vegetation.

In Sinai, the field work was conducted at two sites: El Sheikh Zowaied (Site 2), located 32 km east of El Arish, and El Maghara (Site 3), located 90 km southwest of El Arish. At El Arish the mean annual rainfall is about 100 mm, decreasing southward. Maximum and minimum air temperatures are 30.6 °C and 7.3 °C, respectively. Relative humidity reaches 75% in summer and winds are usually mild.

At Site 2 the field work was carried out at El Sheikh Zowaied Station, Desert Research Center, in two fields: one with bare soil, and the other cultivated with olive and palm seedlings. The soil was an aeolian sand deposit (Typic Torripsamment). Table 2 shows some physical and chemical properties of the upper 5 cm of the soil surface. Two BSNE samplers were positioned 50 m apart in every field. For both fields, samples of soil material from eroding soil were collected during six periods from 25 January to 6 August 1996, at heights of 0.1, 0.5, 0.75, and 1 m from the soil surface.

**Table 2. Physical and chemical properties of surface soil (0–5 cm) at El Sheik Zowaied.**

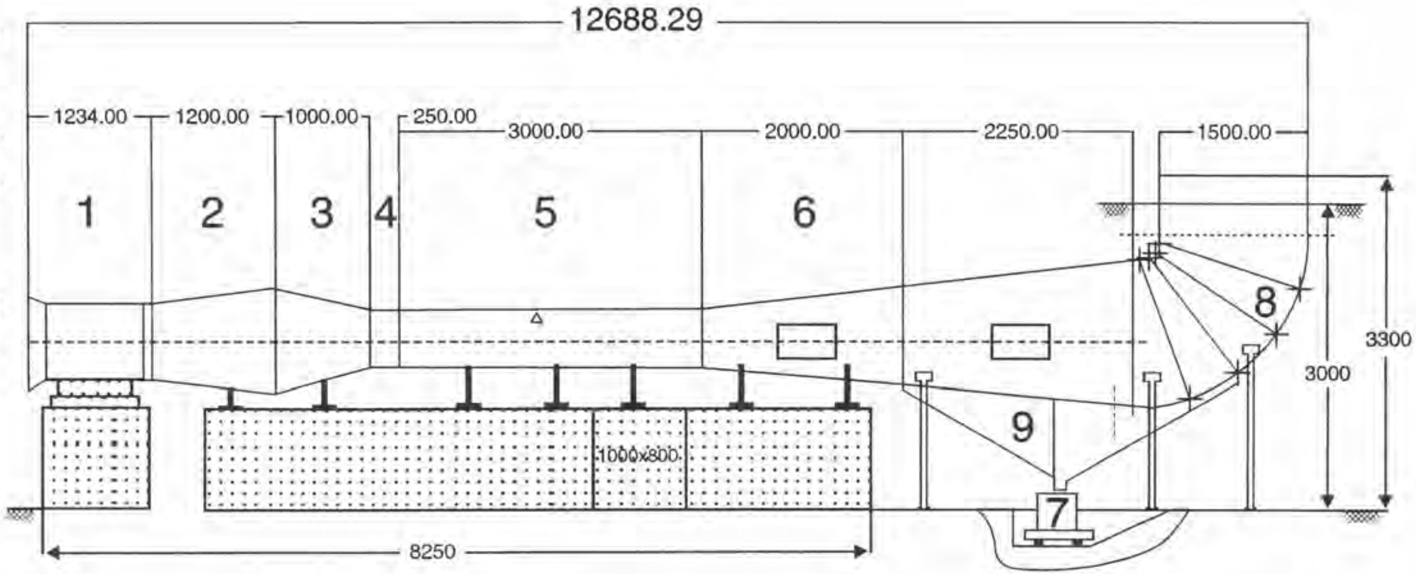
| Particle size distribution (%) | | | Texture class | $CaCO_3$ (%) | EC (dS/m) | Bulk density | Rough-ness factor | pH of soil paste | Total N (%) | OM (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| Sand | Silt | Clay | | | | $g/cm^3$ | | | | |
| 93.3 | 4.6 | 2.1 | Sand | 0.3 | 0.522 | 1.65 | 0.89 | 8.14 | 0.007 | 0.03 |

At Site 3 the field work was conducted at El Maghara Station, Desert Research Center, in two fields: the first bare soil and the second cultivated with five-year-old pistachio. Two BSNE samplers were positioned 50 m apart in each field. The dominant soil is Typic Torripsamment. Physical and chemical properties of the upper 5 cm of the soil surface are shown in Table 3. Samples of soil material from eroding soil were collected from each field during eight periods from 9 January to 15 December 1996 at heights of 0.1, 0.5, 0.75, and 1 m from the soil surface.

**Table 3. Physical and chemical properties of surface soil (0–5 cm) at El Maghara.**

| Field | Particle size distribution (%) | | | Texture class | $CaCO_3$ (%) | pH of soil paste | EC of soil paste extract (dS/m) | Bulk density ($g/m^3$) | Rough-ness factor | OM (%) | Total N (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sand | Silt | Clay | | | | | | | | |
| Bare | 77.1 | 7.16 | 15.71 | Loamy sand | 11.73 | 7.93 | 0.567 | 1.75 | 0.37 | 0.09 | 0.009 |
| Culti-vated | 70.0 | 13.0 | 17.00 | Sandy loam | | 7.90 | 0.569 | 1.60 | 6.25 | 0.07 | 0.02 |

The samples of soil material from eroding soil for every site were dried at 55 °C for 72 hours before weighing, and then dry sieved to determine the size distribution of dry undispersed particles for each sample height (referred to in this paper as particle size distribution). Organic matter, total nitrogen, available phosphorus, and exchangeable potassium were measured on composite samples of airborne material or samples from the upper 5 cm of the soil surface. The methods used are described by Black (1965). Hourly wind speed was measured by a recording anemometer 2.5 m above the soil surface.




1. Motor
2. Long Duct Diffuser
3. Nozzle
4. Connecting Part
5. Test Section
6. Diffuser
7. Sand Collector
8. Outlet Elbow
9. Sand Trap

Figure 2. Layout diagram.

In the laboratory study, the wind tunnel at the DRC was used to study the relation between wind velocity and soil loss, and to estimate the threshold velocity of Abou Lahu soil. The wind tunnel is an open circuit, blower type with a variable pitch-in-motion axial flow fan. A schematic side elevation of the tunnel is shown in Figure 2. The test section was a rectangular duct 0.7 m wide, 0.6 m high, and 3 m long. A sample tray 500 mm × 700 mm × 70 mm was used. The tray was filled with sieved Abou Lahu soil surface <0.5 mm in diameter. Each weighted soil tray was exposed to wind velocities of 7.5, 8.3, 9.0, 10.3, 11.0, 12.0, 13.4, 14.2, and 14.7 m/s. The wind velocity was measured >30 cm from the soil surface by a traverse mechanism system equipped with venterimeters. After each velocity the tray was weighed, additional soil was added then smoothed to a uniform 70 mm depth, and the tray was subjected to the given wind speed. Duplicate 10 minute tests were run for each velocity. The soil loss for every speed was determined using a load cell of accuracy +0.01 kg. The relationship between soil loss and free stream velocity was determined.

## Results

### Field Studies

For Site 1, the mean velocity of erosive wind during the sampling periods was 10.1 m/s. The maximum wind velocity of 14.4 m/s occurred in May. Table 4 shows the quantity of airborne material ($g/cm^2$) during the three periods at 0.05, 0.2, 0.5, and 1 m heights. The quantities are dependent upon the sampling period and sampler height, where, for every period, the quantity was decreased by increasing height (Fig. 3). The relationship between the quantity of airborne material and sampler height was tested using different models, i.e. logarithmic, linear, power, and exponential. The data show that the logarithmic model was the best:

$$Y = a + b \, ln \, x$$

where y = mass of airborne material collected ($g/cm^2$); x = height of sampler, (m); and a, b = regression coefficients.

**Table 4. Eroded soil ($g/cm^2$) collected at four heights during three periods at Abo Lahu.**

| Sampling | Sampler height (m) | | | | a | b | $r^2$ | Q (g/cm |
|---|---|---|---|---|---|---|---|---|
| period | 0.05 | 0.20 | 0.50 | 1.0 | | | | width) |
| 4/8–4/28 | 0.710 | 0.670 | 0.234 | 0.174 | 0.184 | -0.199 | 0.832 | 33.4 |
| 4/28–6/8 | 0.895 | 0.601 | 0.379 | 0.185 | 0.203 | -0.235 | 0.996 | 38.9 |
| 6/8–7/10 | 0.125 | 0.114 | 0.033 | 0.028 | 0.027 | -0.036 | 0.837 | 6.88 |

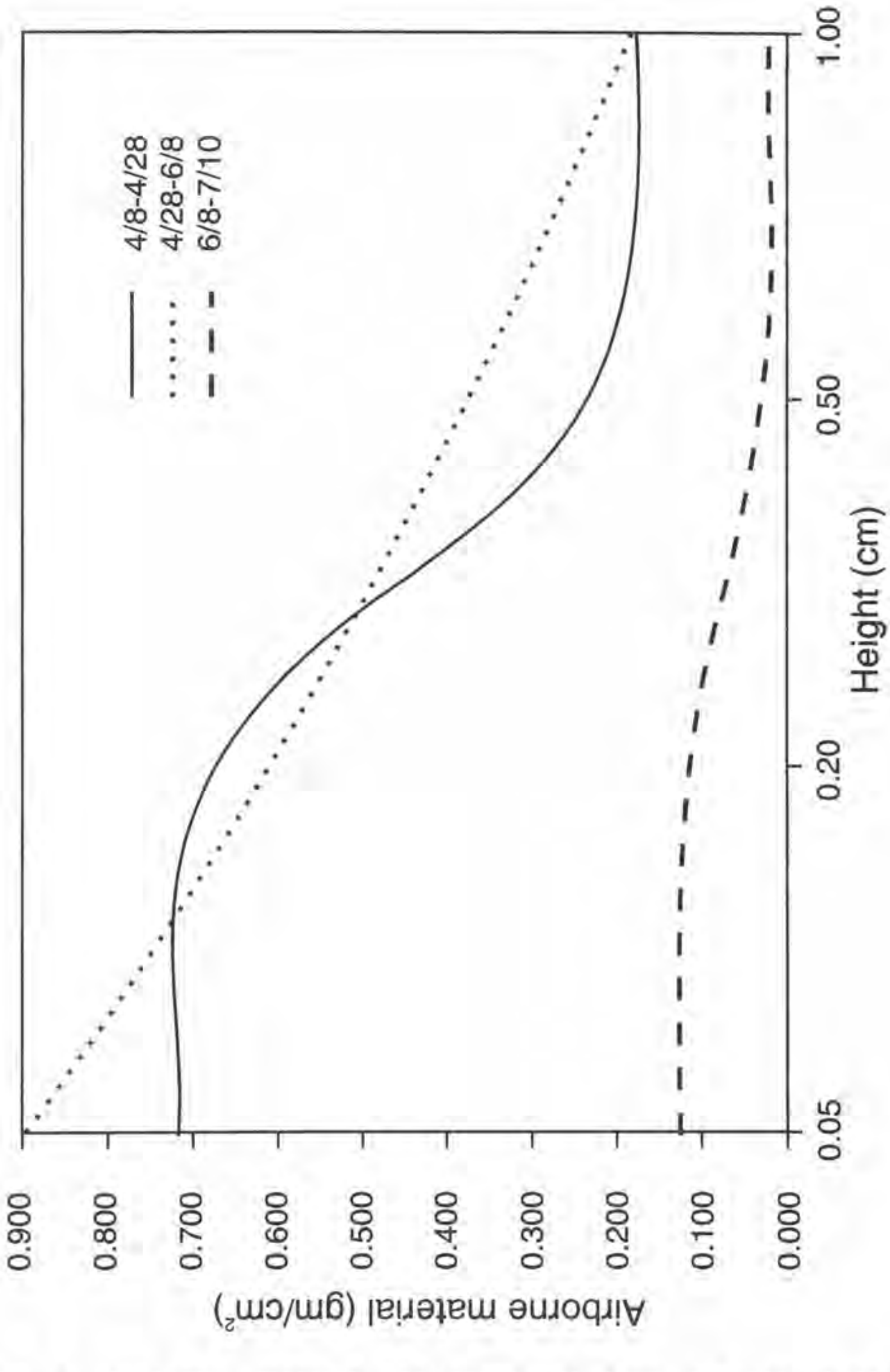



**Figure 3. Airborne material collected at four heights during three periods at Site 1.**

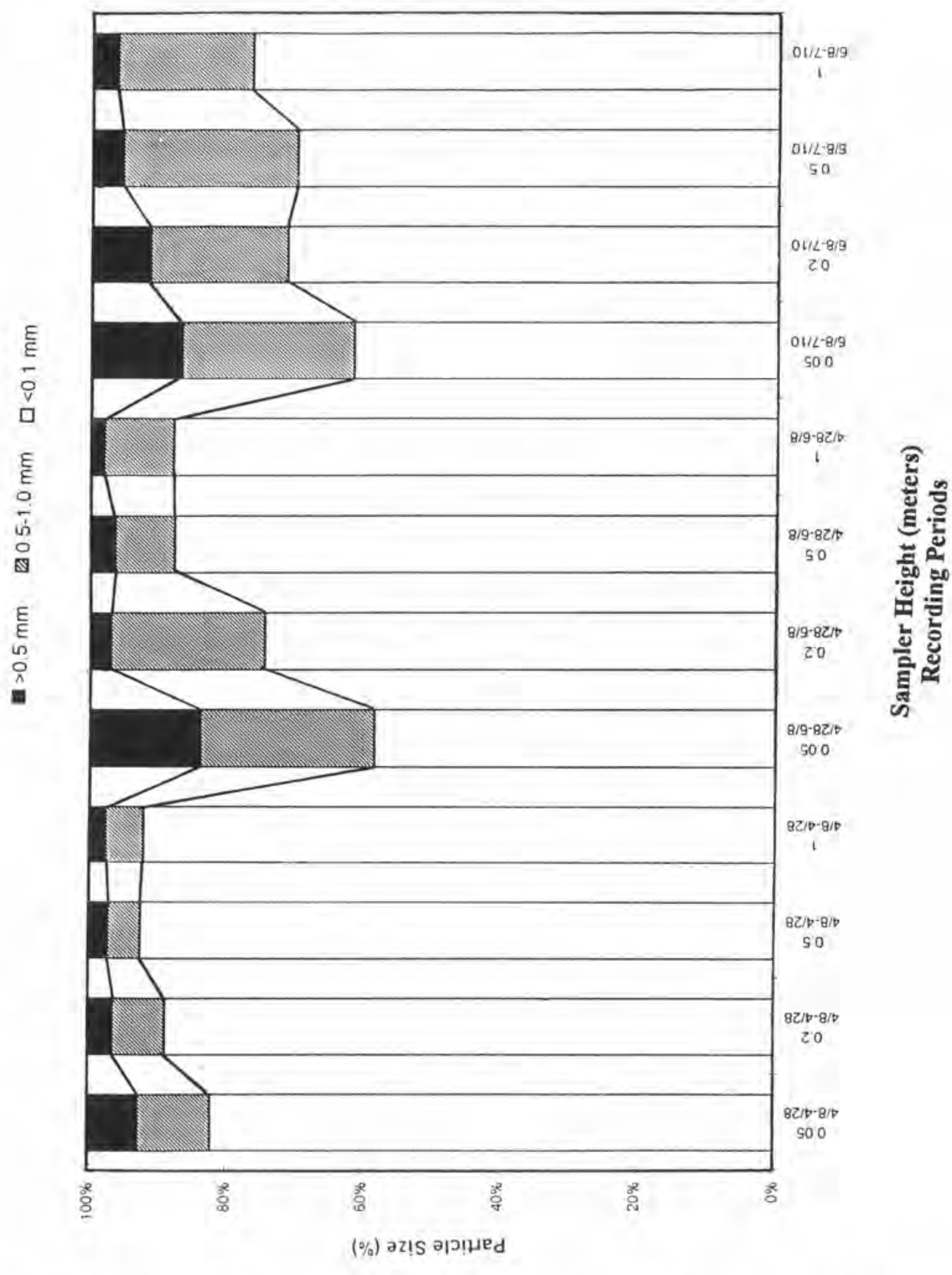



**Figure 4. Particle size distribution (%) of eroded soil at different heights at Abou Lahu.**

The total amount of airborne material (Q) collected by a 1 cm wide slot extending from a height of 0.05 m to 1 m was estimated by integrating the regression equations between the limits of 0.05 m and 1 m. The results are given in Table 4. The greatest Q value was obtained from the longest sampling period. From Q values, the total amount of airborne material during the sampling periods was estimated as 783 kg/100 m width.

Figure 4 shows the particle size distribution of airborne material collected during every period. The data for all sampling periods indicate that particles smaller than 0.1 mm increased with increasing height. These particles reached about 92% at a height of 1 m for the first sampling period.Table 5 shows the chemical composition of airborne material and parent soil, as well as the enrichment ratio (ER) calculated according to the following equation:

$$ER = \frac{\text{The amount of nutrient in the airborne material}}{\text{The amount of nutrient in the parent soil}}$$

**Table 5. Organic matter, total nitrogen, available phosphorus, and exchangeable potassium content of airborne material and parent soil as well as enrichment ratio at Abou Lahu.**

| Chemical composition | Parent soil | Airborne material (1994) | | |
|---|---|---|---|---|
| | | 4/8–4/28 | 4/28–6/8 | 6/8–7/10 |
| Organic matter | | | | |
| % | 0.276 | 2.31 | 1.66 | na |
| ER | na | 8.3 | 6.0 | |
| Total nitrogen | | | | |
| % | 0.031 | 0.025 | 0.025 | 0.044 |
| ER | na | 0.81 | 0.81 | 1.42 |
| Available P | | | | |
| ppm | 1.2 | 4.8 | 3.4 | 2.4 |
| ER | na | 4.0 | 2.8 | 2.0 |
| Exchangeable K | | | | |
| meq/100 g soil | 0.857 | 1.46 | 1.44 | 1.21 |
| ER | na | 1.70 | 1.7 | 1.4 |

na=Data not available.

The data show that the organic matter, available phosphorus, and exchangeable potassium of the airborne material associated with the first sampling period were greater than the other periods. The enrichment ratios of organic matter, available phosphorus, and exchangeable potassium were greater than 1.

Table 6 shows the number of hours that the wind speed was more than 6.1 m/s at a height of 2.5 m for Site 2. Obviously, the highest number was in March, and the lowest in July. Table 6 shows that there were 316 hours of wind speed greater than 5.5 m/s from 6 June to 15 December 1996 at Site 3. The greatest number was obtained in October; and the lowest in November.

**Table 6. Hours of erosive wind at El Shiekh Zowaied and El Maghara (1996).**

| Month | El Shiekh Zowaied wind speed (m/s) | | | El Maghara (wind speed more than 5.5 m/s) |
|---|---|---|---|---|
| | <6.1 | 6.1–8.9 | >8.9 | |
| January | 24 | 20 | 4 | na |
| February | 50 | 47 | 3 | na |
| March | 85 | 71 | 14 | na |
| April | 49 | 49 | - | na |
| May | 30 | 26 | 4 | na |
| June | 11 | 11 | - | na |
| July | 2 | 2 | - | 55 |
| August | - | - | - | 39 |
| September | na | na | na | 69 |
| October | na | na | na | 71 |
| November | na | na | na | 27 |
| December | na | na | na | 45 ‡ |

na=Data not available.

‡ Data until 15 Dec.

Figure 5 shows the amount of airborne material ($g/cm^2$) collected for each sampling period at heights of 0.1, 0.5, 0.75, and 1.0 m for bare and cultivated soils for Site 2. The highest amount of airborne material was obtained during the sampling period from 12 February to 9 March 1996. This is in agreement with the hours of wind speed more than 6.1 m/s in March. For every period, the amount of airborne material decreased with increasing height. The same trend was also seen at Site 3 (Fig. 6).

The relationship between the amount of airborne material and sampler height for bare and cultivated soils was tested using different models. Power and logarithmic equations were best for Sites 2 and 3, respectively.

Total amounts of airborne material for both bare and cultivated soils at Sites 2 and 3 were obtained by vertical integration of the data from the four heights and calculated as kg/100 m width. These data are given in Table 7. Obviously, the values for the bare soil were greater than for the cultivated soil at both sites.

The values for Site 3 were greater than for Site 2. When the soil was cultivated, soil loss (compared to bare soil) was reduced to 12.7% at Site 2 and 94.6% at Site 3.

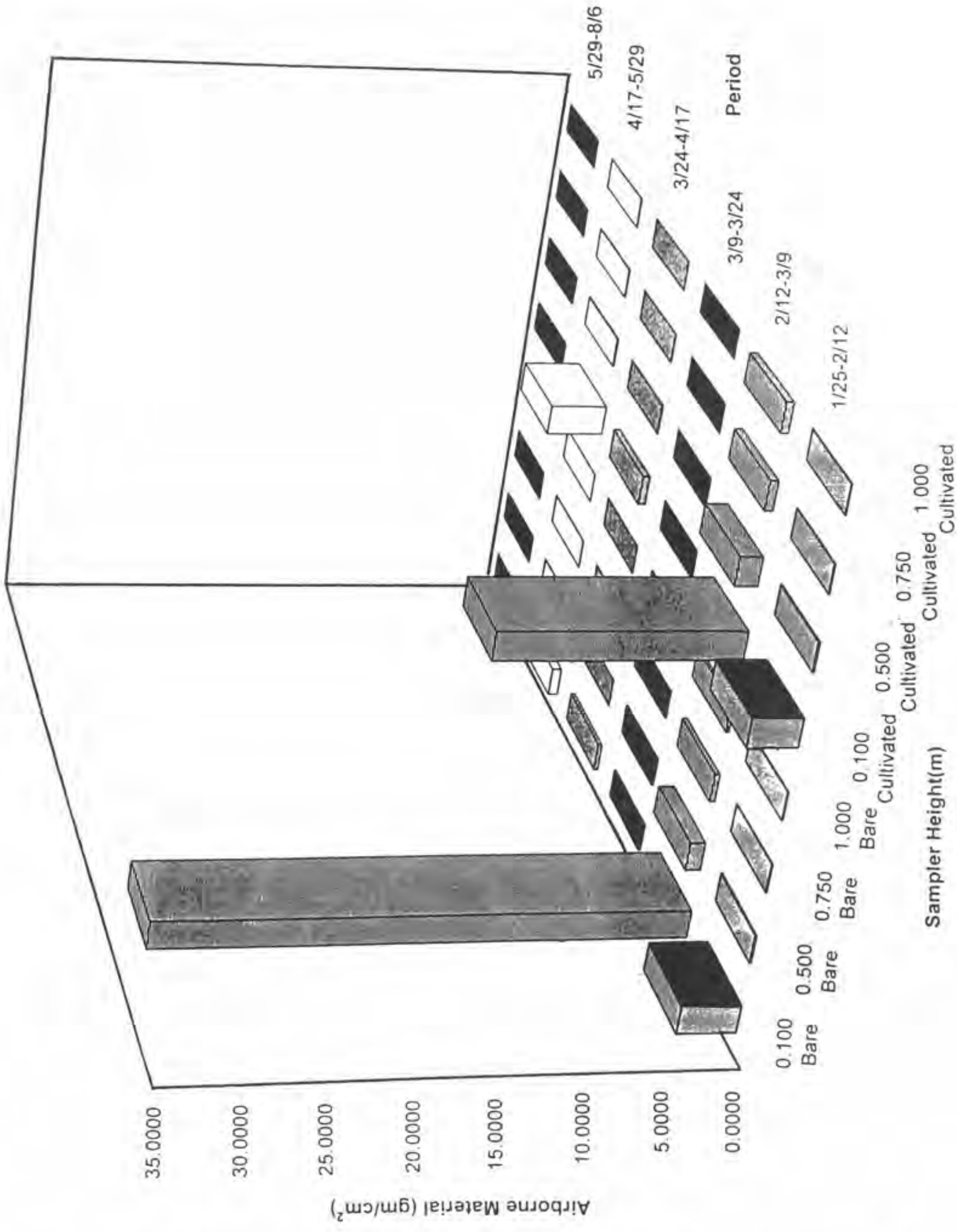



**Figure 5. Airborne material collected at four heights from bare and cultivated soils at Site 2.**

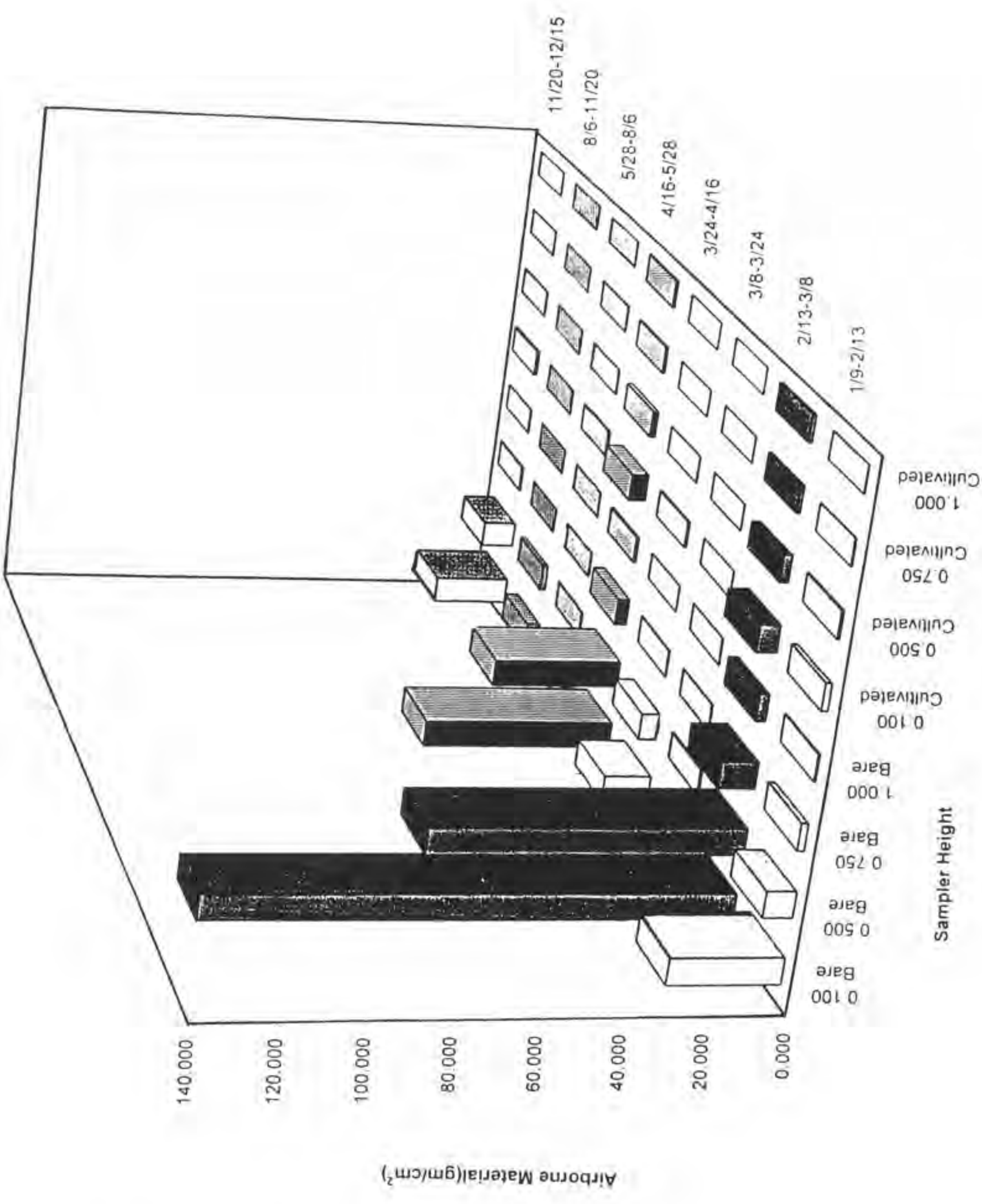



**Figure 6. Airborne material collected at four heights from bare and cultivated soils at Site 3.**

Table 7. Total amount of soil collected at four heights during sampling periods for bare and cultivated soil at El Sheikh Zowaied and El Maghara (Sites 2 and 3).

| Site | Field | Sampler height (m) ($g/cm^2$) | | | | a | b | $r^2$ | Regression equation | Q (g/cm width) | Total amount (t/100 m width) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.1 | 0.5 | 0.75 | 1.0 | | | | | | |
| 2 | Bare | 38.2896 | 1.2674 | 0.4952 | 0.3466 | 0.3062 | -2.0869 | 0.9977 | $y=a+b\ln x$ | 316.0929 | 3.161 |
| | Cultivated | 22.8805 | 1.7667 | 0.6879 | 0.6095 | 0.5317 | -1.6314 | 0.9920 | $y=a+b\ln x$ | 276.19617 | 2.76 |
| 3 | Bare | 248.9183 | 136.1195 | 15.1663 | 4.1623 | 13.0626 | -107.2909 | 0.9146 | $y= ax^b$ | 8619.2485 | 86.192 |
| | Cultivated | 13.1701 | 4.8488 | 2.2747 | 1.8767 | 1.36257 | -5.09227 | 0.99301 | $y= ax^b$ | 463.682 | 4.637 |

Table 8 shows the particle size distribution of airborne materials at heights of 0.1, 0.5, 0.75, and 1.0 m above the soil surface for bare and cultivated soils at Sites 2 and 3. Particles <0.1 mm increased with increasing height in all cases. For Site 2, at heights of 0.1 and 0.5 m, particles between 0.5 and 0.1 mm were dominant; however at heights of 0.75 and 1.0 m particles <0.1 mm were dominant. At Site 3, particles <0.1 mm were dominant at a height of 1 m, particularly for the cultivated soil. A more or less similar trend was previously obtained at the Abou Lahu site.

**Table 8. Particle size distribution (%) of airborne material at four heights for bare and cultivated soil at Sites 2 and 3.**

| Particle size (mm) | Bare soil | | | | Cultivated soil | | | |
|---|---|---|---|---|---|---|---|---|
| | Sampler height (m) | | | | Sampler height (m) | | | |
| | 0.1 | 0.5 | 0.75 | 1.0 | 0.1 | 0.5 | 0.75 | 1.0 |
| | **El Sheikh Zowaied (Site 2)** | | | | | | | |
| 2–1 | | | | | | | | |
| 1–0.5 | 2.39 | 1.95 | 0.06 | 0.05 | 1.31 | 1.19 | 0.42 | 0.09 |
| 0.5–0.1 | 97.52 | 84.95 | 38.15 | 34.0 | 97.27 | 81.25 | 43.94 | 28.06 |
| <0.1 | 0.09 | 13.10 | 61.79 | 65.95 | 1.42 | 17.56 | 55.64 | 71.85 |
| | **El Maghara (Site 3)** | | | | | | | |
| 2–1 | | | | | | | | |
| 1–0.5 | 7.24 | 2.31 | 8.17 | 2.98 | 0.47 | 0.39 | 0.44 | 0.27 |
| 0.5–0.1 | 86.86 | 92.29 | 81.77 | 48.27 | 95.58 | 81.62 | 58.61 | 30.95 |
| <0.1 | 5.90 | 5.4 | 10.06 | 48.75 | 3.95 | 17.99 | 40.95 | 69.48 |

Table 9 summarizes the chemical composition of parent soil and airborne material at four heights of bare and cultivated soils for Sites 2 and 3. It shows that organic matter, total nitrogen, and available phosphorus contents of airborne materials were greater than that of the parent soil for both sites at every height. Organic matter content of airborne material collected from cultivated soil was greater than that of bare soil for both sites. The enrichment ratios of organic matter, available phosphorus, and total nitrogen were greater than 1 for all cases. Enrichment ratios of exchangeable potassium were greater than 1 for bare and cultivated soils at Site 2. The enrichment ratios for all cases, regardless of sampler height, can be arranged in the following order: organic matter > total nitrogen > available phosphorus > exchangeable potassium.

**Table 9. Chemical composition and enrichment ratio of collected soil at four heights for bare and cultivated soil at El-Sheikh Zowaied (Site 2) and El Maghara (Site 3).**

| Site | Chem. comp. | Bare soil | | | | | Cultivated soil | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Parent soil | Airborne material, Sampler height (m) | | | | Parent soil | Airborne material, Sampler height (m) | | | |
| | | | 0.1 | 0.5 | 0.75 | 1.0 | | 0.1 | 0.5 | 0.75 | 1.0 |
| | **Organic matter** | | | | | | | | | | |
| 2 | % | 0.03 | 0.02 | 0.07 | 0.09 | 0.5 | 0.03 | 0.09 | 0.27 | 0.27 | 0.30 |
| | ER | | 0.67 | 2.33 | 3.00 | 16.7 | | 3.0 | 9.0 | 9.0 | 10.0 |
| 3 | % | 0.09 | 0.09 | 0.16 | 0.48 | 0.77 | 0.07 | 0.89 | 0.89 | 0.93 | 0.91 |
| | ER | | 1.0 | 1.77 | 5.33 | 8.55 | | 12.71 | 12.71 | 13.29 | 13.0 |
| | **Total nitrogen** | | | | | | | | | | |
| 2 | % | 0.007 | 0.01 | 0.018 | 0.007 | 0.028 | 0.007 | 0.01 | 0.018 | 0.031 | 0.035 |
| | ER | | 1.43 | 2.57 | 1.0 | 4.0 | | 1.43 | 2.57 | 4.4 | 5.0 |
| 3 | % | 0.009 | 0.02 | 0.024 | 0.024 | 0.035 | 0.02 | 0.039 | 0.05 | 0.044 | 0.059 |
| | ER | | 2.22 | 2.67 | 2.66 | 3.89 | | 1.95 | 2.5 | 2.2 | 2.95 |
| | **Available P** | | | | | | | | | | |
| 2 | ppm | 0.336 | 0.464 | 0.312 | 0.648 | 0.856 | 0.336 | 0.48 | 0.504 | 0.296 | 0.496 |
| | ER | | 1.38 | 0.93 | 1.93 | 2.55 | | 1.43 | 1.50 | 0.88 | 1.48 |
| 3 | ppm | 0.4 | 0.496 | 0.576 | 0.424 | 0.888 | 0.384 | 0.328 | 0.384 | 0.60 | 0.84 |
| | ER | | 1.24 | 1.44 | 1.06 | 2.22 | | 0.85 | 1.0 | 1.56 | 2.19 |
| | **Exch. K** | | | | | | | | | | |
| 2 | meq/100 g | 0.08 | 0.08 | 0.13 | na | na | 0.08 | 0.08 | 0.10 | 0.13 | 0.12 |
| | ER | | 1.0 | 1.63 | | | | 1.0 | 1.25 | 1.63 | 1.50 |
| 3 | meq/100 g | 0.22 | 0.18 | 0.22 | 0.24 | 0.27 | 0.67 | 0.33 | 0.54 | 0.54 | 0.54 |
| | ER | | 0.82 | 1.00 | 1.09 | 1.23 | | 0.49 | 0.81 | 0.81 | 0.81 |

na=Data not available.

## Laboratory Study

Figure 7 shows the relation between soil loss and wind speed. The values over 10 minutes ranged from 0.12 to 11.84 kg/tray. Obviously, the soil loss was correlated with the wind velocity. As velocity increases the soil loss increases. The soil began to move at a wind velocity of 5 m/s. Therefore, the threshold velocity of Abou Lahu soil is 5 m/s. Above the threshold velocity, soil loss increases gradually up to 12 m/s, then increased rapidly. At low velocity, the power equation describes the relation between wind velocity and soil loss (Fig. 8), however, the linear model is better at velocities >12 m/s.

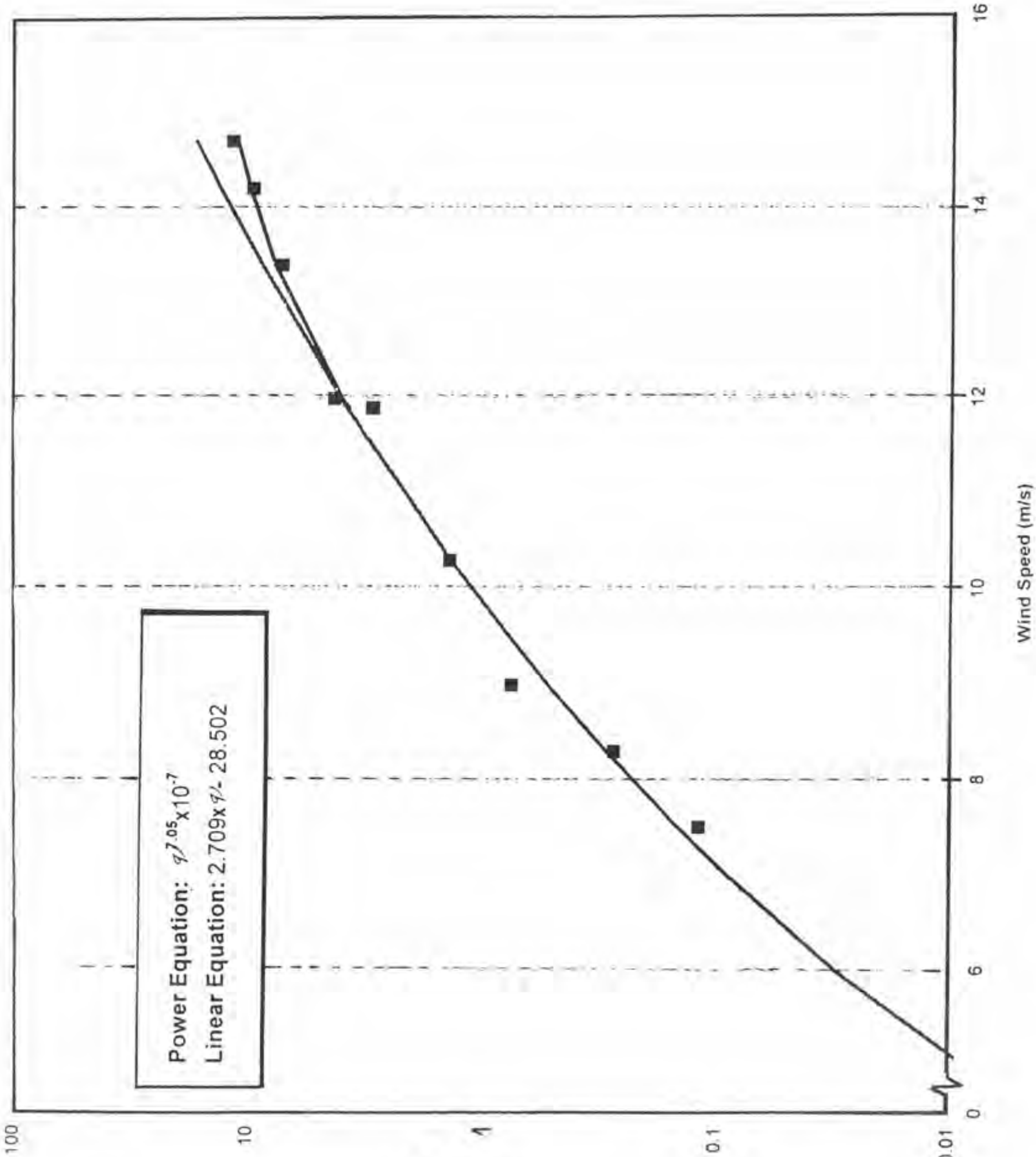



**Figure 7. Threshold velocity of Abou Lahu soil.**

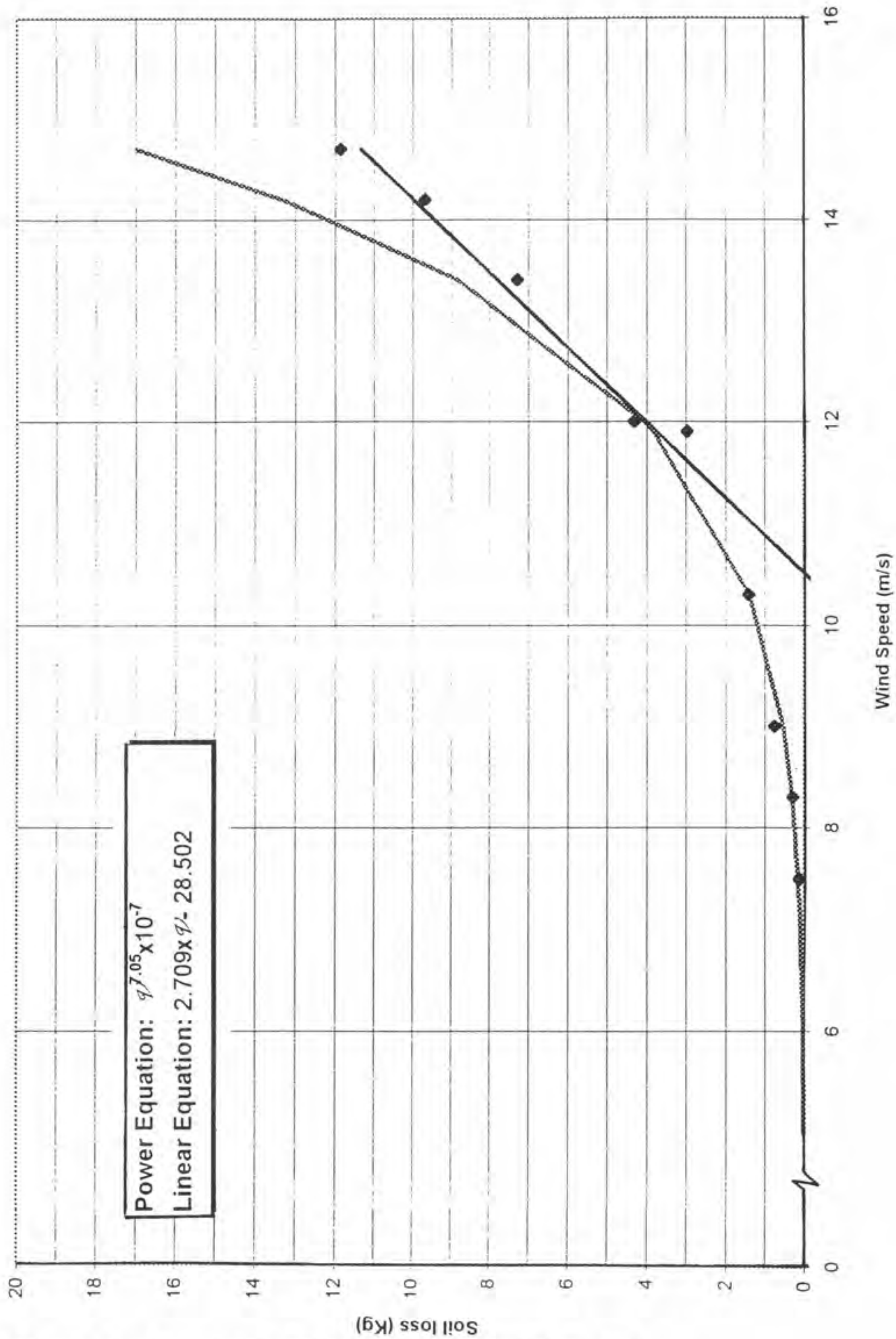



**Figure 8. Threshold velocity of Abou Lahu soil.**

## Discussion

The quantity of airborne material varied considerably among the sites in this study. The amounts of soil loss were 784, 3,161, and 86,192 kg/100 m width for bare soil at the Abou Lahu, El Shiekh Zowaied, and El Maghara sites during 93, 193, and 340 days, respectively. At each site the amount of collected soil decreased with increasing height, and the percentage of particles >0.1 mm increased with increasing height. The highest amount was obtained from bare soil at Site 3. Moreover, the amount of airborne material collected from bare soil was greater than from cultivated soil at both sites. This result is expected, because the vegetative cover protects the soil surface from wind action by reducing wind speed and by preventing much of the direct wind force from reaching erodible soil particles. It also reduces rates of erosion by trapping soil particles, which in turn, prevent the normal avalanching of soil material downwind (Woodruff et al. 1977). This result is in agreement with Dikkeh (1990), who showed that a protective plant cover decreases the rate of soil loss for various soil types by 60–70% compared to a bare smooth surface. Moreover, the cultivated soil was irrigated with a drip irrigation system that increases soil moisture, thereby influencing the susceptibility of soil to wind erosion. Saleh and Fryrear (1995) found that with a small increase in moisture content, a substantial increase in wind velocity is required to initiate soil movement. It is also clear that the reduction percentage of airborne material of cultivated soil at Site 3 was greater than that of cultivated soil at Site 2. This may be due to the roughness factor of cultivated soil at Site 3, which was greater than that at Site 2 (Tables 2 and 3). At all sites, the amount of airborne material ($g/cm^2$) decreased with increasing height. Such a relationship is in accordance with a logarithmic or power equation. The first was acceptable at Abou Lahu and El Maghara, and the second one was acceptable at El Shiekh Zowaied. However, Zobeck and Fryrear (1986) show that the relation between height and quantity of airborne material is best described by the equation $Y = a \times b$.

The particle size distribution of airborne material varies according to sampler height. Fine particles <0.1 mm were the biggest size at the 1 m height. This difference may be due to the type of particle movement, where the transport of fine particles <0.2 mm takes place in suspension (Morgan 1988). However, particles >0.1 mm decreased with increasing height as a result of the transport of these particles in saltation.

Nutrient and organic matter loss is one of the major hazards of wind erosion. Organic matter, total nitrogen, available phosphorus, and exchangeable potassium content in airborne material varied considerably among sites and heights (Tables 5 and 9). In all cases, the organic matter enrichment ratios increased with increasing sampler height (ranging from 1 to 16). This may be due to the small size and low density of such material. Similar results were obtained by Gile and Grossman (1979). In this respect, Woodruff et al. (1977) indicates that the most serious damage from wind erosion is the separation and gradual removal of organic matter from surface soils. The enrichment ratios of total nitrogen, available phosphorus, and exchangeable potassium were 0.8–5, 0.85–4.0, and 0.5–1.7, respectively. Hagen and Lyles (1985) report average enrichment ratios of 3.1, 2.3, and 1.7 for N, P, and K, respectively. In most cases, the enrichment ratio exceeds 1, indicating a greater amount of N, P, K, and organic matter in airborne material than in the parent soil. Therefore, wind erosion causes considerable losses in soil nutrients and organic matter, affecting soil productivity.

The results of laboratory wind tunnel studies show that soil loss is correlated with wind velocity. Similar results were obtained by Van de Ven et al. (1989). The low threshold velocity of the Abou Lahu soil indicates that the rate of wind erosion at the site is high.

## Conclusions

The results obtained in this study point to the selective removal of fine particles, organic matter, and nutrients in airborne material, and show that the relative rate of removal depends upon soil surface conditions. Moreover, the high percentage of particles <0.1 mm and the high concentrations of N, P, K, and organic matter in airborne material lead to degraded soil over a period of several years.

Future research is necessary for the successful planning of soil conservation measures to control wind erosion in Egypt.

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# West and Central Africa

# Extent and Severity of Wind Erosion in West and Central Africa

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## Abstract

The West African Sahel (WAS) is the transition zone between the Sahara desert in the north of Africa and the more humid Sudanian zones in the south. Although diverse in many ways, the WAS countries have in common a fragile agricultural sector, brought about by poor soil, limited rainfall, frequent drought, and wind erosion that accelerates soil degradation and desertification, compounded by rapidly growing populations. Erosive winds occur during two distinct seasons. During the dry season (October–April) the region is invaded by strong northeasterly winds, known as harmattan, resulting in moderate wind erosion. The second and most important wind-erosion period is the early rainy season (May–July), when rainfall comes with heavy thunderstorms that move westward through the Sahel. Wind erosion can be controlled by soil cover, such as a mulch of crop residue, soil roughening, and the reduction of wind speed by annual or perennial grass barriers, artificial barriers, strip cropping, and windbreaks. Based on the strong relationship between the incidence of wind erosion and soil properties, it may be possible to map the incidence of potential wind erosion in the West African Sahel, and hence tell farmers where ameliorative measures can be used to best advantage.

## Introduction

Arid, semi-arid, and dry sub-humid drylands (defined by aridity index criterion) cover 40% of the earth's land surface. Vast areas of drylands, perhaps as much as 70% (3.6 billion ha), suffer from some degree of degradation (Table 1), and roughly 30% (Fig. 1) are located in the West African Sahel (Grainger 1990).

**Table 1. Worldwide status of desertification (UNEP 1992).**

| Classification | Area (million ha) | Total dryland (%) |
|---|---|---|
| Rangelands with soil degradation | 757 | 14.6 |
| Rainfed croplands with soil degradation | 216 | 4.1 |
| Irrigated lands with soil degradation | 43 | 0.8 |
| Total drylands with degradation (GLASOD) | 1,016 | 19.5 |
| Rangelands with vegetation degradation only | 2,576 | 50.0 |
| Total degraded lands (ICASALS) | 3,592 | 69.5 |
| Non-degraded drylands | 1,580 | 30.5 |
| Total dryland (excluding hyper-arid deserts) | 5,172 | 100.0 |

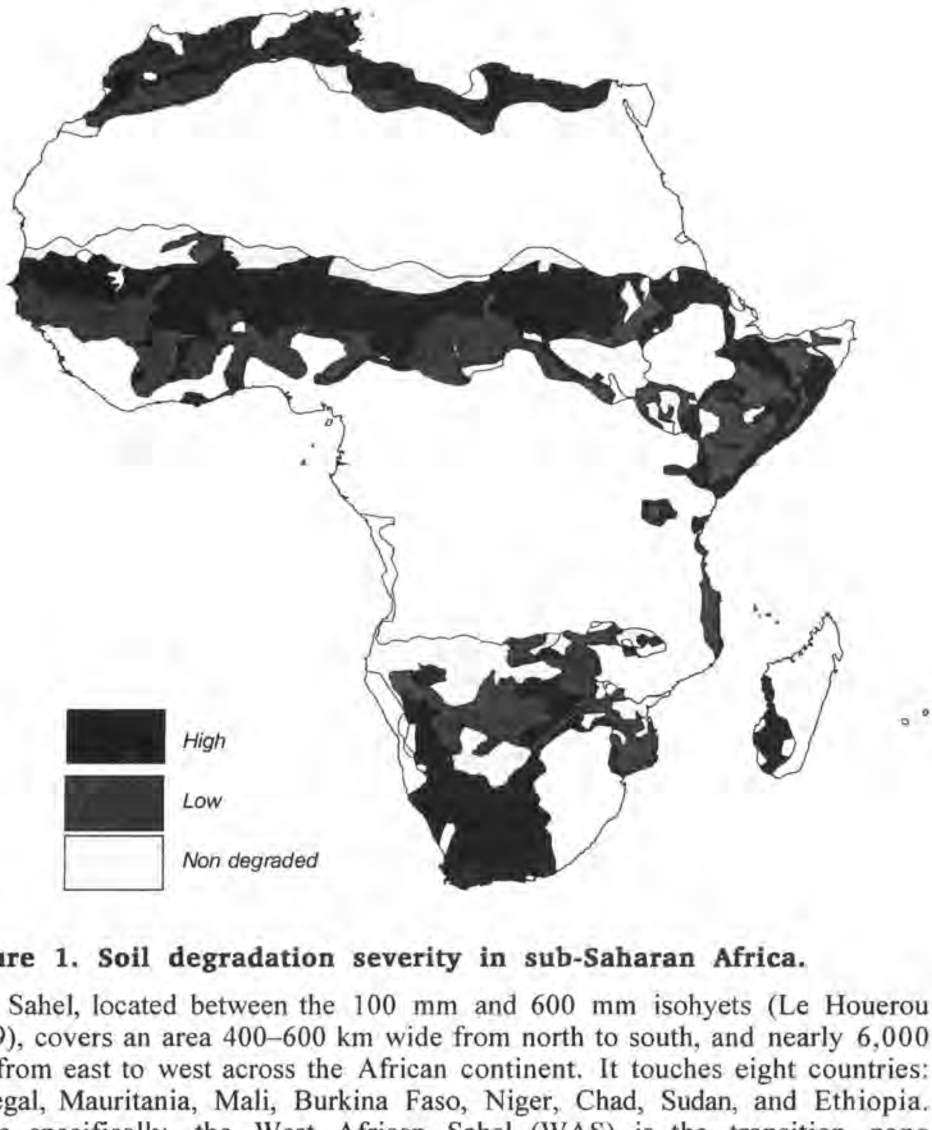



**Figure 1. Soil degradation severity in sub-Saharan Africa.**

The Sahel, located between the 100 mm and 600 mm isohyets (Le Houerou 1989), covers an area 400–600 km wide from north to south, and nearly 6,000 km from east to west across the African continent. It touches eight countries: Senegal, Mauritania, Mali, Burkina Faso, Niger, Chad, Sudan, and Ethiopia. More specifically, the West African Sahel (WAS) is the transition zone between the Sahara desert in the north of Africa and the more humid Sudanian Zones in the south (Lamers 1995). Although diverse in many ways, the WAS countries have in common the problem of a fragile agricultural sector (Table 2). This predicament is caused mainly by poor soils, limited rainfall, frequent drought, and wind erosion that accelerates soil degradation and desertification, compounded by rapidly growing populations (Table 2). The gross domestic product per capita is lower than US$ 500, except for Senegal (Table 2). The contribution of the agricultural sector to the GDP ranges from 31 to 43%, with Senegal (22%) as the only exception (FAO 1995).

**Table 2. Area, population, per capita income, and agricultural statistics in the nine countries participating in the DMI.**

| Country | Total Area (million ha) | Population | | | Fertilizer use (kg/ha) | Millet yield (t/ha) | Sorghum yield (t/ha) | Agricultural contribution to GNP (%) | Per capita income (US$) |
|---|---|---|---|---|---|---|---|---|---|
| | | Number (million) | Density (km²) | Growth (%) | | | | | |
| Burkina Faso | 27,420 | 10.0 | 34 | 3.1 | 2.9 | 0.64 | 0.89 | 41 | 321 |
| Chad | 128,400 | 5.8 | | | | 0.45 | | | 160 |
| Mali | 124,000 | 8.7 | 7 | 2.4 | 5.7 | 0.71 | 0.89 | 43 | 268 |
| Mauritania | 102,600 | 2.1 | | | | 0.19 | | | 480 |
| Niger | 126,700 | 8.7 | 6 | 3.4 | 0.8 | 0.35 | 0.18 | 31 | 262 |
| Senegal | 19,619 | 8.5 | 41 | 3.1 | 4.6 | 0.59 | 0.93 | 22 | 632 |

Sources: Crop Production and Area (FAO 1995); Fertilizers (Mokwunye and Vlek 1986).

The Sahelian soils consist of many different soil types. About 22% of the total area in the Sudano–Sahelian zone is occupied by arenosols (Sivakumar 1989). Most soils are sandy, often with low fertility (particularly phosphorus and nitrogen), humus content, and water retention capacities. Continuous cropping causes soil organic matter and plant-available nutrients to decline. Low fertility is often the major constraint for production of both food grains and natural vegetation, and there is increasing evidence for the use of phosphorus fertilizer to enhance agricultural development. Soils are very susceptible to wind and water erosion, and this forms an additional constraint to food production.

To restore soil fertility, farmers have traditionally kept land under bush fallow for 10–20 years. However, rapid population growth, at an annual rate of 3% in recent decades, has increased food demand. Instead of intensifying farming systems (for example, by using mineral fertilizers), farmers have tried to enhance production by expanding the cropped area. The previously sustainable fallow system has broken down, yields have declined, and marginal land, once used for communal grazing, is now cropped. Over-exploitation has resulted in land degradation, or desertification, on a large scale. Land degradation implies a reduction of resource potential by a single process or a combination of processes acting on the land. These processes include erosion by water and wind, crusting and hardsetting of soils, salinization and alkalinization, and long-term reduction in amount and diversity of natural vegetation (Valentin 1995).

The traditionally livestock-based rural production systems in the Sahelian zone have come under intense pressure through an interaction of factors including drought, population growth, and livestock herd dynamics (Sumberg and Burke 1991). In most of these countries, the forests has declined, and the arable land has also decreased during the past 15 years. Enhanced agricultural productivity requires improvements in input and product markets, rural institutions, and policies creating incentives at the farm level, together with new risk-reducing farming practices that also relieve seasonal labor demands.

Another great constraint for crop production is low and erratic rainfall (Michels 1994). The Sahelian region has a monomodal precipitation pattern, with rainfall between May and September, provoked by monsoon winds coming from the Gulf of Guinea and the northern movement of the intertropical convergence zone (ITCZ; Le Houerou 1989). The ITCZ represents the boundary between the hot, dry air from the Sahara of anticyclonic origin, and the cooler, moister air from the south, of maritime origin (Trewartha 1981). The front of the ITCZ slopes upwards towards the south at a very low inclination angle, since the slope is determined by the density contrast between both air masses.

At the northernmost reaches of the ITCZ, associated thunderstorms occur on an average of 10 days in the year. This number increases southwards, from 20–40 days in the west to 80 days in the Sudan (Martyn 1992 cited in Michels 1994). Wind storms in the Sudano–Sahelian zone are of short duration, less than one hour. During the dry season from November to April, continental northeastern winds, called harmattan, dominate. The average annual wind speed for Dakar is 7 m/s, and for Niamey it is less than 2 m/s (Sivakumar 1986). Air temperatures in the Sahelian zone vary between a mean annual minimum of 18 °C for and a mean annual maximum of 38 °C (Le Houerou 1989).

About 90% of the Sahelian population lives in villages, and is largely dependent on subsistence agriculture (Sivakumar 1989). Insufficient food production threatens the livelihood of the people in this region due to increasing soil degradation, which is often associated with wind erosion (Grainger 1990). Chronic hunger saps people's productivity and increases vulnerability to disease. Food security has deteriorated since independence in sub-Saharan Africa, and severe food shortages are now widespread. Food security at the household level is directly influenced by agricultural performance. In many countries, malnutrition is seasonal and increases before the harvest, when food supplies have dwindled. The gap in food intake widens further in years of drought. Recurrent famines in the 1980s graphically illustrate the high degree of food insecurity in the region (World Bank 1989).

In terms of energy value, food consumption in sub-Saharan Africa between 1965 and 1986 averaged 2,100 calories per person per day, or about 85 percent of recommended requirements. However, averaged over good and bad crop years, one quarter of the population obtains less than 80% of the daily calorie supply recommended by FAO and WHO. In drought and other bad years the undernourished population is even larger.

The Sahelian countries form a core area of food insecurity. To provide universal food security by 2020, action will be needed on both the demand and supply sides. On the demand side, public action will be necessary, especially for households with low or fluctuating incomes or purchasing power. On the supply side, improving agricultural production is imperative, because widespread access to food cannot be adequately ensured without agricultural growth.

Given the magnitude of the food gap, the West African Sahel is far from reaching that goal. Assessing the food needs of African countries up to 2020 for long-term planning is difficult. Such projections are based on assumptions about the prevailing levels of calorie consumption, future population growth rates, and future production performance. Projected food needs were estimated in a World Bank report (1989) under three alternative sets of assumptions:

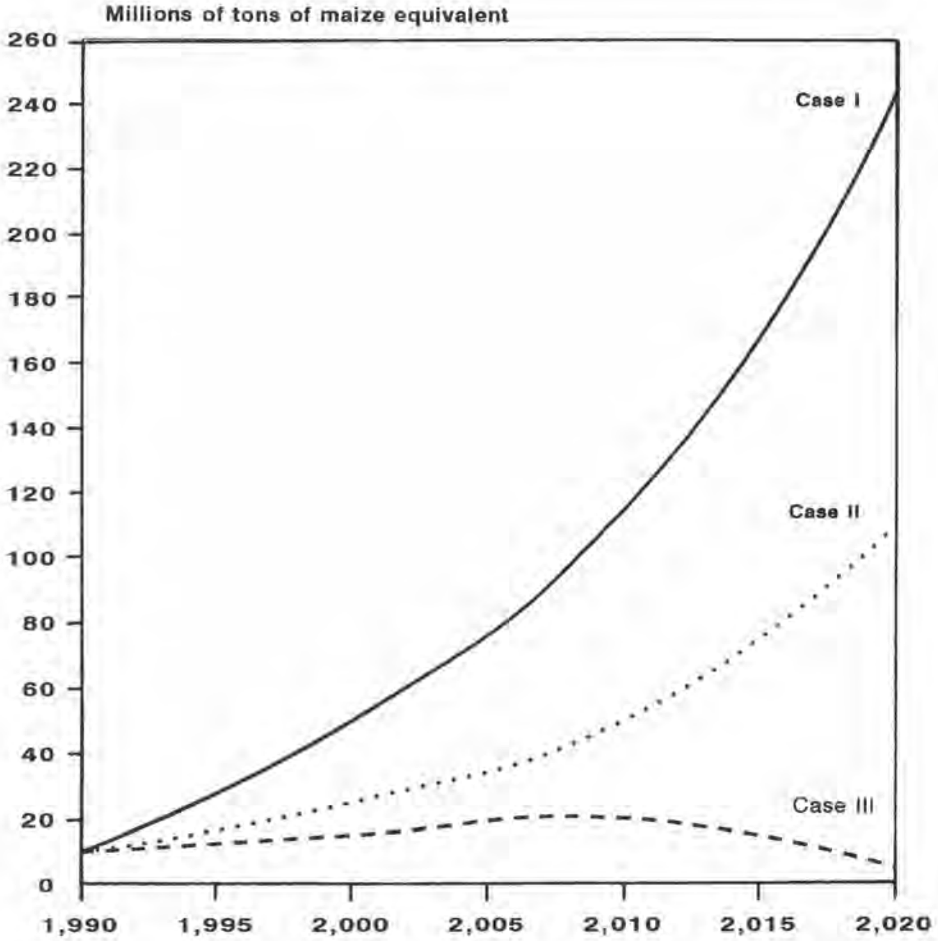
- Production grows at 4% a year, and population growth gradually declines to 2.75% between 1990 and 2020.
- Domestic production grows at 4% a year and population at 3.3%.
- Domestic food production and population grow at 2 and 3.3%, respectively.

These alternatives are shown in Table 3. The sharp widening of the food imbalance in the latter two cases (Fig. 2) shows how crucial it is to maintain a production growth of 4% a year and reduce population growth in order to ensure long-term food security throughout the region. In order to feed the growing population in these countries (even at a reduced growth rate), an increase in food production is necessary. This, however, can only be achieved through yield increases on land already under cultivation and thus, by protecting and conserving this natural resource, especially from wind erosion.

**Table 3. Population and food security in Sub-Saharan Africa, 1990–2020.**

| | 1990 | 2000 | 2010 | 2020 |
|---|---|---|---|---|
| *Case I* | | | | |
| 1. Population (millions) (constant fertility) | 500 | 700 | 1,010 | 1,500 |
| 2. Food production (mtme) (at current trend growth rate of 2% a year) | 90 | 11 | 135 | 165 |
| 3. Food requirement (mtme for universal food security by 2020) | 100 | 160 | 250 | 410 |
| 4. Food gap (mtme) | 10 | 50 | 115 | 245 |
| *Case II* | | | | |
| 1. Population (as in Case I) | 500 | 700 | 1,010 | 1,500 |
| 2. Food production (4% annual growth) | 90 | 135 | 200 | 300 |
| 3. Food requirement (as in Case I) | 100 | 160 | 250 | 410 |
| 4. Food gap (mtme) | 10 | 25 | 50 | 110 |
| *Case III* | | | | |
| 1. Population (millions) total fertility rate declining by 50% to 3.3 by 2020) | 500 | 680 | 890 | 1,110 |
| 2. Food production (mtme at 4% annual growth) | 90 | 135 | 200 | 300 |
| 3. Food requirement (mtme) | 100 | 150 | 220 | 305 |
| 4. Food gap (mtme) | 10 | 15 | 20 | 5 |

mtme=millions of tons of maize equivalent.
Source: World Bank data.




Note: Case I: a 2 percent annual growth rate in agricultural production and a constant fertility
Case II: a 4 percent annual growth rate in agricultural production and constant fertility ra
Case III: a 4 percent growth rate in agricultural production and a declining fertility rate.
Source: Word Bank data

**Figure 2. Projected food gap: alternative scenarios for sub-Saharan Africa (1990–2020).**

## Soil Transport

Wind erosion can become a problem whenever the soil is loose, dry, bare, or nearly bare, and the wind velocity exceeds the threshold velocity for initiation of soil particle movement (Fryrear and Skidmore 1985). In the Sahel, the farming systems and soil conditions are very favorable for wind erosion. Wind erosion is a set of processes that contribute to the motion of soil from its initiation until its final deposition.

The most comprehensive summaries on the movement of surface material by wind action were prepared by Bagnol (1941) for desert sands and by Chepil and Woodruff (1963) for agricultural lands. Wind erosion consists of initiation, transport (suspension, saltation, surface creep), abrasion, sorting, avalanching, and finally deposition of soil aggregates/particles (A/P). Soil transport by wind (Lyles et al. 1974). is commonly described in three distinct modes: suspension, saltation, and surface creep (Fig. 3).

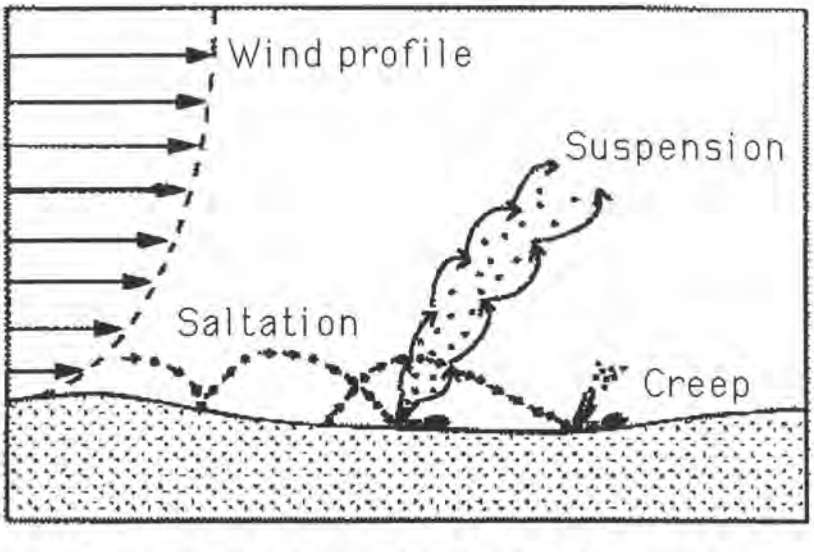



**Figure 3. Three modes of wind-blown particle transport.**

Particles transported by creep are too heavy to be lifted from the surface, and so they roll or slide along the ground. Particles transported by saltation are smaller than particles transported by creep. They move in a series of short hops at heights generally well below 1 m. The smallest particles move in suspension. These particles may be carried with vertical winds to great heights and are subject to long-range transport.

Under typical conditions, Hudson (1973) suggests that particle diameter varies from 0.5 to 2 mm for creep, from 0.05 to 0.5 mm for saltation, and is smaller than 0.1 mm for suspension. The overlap in diameters for suspension and saltation indicates that certain particles may be moved by different transport modes, depending on the particle density and the wind speed. So, the amount of material transported by the three modes depends on wind speed, particle density, and the texture of the topsoil. According to an estimate of Chepil (1945), the proportions vary from 50 to 75% in saltation, 3 to 40% in suspension, and 5 to 25% in surface creep. The smallest and slightest particles become suspended in the air stream and may be transported hundreds or thousands of kilometers.

Erosive winds that exceed the threshold wind-speed may occur during two distinct seasons (Sterk 1996). During the dry season (October–April), the area is invaded by dry and rather strong northeasterly winds, locally known as harmattan, that may result in moderate wind erosion (Michels et al. 1995a). The harmattan winds originate over the Sahara desert, and from January to March they usually carry large amounts of dust from remote sources. Part of the transported dust is deposited in the Sahel, enriching soils with nutrients. Dust deposits are particularly rich in sodium, potassium, magnesium, and calcium, but poor in phosphorus (Herrmann et al. 1996).

The second and most important wind erosion period is the early rainy season (May–July), when rainfall comes with heavy thunderstorms that move westward through the Sahel (Sterk 1996). Within a fully-developed thunderstorm, strong vertical downdrafts occur, causing a forward outflow of cold air that creates the typical dust storms of the Sahel. These events are usually short-lived, approximately 10–30 minutes, but the storms may result in intense soil movement (Michels et al. 1995a).

The major sources of present-day dust emissions are the subtropical desert regions and the semi-arid and sub-humid regions, where dry, exposed soil is subject to severe winds at certain times of the year. The major world dust-producing regions are located in the broad band of arid and semi-arid lands stretching from West Africa to North China, with the majority being in the Northern Hemisphere (Middleton et al. 1986). The Sahara Desert is the world's most important source of dust. The world-wide annual production of dust by deflation of soils and sediments has been estimated at 61–366 million tonnes (Hidy and Brock 1971). For Africa alone, it is estimated that more than 100 million tonnes of dust per annum is blown westward over the Atlantic (Middleton et al. 1986). The frequency of dust storms reaches a peak in regions receiving 100–200 mm of rain per year. As rainfall increases, the frequency of dust storms tends to decrease (Goudie 1978). Dust transported over long distances is composed of particles $<16$ µm in size, as only particles of that size can remain in suspension for long periods. Dust greatly decreases atmospheric visibility and may reduce the amount of incoming solar radiation by up to half that normally received at the ground surface when the air is clear. A persistent dust haze may therefore serve to reduce evapotranspiration rates.

## Aeolian Dynamics

The volume of sand moved by creep and saltation is a power function of wind velocity (Bagnol 1941). It is therefore highly sensitive to surface roughness and the presence or absence of vegetation or other obstacles, as well as antecedent precipitation.

The combination of areas of sand deflation, sand transport, and sand deposits detectable on satellite imagery allows for the concept of a Global Wind Action System (GWAS) in the Sahel (Maingret 1994). A GWAS is a dynamic aeolian system where, in a definite area, particles are imported and accumulated or re-exported as a consequence of wind activity. A GWAS can be an open or a closed system.

A closed GWAS is an area where particles are imported and accumulated but where export is negligible. An open GWAS is defined as a system where, after import and accumulation, particles can be re-exported out of the system. The Sahara, which exports its aerosols towards the north as far as Greenland, towards the east as far as Kazakstan, towards the south as far as the tropical forest of the Gulf of Guinea, and towards the west over the Atlantic Ocean as far as Bermuda and the Nordeste (Brazil), is the best example of an open WAS.

The whole Sahara is one aeolian unit which cannot be separated from the Sahel. Studied on a synoptic scale, the Sahara–Sahel is considered as an open WAS, which delivers sand by saltation from the Sahara to the Sahel, and airborne dust, known as aerosol, in suspension throughout the world. Western Africa is the actual southern limit of this WAS. The system is open and its deflation effects are visible in cultivated land to 13° 50' N.

## Wind-erosion Control Measures

The two flow charts (Figs. 4 and 5) illustrate the processes and feedback involved in the natural stabilization of active sand dunes and the mobilization of dunes following destruction of their vegetation cover (Tsoar and Moller 1986). Any attempt at ecological restoration of degraded dune fields (Wolfe and Nickling 1993) will need to take account of these feedback loops.

Wind erosion is most effectively controlled by reducing the wind velocity at the soil surface or creating a non-erosive soil surface. Wind velocities over large land masses cannot be controlled, but it is possible to reduce the wind velocity at the soil surface with standing vegetation, wind barriers, or non-erodible materials on the soil surface.

Standing vegetation is several times more effective in reducing wind erosion losses than the same quantity of vegetation lying flat on the soil surface (Siddoway et al. 1965). However, weeds must be controlled, and in many developing countries crop residues are utilized by livestock, so it is not always possible to leave vegetation standing for extended periods. In many cropping systems, the entire plant is harvested and no residue is available for controlling wind erosion in the field.

The major objective of a wind barrier is to reduce wind velocity over the greatest distance from the lee of the barrier. The effectiveness of wind barriers depends on the porosity and shape of the barrier to the prevailing wind. The barrier should have about 40% porosity (Chepil et al. 1963) to protect a distance about 10 times the height of the barrier and to reduce wind erosion along the wind direction for a distance about 20 times the height of the barrier

(Hagen 1976). Dense barriers have the greatest wind reduction adjacent to the barrier but shorter protected distance.

Non-erodible elements are material on the soil surface that will not be moved or transported by erosive winds. These include stable soil aggregates, gravel, rock fragments larger than the maximum size that can be transported by wind, and even large sections of un-decomposed plant material. If 30% of the soil surface is covered with non-erodible material, soil loss is reduced by 80%.

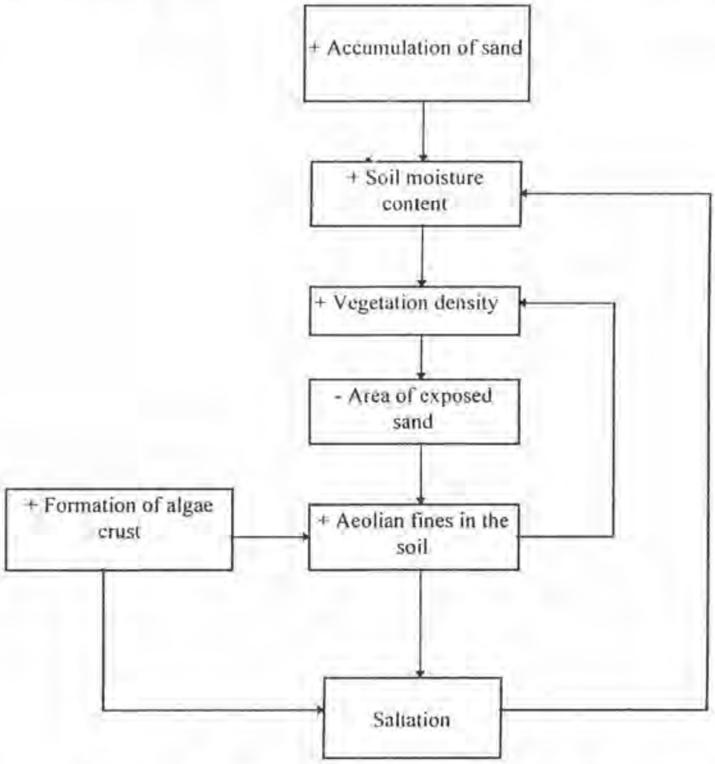



**Figure 4. Flow chart of the processes and positive feedback of the natural stabilization of desert sand dunes. (+) indicates an increase and (-) indicates a reduction (Tsoar and Moller 1986).**

A ridged soil surface reduces wind erosion losses on most soils. The larger the ridge the greater the reduction in soil loss, except for deep sands. Tillage will not control wind erosion on deep sands because the ridges are unstable after rainfall or irrigation.

Wind erosion during crop establishment can destroy young seedlings, reduce crop quality, or delay crop growth. All crops are not equally susceptible to wind damage. As crops mature, their susceptibility to wind damage decreases.

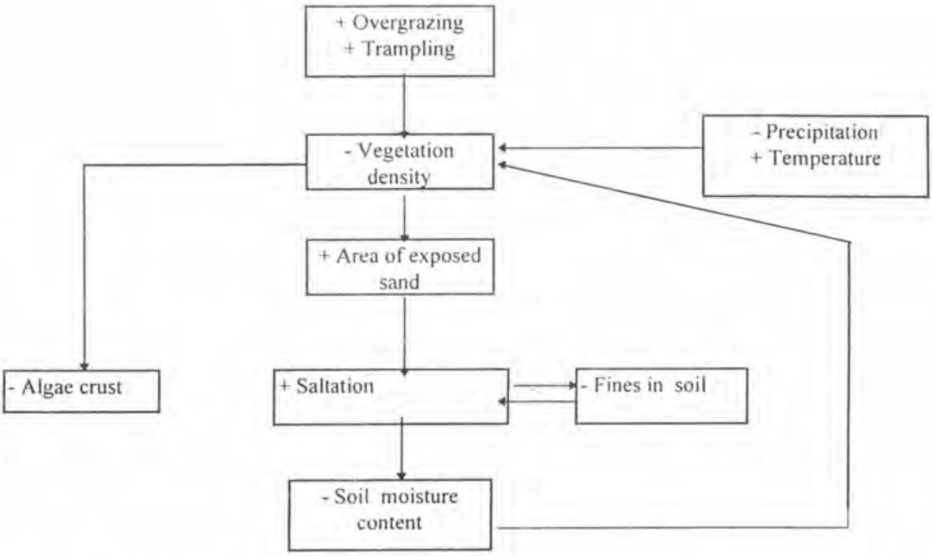



**Figure 5. Flow chart of the processes and positive feedback following the destruction of vegetation on desert sand dunes (Tsoar and Moller 1986).**

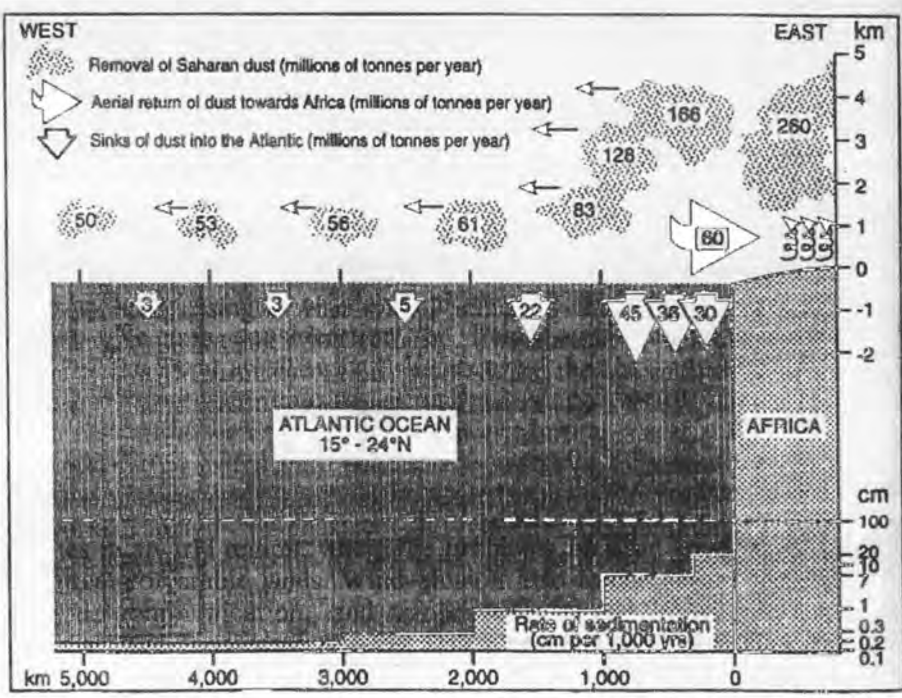



**Figure 6. Aeolian sand budgets for the Sahara. Barbados is roughly 5,000 km west of Dakar (after Middleton et al. 1986).**

## Conclusions

Aeolian translocation of soil material and sediments is a natural process in the arid and semi-arid regions of West Africa. It affects the properties, productivity, and constraints of the soils and ecosystems in the region.

Wind erosion is a major form of land degradation in the West African Sahel. It can be controlled by soil cover, such as a mulch of crop residues, soil roughening, or by the reduction of wind speed by annual or perennial grass barriers, artificial barriers, strip cropping, and windbreaks. The various control techniques can be used according to the scope of the problem. Their relative efficiency depends on: the susceptibility of the soil to wind erosion; drought, which can cause a reduction in vegetation; the prevailing wind direction, which is particularly important when establishing barriers; and the physical properties of the soil, which determine the susceptibility to wind erosion and suitable soil tillage techniques. Therefore the strong relationship between the incidence of wind erosion and soil properties suggests that it is possible to map the incidence of potential wind erosion in West Africa, and hence indicate to farmers where ameliorative measures can be used to best advantage.

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# Wind Erosion Research in Niger: The Experience of ICRISAT and Advanced Research Organizations

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## Abstract

In the Sahelian zone of Niger, wind erosion constitutes one of the major causes of land degradation. This results from low vegetation cover at a time when the most erosive winds are blowing in combination with sandy, easily erodible soils. Through their effect on soil cover, overgrazing by cattle and the rapid expansion of agricultural land have further enhanced the impact of wind erosion on the Sahelian agro-ecosystem. Wind-erosion-induced damage includes direct damage to crops through sandblasting, seedling burial following sand deposition, and topsoil loss. Although seedling burial can substantially impact crop yield in individual years, the loss of topsoil is by far the more worrying consequence of wind erosion because of its potentially long-term effect on the soil resource base. Available data indicate that several tens of tonnes of topsoil and tens of kilograms of plant-essential nutrients per hectare can be lost to the wind in just a few storms under favorable conditions. However, simple and effective wind-erosion control techniques have been developed to reduce or even arrest wind-induced land degradation. The extent of wind erosion in Niger, as well as the efficiency of various control techniques such as ridging, surface mulch, and wind breaks, are discussed here.

## Introduction

Wind erosion is one of the main factors contributing to land degradation in the semi-arid tropics. It has been estimated that in the arid and semi-arid zones of the world, 24% of cultivated land and 41% of pasture land are affected by moderate to severe land degradation from wind erosion (Rozanov 1990). Within these climatic zones, the Sahel is considered to suffer from particularly acute wind erosion problems (UNEP 1992).

In the Sahelian zone of West Africa, the rapid population growth of recent decades has lead to a rapid increase in cultivated area, the expansion of agriculture into more marginal areas, and an increased pressure on land as a result of grazing and deforestation. Consequently, the area of soil left bare, and therefore directly exposed to wind, has increased considerably. In the case of Niger in particular, the effect of these changes in land use on wind erosion is aggravated by the very nature of the soil, which is frequently poorly aggregated and sandy, offering little resistance to wind erosive forces.

Wind-erosion-induced damage includes direct damage to crops through sandblasting, burial of seedlings under sand deposits, and loss of topsoil (see, e.g., Fryrear 1971; Ambrust 1984; Fryrear 1990). The first two types of damage have an immediate effect on crop yield. However, the loss of topsoil is particularly worrying, since it potentially affects the soil resource base and hence crop productivity on a long-term basis, by removing the layer of soil that is inherently rich in nutrients and organic matter. Analysis based on the nature of sand formations in the Sahara and its Sahelian fringe indicates that most of the Sahel is presently a zone of net deposition of wind-transported material (Mainguet 1990). However, because of the diffuse nature of the phenomenon, accurate mass balances on a regional scale are difficult to estimate. Furthermore, as the degradation process proceeds, these balances may be reversed. Mainguet (1990) and Mainguet and Chemin (1991) observed local changes in sand formations and in the particle size distribution of the sand fraction, indicating a shift from net deposition to net soil loss by wind erosion.

Although regional estimates of wind erosion provide valuable information for the global assessment of degradation and the evaluation of off-site impact, such large-scale approaches do not provide information on wind-mediated transfers of soil on the field scale. These transfers of soil within fields or between fields and surrounding land over distances ranging from a few meters to a few kilometers have important repercussions for crop production and for the subsistence farmers living off the land (Sterk et al. 1996). Indeed, these processes may not only result in more rapidly declining yields, but also enhance field-scale variability through the redistribution of soil material (Scott-Wendt et al. 1988), or promote other land degradation processes such as water erosion by increasing the aerial extent of surface crusts.

The importance of wind erosion in the process of land degradation in the Sahelian zone of West Africa was recognized early by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). Starting in 1985, a long series of studies on wind erosion and control measures was initiated, frequently in collaboration with other advanced research organizations, at the ICRISAT Sahelian Center (ISC) in Sadoré, Niger. This paper provides an overview of past collaborative research at ISC, and ongoing research projects in wind erosion by scientists from ICRISAT and other international institutes.

## Physical Environment

### Rainfall

The climate in the Sahelian zone of Niger is to a large extent regulated by the seasonal fluctuations of the Intertropical Convergence Zone (ITCZ). The

ITCZ travels north and south in response to the apparent movement of the sun. Rainfall generally follows the passage of the ITCZ, with most rainfall falling in a 75–90 day period from June to September. Rainfall ranges from 300 mm in the northern Sahelian zone to 600 mm at its southern limit. Rainfall is highly variable in time and space (Sivakumar et al. 1993) and often comes in the form of convective storms. In Niamey, the average monthly maximum (daytime) temperature ranges from 33 °C in January to 41 °C in April. PET at Niamey amounts to 2,294 mm per year and exceeds rainfall in all months except August (Sivakumar et al. 1993).

Rainfall is frequently preceded by strong winds lasting from a few minutes to an hour, with maximum wind speeds seldom exceeding 15 m/s (Table 1; Michels et al. 1995b). A prolonged dry season lasts from October to May. Periods of dry easterly harmattan winds loaded with fine dust dominate from October to March. Harmattan wind speeds are lower than for the convective storms, usually less than 7 m/s (Michels et al. 1995b). From April to the start of the rainy season, one observes a mixture of easterly harmattan winds and southwesterly monsoon-type winds. Total sand flux during the dry season, measured at 0.1 m above the soil surface, constitutes less than 15% of the total annual sand flux (Michels et al. 1995b).

**Table 1. Duration and maximum wind speed registered for wind storms during the 1992 rainy season (Michels et al. 1995a).**

| Date | DAE | Wind storms | | |
|---|---|---|---|---|
| | | Duration (min) | Duration >6 m/s (min) | Maximum speed (m/s) |
| 6 May | | na | na | na |
| 12 May | | 35 | 9 | 7.0 |
| 24 May | | 56 | 7 | 9.5 |
| 25 May | | 4 | 3 | 6.7 |
| 28 May | | 19 | 16 | 13.6 |
| 1 June | 2 | 69 | 57 | 19.6 |
| 4 June | 5 | 64 | 37 | 11.3 |
| 13 June | 14 | 42 | 11 | 7.8 |
| 14 June | 15 | 12 | 7 | 7.2 |
| 20 June | 21 | 41 | 37 | 8.9 |
| 24 June | 25 | na | 0 | 5.8 |
| 2 July | 33 | 28 | 25 | 10.3 |
| 18 July | 49 | 75 | 47 | 8.1 |
| 27 July | 58 | 18 | 18 | 9.7 |
| 31 July | 62 | 154 | 34 | 13.3 |

## Soil and Vegetation

A wide diversity of soils is found in Niger. However, arenosols—deep sandy soils—occupy by themselves 43% of the land used for agro-sylvo-pastoral activities in the Sahel of Niger (100–600 mm; FAO 1973). These soils typically contain >85% sand, have a particulate structure, especially in the surface horizon, and low organic matter content. Water-holding capacity is low, and the infiltration rate is high in the absence of surface crust. As a result, the soil surface dries out rapidly, rendering it sensitive again to wind erosion very soon after rainfall. At ISC, soils belong to the order of arenosols. They have developed from aeolian sandy deposits. In the A-horizon, they typically contain 3% clay and 90% sand, of which 95% is between 0.05 and 0.5 mm (West et al. 1984). Organic C is generally less than 0.3%. The rainfall and temperature of the Sahel lead to the development of an open savanna of grasses and low bushes, scattered with individual trees. At the end of the dry season, the vegetation cover is often very low, as a result of the prolonged dry season and grazing by cattle.

## Farming Systems

In Niger, as in most of the Sahel, decision making by farmers concerning the management of their agricultural land is largely governed by the need to ensure short-term food sufficiency at the household level. Agriculture has therefore remained extensive in nature, with low levels of external inputs. Fertility maintenance relies heavily on the practice of fallowing, with additional inputs of nutrients from cattle feces.

Millet or millet-based intercropping occupies 90% of the agricultural land. Yield in Niger over the 1989–1991 period averaged 340 kg grain/ha and approximately 1,200 kg straw/ha (Baidu-Forson and Williams 1996). Land preparation is minimal, other than the clearing of vegetation and sometimes the burning of crop residue. At the start of the rainy season, residue levels seldom exceed 500 kg/ha as a result of grazing, decomposition by termites, or their use as construction or fencing material (Lamers and Buentrup 1996). However, farmers sometimes consciously concentrate crop residues in order to reclaim low productivity areas in their fields. The trapping of wind-blown sediment by residue is thought to contribute to the reclamation process (Chase and Boudouresque 1987; Lamers and Feil 1995; Léonard and Rajot, 1997).

Millet is generally sown with the first good rain. The low planting density (3,000–5,000 hills/ha) and low levels of surface residue mean that the soil is left with little or no protection against wind erosion for several months before planting and for at least 6–8 weeks after the start of the rainy season. Manual weeding is practiced 1–3 times per season, which further reduces surface roughness and accelerates surface drying. The traditional sowing practice, which consists of throwing 20–40 seeds into a shallow hole dug with a hand-held hoe before closing it with the foot, leaves behind small depressions which favor sand accumulation and burial of the seedlings.

## Research Highlights

### Soil and Nutrient Loss and Deposition

Research on the extent of soil and nutrient transfers through wind-blown sediment in Niger has focused on two main areas: 1) the quantification of vertical particle flux, mainly dust deposition, and 2) the measurement of horizontal soil flux across fields by the combined processes of saltation and suspension.

### Dust transport

Dust refers to particles <60 mm in equivalent diameter. This fine fraction is often rich in mineral elements. Because of their small size, dust particles are transported by suspension in the air and are susceptible to being carried by wind over considerable distances. The quantification of dust uplifting, transport, and deposition in areas prone to dust storms is therefore important in view of the potentially significant contribution of this sized fraction to the nutrient balance of the agro-ecosystems.

Two studies on dust deposition have been reported in Niger since 1985 (Drees et al. 1993; Herrmann et al. 1996). An additional study was initiated in 1995 by ORSTOM in Banizoumbou, Niger, 60 km east of Niamey. All three studies made use of passive dust catchers to quantify dust deposition rates. The catchers comprise boxes (that open horizontally) placed a few meters above the ground. The measured total annual deposition of dust particles in the region of Niamey ranges from 740 to 1,640 kg/ha/yr (Table 2). There was a tendency towards a decrease in the annual deposition rate over the 1985–1996 period.

**Table 2. Annual deposition rate of dust in the region of Niamey, Niger, and percentage deposited between mid-April and mid-July (early Monsoon period).**

| Year | Annual deposition (kg/ha ) per year | Early monsoon (% of annual) |
|---|---|---|
| 1985–1986[†] | 1,640 | 50 |
| 1992[‡] | 1,250 | 58 |
| 1993[‡] | 820 | 50 |
| 1994[‡] | 760 | 59 |
| 1996[§] | 740 | 49 |

[†]ISC (Drees et al. 1993).
[‡]ISC (Herrmann 1996).
[§]Banizoumbou, unpublished.

Between 21 and 40% of the annual dust deposition occurs between mid-October and mid-April. The main deposition events during this period result from the passage of dust clouds carried by harmattan winds, which often last for several days. Forty nine to fifty nine percent of the annual dust deposition occurs between mid-April and mid-July, as a result of monsoon winds and the passage of convective storms (Table 2). As opposed to the harmattan dust storms, these deposition events last for less than one day. Herrmann et al. (1996) found that, on average, over 11 storms, 60% of dust deposition during the rainy season, occurs as rainout, i.e., as a result of dust trapping by raindrops.

On the basis of the mineralogical composition of dust samples, Herrmann et al. (1996) conclude that airborne dust during the harmattan events originates in Tchad, south of the Tibesti mountains. Furthermore, he observes that the <63 mm fraction (potential dust fraction) of the top 3 cm of the soil has a similar mineralogy and silt/clay ratio to the harmattan dust, and is markedly different from the fine fraction of the B-horizon. This similarity between the potential dust fraction of the soil and the harmattan dust provides evidence for the occurrence of net deposition of dust during the harmattan season (Herrmann et al. 1996). Total elemental chemical analysis shows that the nutrient content of the potential dust fraction of the top 3 cm of the soil is comparable to the dust fraction collected after the passage of convective storms (Table 3). It is, however, poorer in nutrients than the dust deposited during harmattan dust storms, probably as a result of weathering and leaching during the rainy season. These findings suggest that most of the dust caught during the rainy season is remobilized locally during the convective storms.

**Table 3. Element content of dust and clay + silt fraction (<63 μm) of soil at Sadoré, Niger (Herrmann et al. 11996).**

| | | Na (%) | K (%) | Ca (%) | Mg (%) | P (mg/kg) |
|---|---|---|---|---|---|---|
| Harmattan dust | Jan. 1992 | 0.46 | 1.58 | 1.91 | 0.77 | 638 |
| Convective storm dust | June 1992 | 0.13 | 1.03 | 0.38 | 0.3 | 389 |
| Surface soil | 0–3 cm† | 0.11 | 1.15 | 0.25 | 0.32 | 660 |
| Subsoil | 38–60 cm† | 0.15 | 0.55 | 0.05 | 0.12 | 377 |

†Sampling depth.

Herrmann (1996) demonstrates the existence of a strong north–south gradient in dust deposition rates, from 1,560 kg/ha per year at Ouallam (14° 19' N) to 620 kg/ha per year at Tara (11° 55' N), i.e. a southward gradient of approximately -3 kg/ha per year per kilometer. The author attributes the decrease in dust load to the gradual deposition of dust particles by gravitational settling as the distance from the dust source increases. This process is mostly applicable during the harmattan season, when the dust travels over large distances. In addition, during the rainy season, the intensity of deposition is closely linked to the number and severity of convective storms, both of which decrease southward.

On the basis of the total elemental chemical analysis of dust and rainwater, it was estimated that an average of 12.7, 16.3, 5.3, and 0.7 kg/ha of K, Ca, Mg, and P, respectively, could be deposited annually as a result of dust deposition at Sadoré, Niger (13° 15' N). Most of this is deposited as solids, except for Ca, for which 58% of the deposition occurs in dissolved form. By comparison, a millet crop of 2,000 kg/ha straw and 600 kg/ha grain requires approximately 60 kg K/ha and 5 kg P/ha (Buerkert 1995). Hence, if all dust trapped in the passive dust catchers were effectively deposited at the soil surface without further re-entrainment, the input of nutrients through dust would amount to about 20% of the mineral requirement for the production of a good millet crop.

Little data exists on the extent of re-entrainment of fine particles by wind. Rajot et al. (1996) measured vertical fluxes of dust particles from a bare field during a single monsoon wind event prior to the start of the rainy season. They estimated losses at 2 kg dust/ha. In the absence of subsequent rain, this fine sediment can potentially be transported over long distances. Furthermore, since no rain occurred prior to the measurement, one may assume that a large fraction of this entrained sediment corresponds to recently deposited dust. Although the calculated value would indicate rather low rates of re-entrainment, further measurements are required for a better evaluation of this term.

The studies of Herrmann et al. (1994) point to the existence of close interactions between the processes of dust deposition and crust formation. Indeed, the authors observe higher silt contents in the top 3 cm than in the immediately underlying layers. On these sandy soils, crust formation is very sensitive to small changes in silt + clay content. Hence, dust deposition may enhance crust formation on these coarse-textured soils. At the same time, crust formation leads, in its initial stage, to a segregation of particles in the top few millimeters of the soil, leaving the sand particles at the surface (Bielders and Baveye 1996). This particle segregation process induced by drop impact can in turn favor the subsequent entrainment of sand particles by wind.

## Soil transport

In this section, we discuss the transport of soil irrespective of particle size, by the combined processes of creep, saltation, and suspension. However, because of the texture of the soil considered here, the bulk of the mass transport relates to particles >60 mm. In all cases the data presented refers to horizontal fluxes of sediment.

Earlier studies on wind erosion were restricted to measurement of the intensity of horizontal flux of airborne sediment as affected by specific surface conditions (see, e.g., Banzhaf et al. 1992; Buerkert et al. 1995; Michels et al. 1995b). Since the experimental setup did not allow for any mass balance calculations to be made, such data cannot be used to calculate actual soil losses by wind erosion. More quantitative data has been obtained from measurements of changes in surface elevation of plots exposed to wind action. After a four year period, Renard and Vandenbeldt (1990) found a difference in elevation of 150 mm between adjacent bare millet plots and plots planted with the perennial grass *Andropogon gayanus*. Similarly, Geiger et al. (1992) observed height differences of 150 mm between bare millet plots and plots that received 2 t/ha of millet stover over five years. For both these studies, one cannot distinguish between the respective contribution of erosion and deposition to the measured changes in elevation, since only relative height difference was measured. Michels et al. (1995b) and Buerkert et al. (1996) carried out repeated measurements of surface topography over time on the same plots. Michels et al. (1995b) reports an average decrease in surface elevation of 33 mm in bare millet plots after 1 year. The data need to be interpreted with caution, however, as the number of elevation measurement points was very low. Between mid-September and the end of July 1994, Buerkert et al. (1996) measured a change in elevation on bare millet plots of 12 mm, equivalent to a soil loss of about 190 t/ha. The measured soil losses are, however, the result of the combined action of wind and water erosion, the control plots having developed extensive erosion crusts over time.

Probably the most accurate estimates of soil loss by wind erosion for Sahelian conditions have been reported by Sterk and Stein (1997), following intensive monitoring of soil mass flux at 21 locations in a 40 × 60 m experimental plot covered with a 0.8 t/ha millet stover mulch. Using geostatistical procedures, they derived precise estimates of incoming and outgoing horizontal mass transport rates. Mass balance calculations revealed a total soil loss of 45.9 t/ha during four convective storms (Table 4). Soil losses of similar magnitude were measured in an on-farm experiment at Banizoumbou, Niger. Based on measured soil fluxes between 0 and 35 cm above ground on bare plots, we have estimated from mass balance calculations that at least 55 t soil/ha were lost during the 1995 rainy season (Fig. 1) and 24 t soil/ha during the 1996 season. Using the $^{132}Cs$ technique, Chappell et al. (1996) estimated soil erosion losses on sandy plains close to Banizoumbou at 50.3 t/ha per year over the last 30 years. Although wind erosion may have contributed significantly to the total soil loss, one cannot estimate its contribution precisely, since the $^{132}Cs$ technique does not discriminate between losses by wind or water erosion.

**Table 4. Calculated soil and nutrient losses during four storms in 1993 (Sterk et al. 1996).**

| Date | Soil loss (t/ha) | N loss (kg/ha) | P loss (kg/ha) | K loss (kg/ha) |
|---|---|---|---|---|
| 13 June | 12.5 | 4.9 | 0.9 | 11.2 |
| 27 June | 2.0 | na | na | na |
| 30 June | 4.6 | na | na | na |
| 1 July | 26.8 | 13.4 | 5.2 | 45.9 |
| Total | 45.9 | 18.3 | 6.1 | 57.1 |

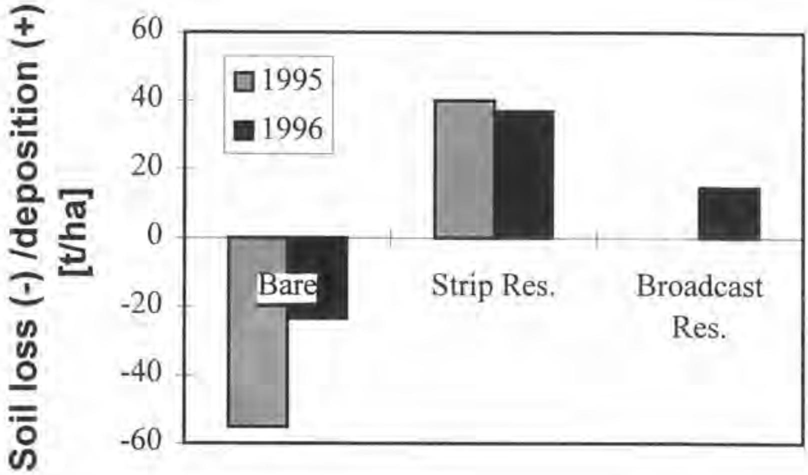


**Figure 1. Total soil loss or deposition during the 1995 and 1996 rainy seasons at Banizoumbou, Niger, on bare plots and plots with 2 t/ha of millet stover mulch applied either in strips or broadcast (1996 only). Stover was applied at the start of the season.**

The above data provide strong evidence of extensive losses of soil for bare fields directly exposed to the erosive action of wind. However, the reported rates of soil erosion by wind may represent extremes, since they were measured on bare plots devoid of any crop residue. In practice, in farmer fields, residue levels at the start of the rainy season are generally of the order of 0.3 to 0.5 t/ha. However, such low levels of crop residue may have very little impact on the intensity of soil erosion by wind, especially at high wind velocities (Michels et al. 1995b; Sterk 1997).

For the sandy soils considered here, one can assume that most of the mass transport by wind occurs through creep and saltation. Such processes are effective only over relatively short distances. Changes in surface roughness such as a transition from cultivated to fallow land, or variations in the surface mulch, could have a large effect on mass transport and even shift the mass balance from erosion to deposition. Reports on the occurrence of soil deposition are mainly limited to cases with high levels of crop residue mulch. For instance, Léonard and Rajot (1996) observed sand accumulation of up to 50 mm over two years in small degraded plots covered with 10 t/ha of grass straw and small branches. Recent measurements on fallow land at Banizoumbou, Niger confirm the very low horizontal soil flux compared to millet fields (Bielders, unpublished data). These observations emphasize that, on a mass basis, wind erosion on sandy soils consists in a local redistribution of soil material on the field scale. Despite the short-range transport, this process cannot be considered negligible because of the strong impact such soil loss may have on field-scale crop productivity. Once degraded, it may be virtually impossible, within the means accessible to farmers, to reclaim degraded land. Furthermore, as opposed to soil, nutrient transport is not restricted to local redistribution, since a large fraction of the total nutrients is present in the fine sediment, which can travel in suspension over large distances.

Sterk et al. (1996) provide the only estimates of nutrient loss by wind erosion for Niger. For the experiment described above, they calculated nutrient flux based on the nutrient content of the trapped sediment for the two largest storms. The results show a total loss of 57.1 and 6.1 kg/ha of K and P, respectively (Table 4). These amounts are roughly equivalent to the quantity of K and P required to produce a millet yield of 2,000 kg straw and 600 kg of grain/ha. They also correspond to approximately 3% of the nutrients contained in the top 10 cm of the soil. Over the same period, Sterk et al. (1997) measured nutrient inputs of 2.5 and 0.2 kg/ha of K and P, respectively, from dust deposition. This study emphasizes the potentially dramatic negative impact of wind erosion on soil productivity.

## Crop Damage

Direct damage to crops during sand storms can result in the loss of plant tissue and reduced photosynthetic activity as a result of sandblasting, or in the burial of seedlings by deposited sand. These aspects were studied for millet under field conditions at ISC and in wind tunnel experiments at the USDA Wind Erosion Laboratory in Manhattan, Kansas.

Michels et al. (1995a) report on the effect of wind speeds ranging from 8 to 14 m/s, and sand fluxes ranging from 0 to 42 g/m per second on millet growth and photosynthetic activity in a wind tunnel experiment. Plants were exposed for 15 minutes at 8 days after emergence (DAE), 16 DAE, or on both dates. The authors observed that millet survival was 100% in all cases, indicating a much higher tolerance of millet against sandblasting damage than for other crops (Fryrear 1971; Fryrear and Downes 1975). However, sandblasted plants saw their viable leaf area reduced by an average of 19% across all treatments at 21 DAE, compared to the control. New leaves were observed to grow rapidly after exposure, and at 57 DAE no significant difference could be found between twice-exposed plants and the controls. In addition to the loss of viable leaf area, sandblasting affected photosynthesis in the viable parts of the leaves (Michels et al. 1995a). The photosynthetic activity of viable leaves for plants exposed 8 DAE was reduced by an average of 55% one hour after exposure, and was still reduced by 28% four days later. Exposure to sandblasting also reduced millet dry weight at the early stages of development. At 57 DAE, the dry weight of plants exposed once was not significantly different from the control. Plants exposed twice had 5% less dry matter than once-exposed plants.

No final harvest data are available for the above experiment. However, the data indicate that, under optimal recovery conditions, millet has a good ability to recover from losses in viable leaf area and reduced photosynthetic activity induced by sandblasting. Brenner (1991) similarly reports reduced leaf area and dry matter production of young millet plants as a result of sandblasting during violent storms. However, at 46 days after sowing the crop had entirely recovered from these stresses.

As a result of the traditional sowing technique, which leaves behind small depressions, burial of seedlings under deposited wind-blown sand frequently occurs during convective storms, sometimes necessitating partial or total resowing of the crop. In a 1990 field experiment sown in the traditional way, 90% of millet hills were covered by sand 23 DAE, which necessitated re-sowing and therefore increased the risk of exposure of the crop to an end-of-season drought (Fig. 2; Michels et al. 1993). Hence, the most extensive damage to crops in that experiment resulted from burial. However, for those hills that were not entirely covered by sand, the number of leaves per plant and LAI were significantly higher throughout the season for unburied plants than for plants that had been partially covered. Final grain yield was reduced by half for partially covered hills, from 0.57 to 0.3 t/ha (Fig. 3), which was largely attributable to a lower average number of grains per panicle.

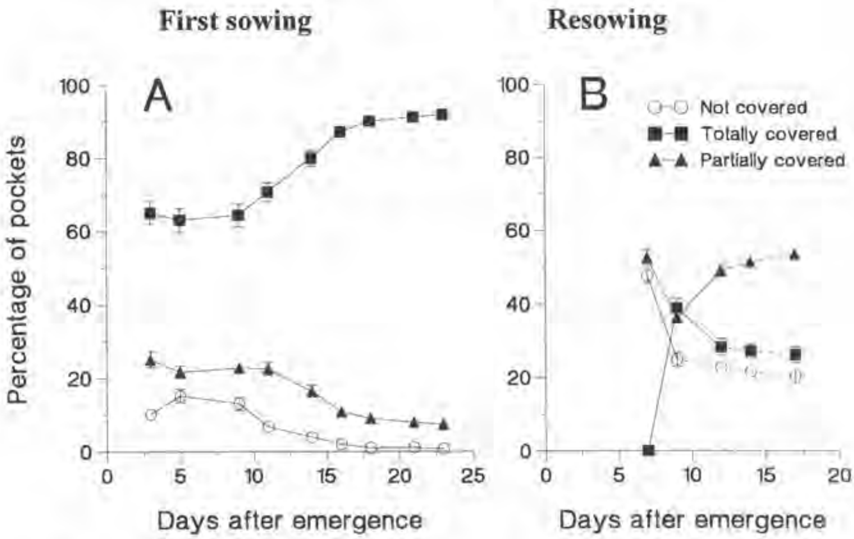


**Figure 2. Coverage of millet pockets with soil during the 1990 rainy season at ISC (Michels 1994).**

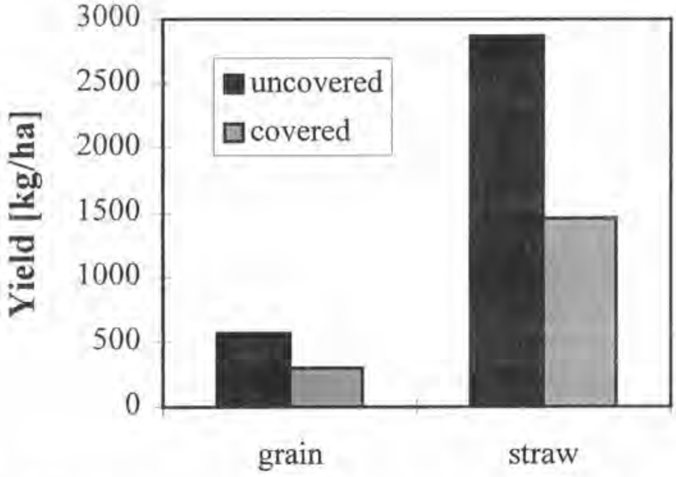


**Figure 3. Effect of partial seedling burial by sand on millet grain and straw yields (Michels 1994).**

It is commonly argued that planting in tufts, as practiced by Nigerian farmers, improves emergence by reducing sandblasting damage to seedlings. For instance, Klaij and Hoogmoed (1989) observed that seedling survival under field conditions was better with hill planting of 20–30 seeds per hill than with direct drilling. Michels et al. (1995a) investigated the effect of the seeding system (3 or 15 seeds per pot) and burial under 15 mm of sand on potted plants exposed to a wind tunnel sandstorm at 2, 5, and 8 DAE. Non-buried plants showed 100% survival, corresponding to the presence of at least three plants per pot. For buried plants, the highest survival rate was observed for millet planted in tufts. Similarly, dry matter at 70 DAE was nearly five times larger for buried plants sown in tufts than for single plants. However, dry matter production for unburied millet planted in tufts was 5% lower than for single-planted seed at 70 DAE, perhaps as a result of increased competition for nutrients at the higher sowing density. These results show that the advantage of planting in tufts seems to lie in the better recovery of buried plants rather than reduced injury. Michels et al. (1995a) also found that survival was higher for plants buried 2 DAE than at later dates, which they attribute to the higher seed reserves available to younger seedlings for growth through the added sand layer. Dry matter production followed the same trend.

In addition to direct effects of partial burial on yield-determining factors, such as number of tillers and panicle length, partially-buried plants show delayed development compared to unburied plants. Michels et al. (1993) found that panicle development was delayed approximately two weeks after partial burial.

The results of Michels et al. (1995a) indicate that millet shows a remarkable ability to recover from wind-erosion-induced damage under optimal recovery conditions. Since damage to millet strongly depends on plant age, the risk posed by sandblasting and burial will, to a large extend, depend on the strength and timing of sand storms with respect to the time of sowing. Furthermore, the evidence indicates that decisive damage may occur when several sources of stress are combined, as may frequently be the case under field conditions. For instance, although it had no effect on unburied plants, exposure of seedlings to sandblasting prior to burial reduced dry matter production at 70 DAE by 47% compared to unexposed buried plants (Fig. 4; Michels et al. 1995a). The delayed development resulting from burial of seedlings may further increase the risk of an end-of-season drought stress to millet by extending the crop cycle beyond the usual growing season. More generally, burial of seedlings may accentuate the effect of high surface temperatures by bringing the meristems of young seedlings directly into contact with the hot soil surface. Nutrient and water deficiencies at this critical stage may further hamper seedling recovery.

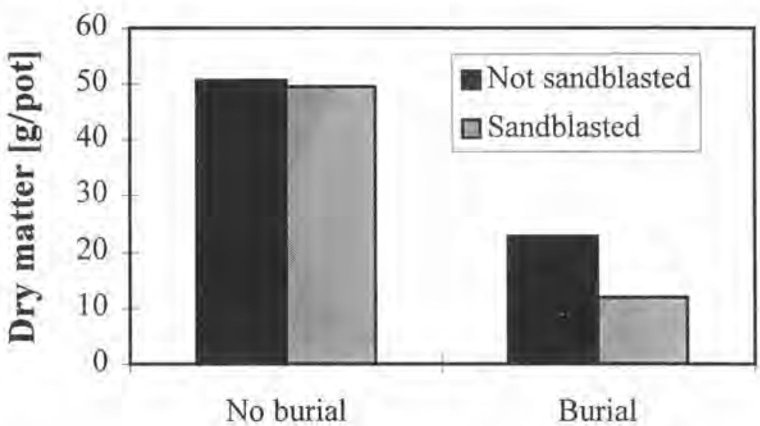


**Figure 4. Effect of sandblasting and burial on millet dry matter at 70 DAE (Michels 1994).**

## Wind-erosion Control Measures

Wind-erosion control measures can generally be fitted within one of three categories: mechanical tillage operations, residue management, and vegetative barriers. These methods aim at decreasing wind speed at the soil surface by increasing surface roughness and/or increasing the threshold friction velocity needed to initiate particle movement by wind. Besides their use for soil conservation, erosion control methods can also reduce direct damage to crops, as discussed in the previous section. Extensive research has been carried out at ISC on all three types of wind-erosion control measures.

## Crop residue management

From a technical point of view, crop residue management is probably one of the simplest alternatives for wind-erosion control in a resource-poor environment such as the Sahel. Although farmers occasionally use branches from bushes or trees, or other sources of organic mulches for the reclamation of degraded spots (Lamers and Feil 1995), the most widespread source of mulch is millet stover. Because of its value as feed for cattle as well as for other household purposes, the quantities of millet stover available at the start of the rainy season are generally low and this limits the widespread use of crop residue for mulching.

Nevertheless, the potential of crop residue mulches as a cheap and effective means of controlling wind erosion is widely recognized, even among farmer communities. Research has therefore been carried out at ISC on the use of millet stover mulches for improving plant stand establishment and reducing soil loss under Sahelian conditions, to define optimal quantities and appropriate crop residue management practices.

The effectiveness of various levels of crop residue for reducing soil loss has been studied by Michels et al. (1995b), Buerkert et al. (1995) and Sterk (1997). Over a two year period, Michels et al. (1995b) observed that the application of 2 t/ha of millet stover reduced soil flux at a 0.1 m height by an average of 47% during the rainy season (Fig. 5). No significant reduction in soil flux could be measured with a 0.5 t/ha application. In a different experiment, involving seven windbreak species, Michels (1994) reported an average reduction is soil mass flux of 56% over three years following the application of 2 t/ha of crop residue, irrespective of the windbreak species.

Buerkert et al. (1995) measured an average decrease in mass transport of 42% over two years in the presence of a 2 t/ha millet stover mulch, a reduction similar to that found by Michels et al. (1995b). Whereas bare plots lost 190 t/ha (12 mm) of topsoil between mid-September 1993 and the end of July 1994, topographical measurements on the mulched plots indicated a net soil deposition of 270 t/ha (17 mm) over the same time period (Buerkert et al. 1995). Of this 270 t/ha, 107 t/ha was deposited during the late dry season, probably mainly due to Monsoon-type winds. In accordance with the data of Buerkert et al. (1995), Geiger et al. (1992) found that relative height differences of 150 mm developed over five years between the surface of bare plots and mulched plots. In this latter case, however, one cannot distinguish between the respective contributions of losses on bare plots and deposition on mulched plots.

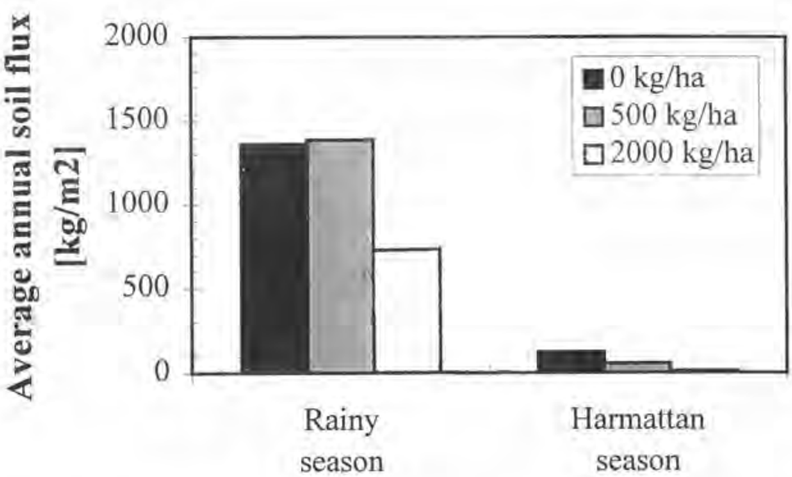


**Figure 5. Average annual soil flux (1991/92) at a height of 0.1 m as affected by mulching rate during the rainy season and the dry harmattan season (Michels 1994).**

Following upon the work of Michels et al. (1995b), Sterk (1997) tested two intermediate mulch application rates, namely 1 and 1.5 t/ha. This author observed a tendency for the effectiveness of crop residue mulches to decrease with increasing wind velocity. For wind velocities increasing from 8.3 to 10.6 m/s, mass flux reduction efficiency dropped from 80 to 50% at the mulching rate of 1.5 t/ha. Michels et al. (1995b) observed similarly that the efficiency of millet stover for reducing soil flux was higher during the dry season than during the rainy season (53% and 92% for the 0.5 and 2 t/ha application rate respectively), which was attributed primarily to the lower average wind speeds that characterize the harmattan winds (Fig. 5). These authors also observed that the effectiveness of crop residue seemed to increase as the severity of the sand storm decreased. The overall higher flux reduction efficiencies found by Sterk (1997), compared to Michels et al. (1995b), are likely to be the result of a different experimental set-up as well as to differences in the type of sand trap used and in the procedure for calculating the flux reduction.

At a wind velocity exceeding 11 m/s the presence of 1 t/ha millet stover actually enhanced wind erosion (Sterk, 1997), although this observation was limited to a single storm. This was ascribed to the increased turbulence near the soil surface due to the roughness created by the millet stems. Whether the same effect also occurs for the 1.5 t/ha rate and at what wind speed could not be assessed from the data.

In an ongoing experiment at Banizoumbou, 60 km northeast of Niamey in a farmer's field, we tested the effect of application mode of a 2 t/ha millet stover mulch on soil loss by wind erosion (unpublished data). In 1995, it was estimated, from the difference in input and output sand flux between 0 and 35 cm height, that bare plots lost an average of 55 t/ha, whereas deposition occurred in plots with residue placed in 30 cm wide strips amounting to 40 t/ha (Fig. 1). Actual soil loss/deposition is likely to have been higher because the mass balance calculations were restricted to events with approximately easterly winds as a result of the experimental layout. Although the convective storms frequently originate from the east, erosive events with different wind directions are also observed during the rainy season. Net soil loss on bare plots and deposition on residue plots was consistent over the entire season. In 1996, an estimated 37 t soil/ha was deposited on the mulched plots, compared to a net erosion of 24 t/ha on bare plots. In this second year, strip residue was compared with broadcast residue at the same application rate. Calculations indicate that the broadcast application trapped approximately 60% less soil than banded residue. It is believed that this effect is largely related to the greater "dead volume" within the strips, which is capable of trapping and protecting from further erosion large quantities of sand. For residue broadcast at a rate of 2 t/ha, which corresponds to a surface coverage of approximately 7% (Michels et al. 1995b), such trapping occurs mainly in the immediate vicinity of the millet stems.

As a result of the degradation that took place following wind erosion on bare plots at Banizoumbou, millet yield dropped from 328 kg grain/ha in the first year to 78 kg/ha in the second year (Fig. 6). Millet grain yield in the residue plots remained stable at about 500 kg/ha, indicating relatively comparable environmental conditions in the two years of the experiment. Although nutrient depletion may contribute to degradation, it is likely that rapid decline in soil productivity results from large losses of topsoil by wind erosion.

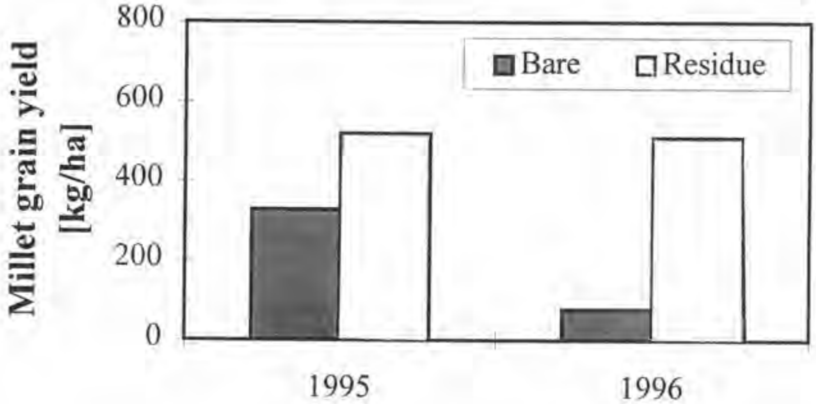


**Figure 6. Effect of strip application of millet stover on millet yield at Banizoumbou, Niger.**

The application of 2 t/ha of crop residue significantly modifies the surface properties of the soil. Michels et al. (1995b) found an increase in fine sand and clay and a decrease in the coarse sand fraction in the top 1 cm. The absence of mulch seems to have favored the disappearance of the 63–200 μm fraction, a fraction that is highly sensitive to transport by wind. Changes in soil chemical properties were found only in plots with the 2 t/ha application rate, with significant increases in pH, organic C, and ECEC. The respective contributions of wind erosion/deposition and decomposition of crop residue in these observed changes could not, however, be evaluated.

Buerkert et al. (1995) attempted to separate the physical "soil conserving" functions of crop residue from the chemical and the physical effects due to residue decomposition and the stimulation of soil fauna during a three year experiment. They compared a millet stover mulch at a rate of 2 t/ha with a synthetic mulch of comparable physical properties. The synthetic mulch was equally effective at reducing wind blown sand flux, yet soil deposition was more than doubled on the millet stover plots compared to the synthetic mulch. This may have been caused by the gradual decay of the synthetic mulch, which was not renewed during the course of the experiment, and by a difference in the effectiveness in the control of water erosion rather than wind erosion. These two degradation processes were largely confounded in this experiment. In the first year the synthetic mulch did not increase millet yield over the bare control, whereas it did improve millet grain and dry matter in the second year. This probably reflects the faster degradation taking place on the bare plots. The positive effect of the synthetic mulch cannot be attributed solely to soil conservation, however, since it was shown that the mulch also significantly reduced soil mechanical resistance.

The effect of millet stover mulching on millet stand establishment was studied by Michels et al. (1995c), who observed that, in agreement with soil flux data, the number of hills not covered by sand in the first weeks following sowing was highest for the 2 t/ha application rate. No significant difference in terms of seedling burial could be found between the 0.5 t/ha rate and the bare controls over the two years of the study. Final yield increased with the application rate of crop residue, which is likely to be the result of the combined effects of the physical, chemical, and biological changes in soil properties induced by crop residues. However, based on the earlier-discussed finding that total dry matter of millet from uncovered hills was higher than for partially covered hills, it may be concluded that the yield increase at the higher application rate could be partly due to the physical protection of seedlings against burial by sand.

Based on the soil flux and seedling burial data presented above, it is clear that an application rate of 0.5 t/ha of millet stover provides insufficient protection against wind erosion. Because of the overall higher efficiency in soil mass flux reduction of the 1.5 t/ha application compared to 1 t/ha, Sterk (1997) recommends the use of the higher application rate for wind-erosion control. This rate is somewhat more accessible to farmers than the 2 t/ha rate tested by

Michels et al. (1995c). It is not known whether this rate would also provide suitable protection of seedlings against burial. The data of Michels et al. (1995c) indicate that even at a rate of 2 t/ha, the protection against burial is only partial. However, whether at a rate of 1.5 or 2 t/ha, it is evident that the widespread use of mulching will require substantial increases in dry matter yield, which can only be achieved through improved management practices, including the use of inorganic fertilizers.

## Mechanical measures

As opposed to crop residue, the use of tillage operations to control wind erosion damage is, in principle, not constrained by the present levels of productivity in the Sahel. However, because of the need for animal traction, the weakness of animals at the end of the dry season, and the detrimental effects of delayed sowing on millet yield, tillage is not widely practiced on the sandy soils of the Sahelian zone. Tillage nevertheless constitutes a potential alternative for wind-erosion control where residue management is constrained by availability.

The beneficial effects of plowing and ridging on millet-stand establishment have been well documented. In a three year experiment Klaij and Hoogmoed (1993) showed that early plant establishment was highest for plowed soil, followed by ridging and no-till plots (Fig. 7). The effect of tillage on establishment was strongest in the two years when sowing was followed by strongly erosive events. However, particularly in the case of ridging, the positive early effect of tillage was lost later during the season. In two years out of three the final stands at 80–90 days after sowing were essentially identical for ridged and no-till plots. On the contrary, plowed plots consistently maintained a higher population density than the other treatments. In the first year (1984), no grain was harvested because of a severe end-of-season drought. Over the last two years of the experiment, ridging and plowing improved millet yield on unfertilized plots by 30 and 83%, respectively, over the no-till plots. Similar trends were reported by Klaij and Hoogmoed (1993) for another experiment.

On the weakly-structured sandy soils typical of the region, the effect of plowing on surface roughness is rather short-lived. The beneficial effect of plowing on plant stand establishment is therefore likely to have been caused by improved root growth due to soil loosening rather than any protection against wind erosion. The same probably applies, to some extent, to the ridged treatments, although the rugosity created by ridges will last for at least a few weeks, depending on climatic conditions, and therefore will be more effective at reducing wind velocity. In addition to the lower sand flux occurring over ridged plots, it is likely that planting on top of the ridge also prevents seedling burial from occurring, although no firm data exist on this aspect. In a 12 year experiment at a site that is sheltered against the effect of wind, ridging and plowing consistently improved millet grain and straw yields (Klaij, unpublished data), but the yield advantage of ridging in this case was on the order of 10%

only. It is possible that the yield advantage of ridging is higher on plots exposed to the erosive action of wind than on protected plots, although insufficient data is available to support this assertion.

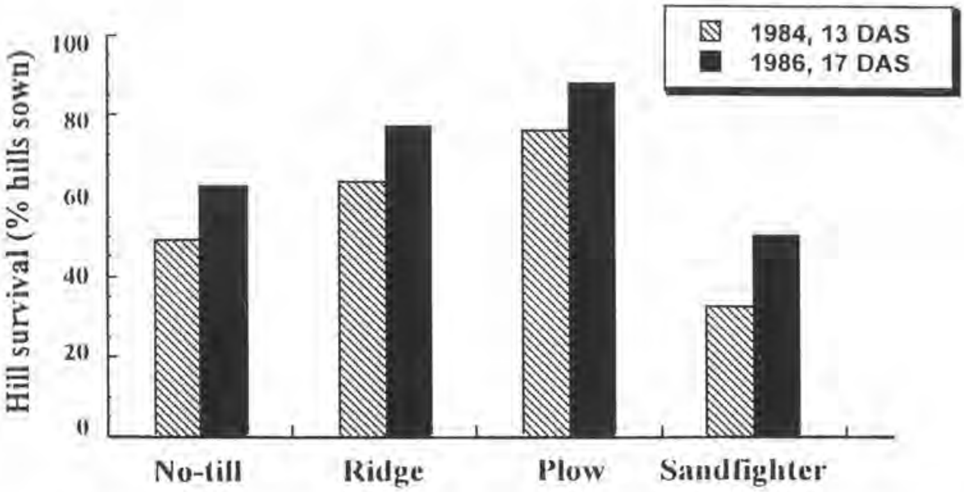


**Figure 7. Hill survival as affected by primary tillage (Klaij and Hoogmoed 1993).**

In a three year study, Leihner et al. (1993) did not find any yield response of millet to ridging compared to a no-till control in a low-windbreak system with spacing up to 90 m. On the contrary, cowpea produced significantly more dry matter and grain on ridged plots in two years out of three. The authors did not detect significant differences between ridged and no-till plots in terms of wind speed or total amount of wind-blown sand between 0.05 and 0.5 m above the ground. As the windbreak spacing was reduced from 90 to 6 m, larger reductions in soil flux were measured on no-till plots than on ridged plots. The absence of response to ridging in this experiment was attributed primarily to the low cloddiness of the sandy soil and weak cohesion of the ridges, making the ridges ineffective for erosion control. It is likely that the response of cowpea to ridging was not the result of better wind-erosion control but of improved soil physical conditions. The lack of response of millet to ridging went unexplained.

In an experiment conducted over three years to test the effectiveness of crop residue application and ridging on millet productivity and sand flux (Klaij, unpublished data), ridging was found to have consistently improved millet grain yield by an average of 80%. No positive effect of ridging on early millet stands was observed in two years out of three, but analysis did reveal that ridging significantly decreased sand flux at a 0.1 m height by an average of 26% over three years (Fig. 8). In the ongoing experiment at Banizoumbou, we measured a net soil loss of 16 t/ha in ridged plots in 1995, compared to a loss of 19 t/ha in bare plots for the period following ridge construction. Ridges were built perpendicular to the dominant easterly monsoon winds. In 1996, soil loss was 19 and 8 t/ha on bare and ridged plots, respectively. Despite the significant loss of topsoil, no overall decline in cowpea yield was observed over the two years. This is attributed to the particularly poor establishment of cowpea in 1995, irrespective of the treatment.

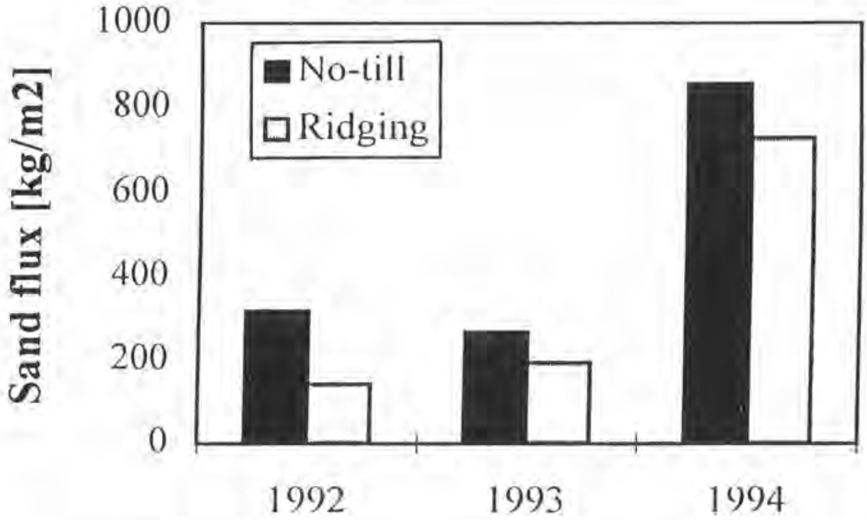


**Figure 8. Annual sand transport measured at a height of 0.1 m as affected by ridging (Klaij, unpublished).**

The use of a sandfighter—a shallow tillage operation used to increase surface roughness after each rainfall—did not improve plant establishment in one experiment and actually reduced early plant stands in another (Fig. 7; Klaij and Hoogmoed 1993). Final yield directly reflected this observation. The use of a sandfighter can therefore not be recommended for the weakly-structured sandy soils of the Sahel.

The results of the studies carried out at ISC over the last decade indicate large differences in response to ridging between experiments. This cannot be attributed solely to interannual variability. In a long-term experiment, ridged plots outyielded no-till plots in eight out of the last nine years (Klaij, unpublished data). Only in the first two years of this 11 year experiment was yield in the ridged plots lower than in the controls. Hence, some of the observed variability must come from site-specific conditions, which may be related to differences in the way the experiment was conducted or to external factors such as the degree of sheltering from wind effects. In order to clarify these observed differences, there is a need for a carefully designed experiment in which all relevant climatic, sand flux, and agronomic data are collected.

## Vegetative barriers

To compensate for the fast-disappearing natural vegetation, it is a logical step to try to re-establish vegetative strips that can serve the purpose of reducing environmental degradation, increasing crop yield, and providing farmers with useful and sometimes marketable products. This line of thought has been pursued actively at ISC since the inception of wind erosion research at ICRISAT.

One can identify essentially three categories of windbreaks: windbreaks made up of perennial woody species (bushes or trees); windbreaks composed of perennial grasses; and mixed windbreaks. Banzhaf et al. (1992) and Leihner et al. (1993) report on the effectiveness of a windbreak made up of natural savanna vegetation, i.e., annual grasses approximately 0.6 m high, interspersed with scattered *Guiera senegalensis* bushes and the perennial grass *Andropogon gayanus*, 2.5 to 3m high. Compared to plots with windbreaks spaced 90 m apart, soil flux midway between windbreaks was reduced by 70% with 6 m spacing and by 53% with 20 m spacing (Banzhaf et al. 1992). Wind speed was reduced by more than 20% up to 10 m from the windbreak, i.e., up to 17 times the height of the grassy vegetation. In the last year of the experiment, early millet growth at the five leaf stage was increased by 90% when windbreak spacing was decreased from 90 to 6 m (Leihner et al. 1993). Data on this factor was not available for the first two years. This may indicate a beneficial effect of windbreak on yield through plant damage control, despite some evidence of increased competition for water at the narrower windbreak spacing. However, for all spacings, there was no significant effect of the windbreak on final millet yield in any of the three years of the experiment. This reflects the ability of millet to recover following initial poor growth.

Michels (1994) tested seven windbreak species during a two year study. All species were pruned to a height of 2 m and planted in double rows. Windbreak spacing was 30 m. Sand flux was measured only in plots with *Andropogon gayanus* and *Bauhinia rufescens* windbreaks. Sand flux was reduced by 25 and 58% over the two years for *A. gayanus* and *B. rufescens* windbreaks, respectively. A significant reduction in sand flux was measured, up to seven times the windbreak height for *B. rufescens*. For *A. gayanus* windbreaks, this effect was extended up to five times the height. Brenner et al. (1994) found that, in order to compensate for the loss of land allocated to the windbreak, and reduced yield close to the windbreak as a result of competition, the optimal spacing is 10–15 times the windbreak height. Hence, if this recommendation were to be followed, neither *A. gayanus* nor *B. rufescens* would provide adequate erosion control over the entire field. The difference between the results of Banzhaf et al. (1993) and Michels (1994), with respect to the windbreak zone of influence, is probably due to the use of different criteria for estimating the distance of influence.

For the two years of study, windbreak species did not have any effect on the number of hills buried under deposited sand, nor did Michels (1994) detect any effect of the distance from the windbreak on this factor. The authors argue that this may have been due to favorable climatic conditions related to the occurrence of sandstorms with respect to sowing. No consistent effect of windbreak on millet yield was observed over the two years. Some species tended to stimulate crop growth, while others depressed yield. Millet yield 1–3 m away from the windbreak was depressed by all species except *Faidherbia albida*, which is leafless during the rainy season. In accordance with the results of Banzhaf et al. (1992) and Leihner et al. (1993), the results of Michels' studies indicate that windbreaks are an effective means of controlling soil degradation through wind erosion. However, their effect on millet productivity is less clear-cut and subject to substantial variation. In terms of millet production, *F. albida* windbreaks were by far the most successful at increasing yield, even though the leafless nature of the tree in the rainy season probably makes it a poor windbreak, *per se*. The positive effect of this tree on its immediate surroundings is widely recognized, and can be attributed to changes in microclimatic conditions as well as in soil chemical fertility.

It has been shown that the profitability of windbreaks comes primarily from increases in millet yield. Nevertheless, the value of products derived from the windbreak species is an important determinant for their adoption. Data on the establishment, growth, and nutritional and calorific value of the seven species tested by Michels have been reported by Lamers et al. (1994) and will not be discussed here.

*Andropogon gayanus* is a grassy perennial species commonly found at the borders of farmers' fields and used for fodder and construction purposes. The value of this species for wind-erosion control was studied by Renard and Vandenbelt (1990) in a four year study. Ten meter wide strips of *A. gayanus* alternated with equally wide strips of millet. No data on sand flux were collected, but the authors measured a 15–20% reduction in wind speed in plots protected by *A. gayanus*. After a three year period, topographic measurements revealed a height difference of 150 mm between the *A. gayanus* strips and the unprotected plots, equivalent to 2,250 t soil/ha. Except in the first year, millet grain yield in protected plots tended to be depressed compared to unprotected plots. This may have been caused to some extent by competition for water, of which Renard and Vandenbelt (1990) showed some evidence. The authors recognized that the area of land dedicated to the *A. gayanus* borders in their experiment could not be recommended in practice. Nevertheless, they reckoned that, in view of the large amount of soil trapped by the grass, promoting the use of *A. gayanus* for field borders may provide an effective means of alleviating the soil degradation process in the Sahel.

## Conclusions

A study carried out by Baidu-Forson and Ibro (1995) shows that farmers favor those wind-erosion control interventions that are low cost, simple to implement, and rely on local skills and inputs. On this basis, crop residue management probably comes closest to farmer expectation. Millet stover mulches are indeed occasionally used by Sahelian farmers for wind-erosion control, which can probably not be said for windbreaks and tillage. Based on the results presented earlier, the minimum rate under Sahelian conditions probably lies around 1.5–2 t/ha of millet stover in order to achieve effective soil loss and crop damage control. The widespread application of millet stover mulches at such rates is presently constrained by the low levels of productivity in Niger. Effective prevention of soil degradation through surface mulches will therefore require substantial productivity increases, achieved through the judicious integration of soil conservation measures with recommended management practices of organic and inorganic amendments, livestock, trees, and bushes.

As has been shown, windbreaks and tillage constitute effective alternatives for wind-erosion control under certain circumstances. However, as opposed to crop residue, the positive effect of these practices on millet productivity remains open to debate, and seems highly dependent on climatic and site conditions. Elucidating the reason for the large differences in response to tillage and windbreaks between experiments may require additional, carefully controlled experiments with comprehensive monitoring of all relevant factors. Nevertheless, under favorable circumstances, the establishment of windbreaks may help control wind erosion and therefore allow the use of lower levels of crop residue for mulching. Based on existing data, it is less evident that the combination of residue and ridging, or ridging and windbreaks, would enhance the effectiveness of either technique alone.

Several researchers have described the effect of sandblasting and burial on early millet growth and establishment. Except in the most severe cases, the studies show the remarkable ability of millet to recover from initial damage. Only seedling burial at specific early stages of millet development seems to significantly affect final yield, but the recurrence of such events is not known. Although interannual variability is high, the loss of topsoil by wind erosion is a continuous process which is much less sensitive to the timing of occurrence of the storm. As with water erosion, most soil is lost through a few intense storms. Although natural environments certainly show a significant resilience, it may take decades to restore the fertility of soil degraded by just a few sand storms. Soil degradation from wind erosion therefore constitutes a much stronger incentive for the large-scale implementation of erosion control techniques than the prevention of direct damage to crops.

## Research Needs

Extensive research on wind erosion has been carried out by ICRISAT and advanced international research institutes at ISC and other parts of Niger. Although not reported here, a fair number of studies has also been dedicated to the understanding of constraints for implementation of wind-erosion control techniques as well as their financial evaluation (e.g., Buerkert et al. 1997). It is clear from these studies that none of the proposed techniques are quite suitable for immediate large-scale adoption under the prevailing socioeconomic conditions in Niger. Although improvements in this aspect may come from a shift in subsistence agriculture to a more market-oriented agriculture, there is scope for improving the technical aspects as well. In particular, there is a need to better integrate soil conservation technologies with soil fertility management practices into the current farming systems to make them more attractive to farmers. One option that deserves further investigation is the use of natural vegetation strips to trap wind-blown sediment and reduce wind erosion in adjacent fields. Even though natural vegetation may not be as effective as a dedicated windbreak, the establishment of natural vegetation strips would, in principle, answer some of the farmers' concerns in terms of low cost, ease of implementation, and local availability.

The data presented in the section on soil and nutrient loss clearly shows that there is a lack of reliable quantitative data on the severity of wind erosion in the Sahel. Only recently have there been attempts to quantify soil loss and deposition resulting from wind erosion. Indications are that soil loss could be even more substantial than sometimes expected, and by far exceed loss by water erosion. Collinet and Valentin (1985) show that the potential soil loss by water erosion of bare soil in sub-Saharan Africa steadily decreases from approximately 80 t/ha per year for the 2,000 mm rainfall zone in Côte d'Ivoire to 2 t/ha per year at the northern edge of the Sahel (150 mm rainfall). Perhaps the most reliable data so far presented on soil loss by wind erosion in the Sahel is by Sterk and Stein (1997), who measured losses of the order of 45 t/ha in just four storms. Similar results were obtained on-farm at Banizoumbou, Niger, in 1995/96. Even higher values have been reported by Buerkert et al. (1994), on the order of several hundreds of t/ha per year. Although some caution is required in using this latter data to estimate the extent of wind erosion, it points to the fact that wind erosion constitutes a much larger threat to the soil resource than water erosion in the Sahelian zone. There is thus an urgent need to better quantify soil and nutrient flux resulting from the erosive action of wind under on-farm conditions. Besides more intensive monitoring, the quantification of the impact of wind erosion on soil and nutrient budgets will require methodological developments for more accurate measurement of wind-blown sediment, particularly with respect to the dust fraction, which is inherently richest in nutrients, and transport by surface creep, which may contribute significantly to the development of field-scale variability.

In addition to the evaluation of present mass and nutrient transfer by wind, the effect of changes in land use on soil and nutrient budgets, and on long-term productivity, must be quantified. One first step is the establishment of a potential wind-erosion risk map based on soil properties, and, wherever possible, wind characteristics. Steps have already been taken towards this goal. Estimates of actual wind erosion will require integration of information on vegetation and land use. After appropriate calibration, models could be used to predict soil loss by wind erosion for certain combinations of soil, vegetation, and land use. The same approach could then be used to estimate the effect of changes in land use, or of the aridification of the climate observed over the last two decades (Sivakumar et al. 1993).

In the Sahelian zone, land degradation does not only take place through wind erosion. Overgrazing, nutrient mining, and water erosion all contribute to the overall impoverishment of the environment. At present, to the authors' knowledge, there have been no attempts to study the interactions between these major soil degradation processes. For instance, it is readily apparent in existing trials that wind erosion increases the aerial extent of erosion crust by removing the loose sandy material that forms the surface of structural crusts. Erosion crusts are the least permeable of the crust types identified by Casenave and Valentin (1989). Herrmann et al. (1994) present evidence that crust formation may actually be enhanced by the deposition of dust particles during the harmattan and early wet season. By inducing a segregation of particles at the surface, raindrop impact during storms leads to the accumulation of the sand fraction at the soil surface (Bielders and Baveye 1996), a fraction that is highly sensitive to wind erosion. One can already see close interactions between the processes of crust formation, wind erosion, and water erosion. Besides the effects of water erosion, we need to be able to separate the effects of nutrient mining and wind erosion on nutrient depletion in the soil. Interactions between overgrazing and wind erosion occur mainly through the changes in vegetation induced by high grazing activity and the disturbance of the soil surface. Hence, there is a clear need to begin studying the interactions between various degradation processes to better quantify present and future land degradation and identify appropriate means to halt desertification.

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# Wind Erosion in Niger: Extent, Current Research, and Ongoing Soil Conservation Activities

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## Abstract

Niger, a typical Sahelian country, has always been concerned with wind erosion and its consequences. The present paper deals with the phenomenon as it occurs and its consequences. The physical mechanisms underlying the phenomenon and its relationship with the atmosphere and climate are quantified. Food production quality is discussed. Ongoing activities to combat wind erosion in Niger are presented, along with proposals for development research.

## Introduction

All levels of today's international community (scientific, political, and media) devote a lot of attention to environmental problems and climate change. In our opinion, because of a drought lasting some 30 years, there is no place in the world where climatic variability is as pronounced as it is in the Sahel. It seems that in this case we are no longer dealing with inter-annual variability, but with long-term trends, and we do not as yet know the causes, periodicity, and reversibility or otherwise of the phenomenon in the medium term.

The most evident manifestation of wind erosion in West Africa is unusual dust loading of the atmosphere during the so-called dry season. This is increasing with time, and suggests that the Sahel is the area with the highest atmospheric turbidity values in the world (Ben Mohamed et al. 1983, 1986, 1992). This dustiness appears to be both the cause and the consequence of the desertification process. The Sahara desert and its surroundings are nowadays considered the most important source of aeolian dust in the world. When the Intertropical Convergence Zone (ITCZ) reaches its lowest latitude, the dust over the Sahel can reach equatorial zones in winter.

## Generation Mechanism, Spatial Extent, Climatology and Climatic Consequences of Aeolian Dust in the Sahel

The two main mechanisms of the origin of aeolian dust mobilization and loading in the atmosphere in the Sahelian region are:

- The strengthening of the Libyan subtropical highs (Maghrebian–Libyan wedge), which causes a tightening of the pressure gradient (displacement of the 1,015 hpa line at a rate of 5° latitude per day).
- The occurrence of a trough over the Maghreb region and its prolongation to the Sahel, with low pressure minima over the Sahara desert.

Due to aeolian dust during such events, horizontal visibility is less than 5 km. Millions of tons of dust lie in quasi-permanent suspension over millions of square kilometers from November to April, between 0 and 20° N latitude. From a climatological point of view, negative rainfall anomalies, as defined by Lamb (1982), are correlated with positive anomalies of dustiness (lag=1), as shown in Figure 1. From 1970 to 1974, and again from 1983 to 1987, the number of hours of visibility less than 5 km was 3.5 times higher than normal (Ntchayi 1992).

Wind erosion therefore effects the West African climate due to the quasi-permanent status of aeolian dust in the atmospheric lower layers. The effects are a lowering of surface maximum temperatures and a heating of lower atmospheric layers. These two effects can combine to result in lower convection and hence cloud formation. This could be the origin of the negative feedback mechanism (Nicholson 1989), droughts leading to increased aeolian dust production, and dustiness-enhancing drought (Fig. 1).

## Chemical Composition and Mineralogy of Aeolian Dust

Recent studies carried out in this sub-region (Herrmann et al. 1996; Coudé-Gaussen et al. 1994; Modi et al. 1995), dealing with the chemical characteristics of aeolian dust collected in Niger and the Atlantic Ocean, provide good examples of the impact of wind erosion on crop production in the area.

It is well established that this dust contains a large quantity of clay (2 μm) and fine silt (2–20 μm). The dust mineralogy is characterized by the presence of quartz, feldspar, and often calcite, and the clay fraction contains compounds of kaolinite, illite, and chlorite. The presence of major elements (N, K, Ca, Mg, Na, and P), cited by these authors, along with the dry and humid deposition rates, gives evidence of the long-term impact of dust on soil surface horizon. Management practices that retain the aeolian dust will probably cause a more rapid growth of plants and increased yield due to soil surface enrichment.

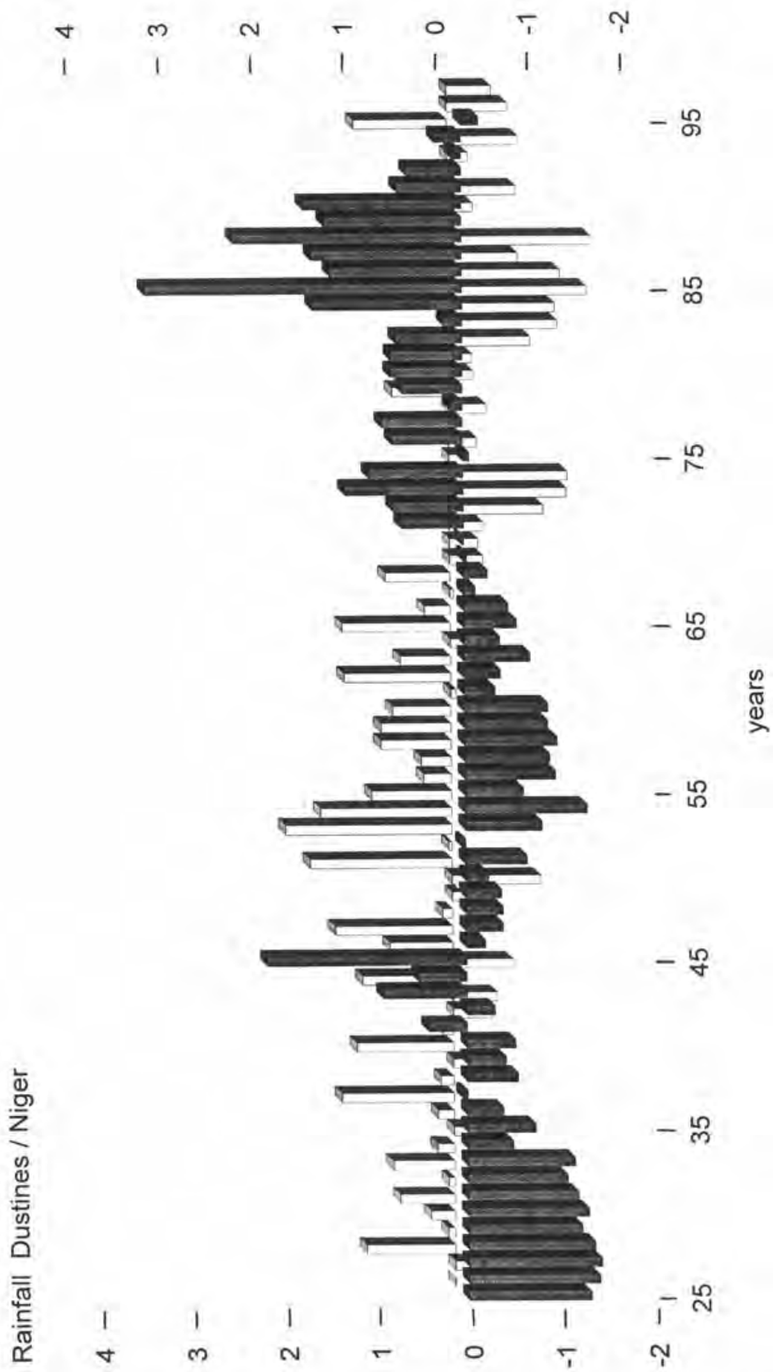


**Figure 1. Total rainfall and dustiness anomalies between 1925 and 1995 in Niger.**

# Measures to Combat Wind Erosion and Sand Encroachment in Niger

In Niger, these activities are usually conducted within the framework of rural development projects. The main projects are the Regional Program on Soil Conservation and Reforestation of CILSS for Niger, the project for combating sand encroachment of cultivated lands, the project on sand dune fixation in Zinder and Diffa, the Keita project, etc.

The Ministries of Hydraulics and Environment, Agriculture and Husbandry, Transport and Equipment, Internal Affairs and Land Management are responsible for field operations.

Wind erosion is particularly severe in the northern and eastern parts of the country, especially in the Diffa area, which is the most concerned with sand encroachment. Water erosion is also present and causes damage in all of Niger below 14° latitude during the monsoon rain season. This is turn enhances wind erosion during the dry season.

## Conservation Measures

Conservation measures in Niger have been undertaken since the early 1960s. Before 1990, only 3,000–4,000 ha/year were protected. Overall, less than 100,000 ha has been protected over the last 20–25 years.

The main conservation techniques used are (Toudjani 1997):

- Windbreaks: consisting of linear planting of trees in alternate rows around valleys, fields, orchards, etc. The species currently used are: *Prosopis juliflora, Azadirachta indica, Acacia holosericea,* and *Eucalyptus camaldulensis.*
- Shelter belts: linear plantations around orchards, valleys, cultivated fields, etc. The species used are *Prosopis juliflora, Prosopis chilensis, Acacia holosercea,* and *Moringa oleifera* at a high-density planting (0.5 m spacing).
- Fallow: this is being reduced because of increasing population pressures. Traditionally, fallow involves a cultivated field, which has lost its fertility, being left unused for many years in order to combat wind erosion by modification of surface roughness.
- Area protection: used mostly in pastoral zones by development projects in order to regulate cattle movement. Degraded areas are fenced and guarded, and sometimes used for cultivation of forage species. However, this kind of operation means investment by farmers and for this reason is less used.

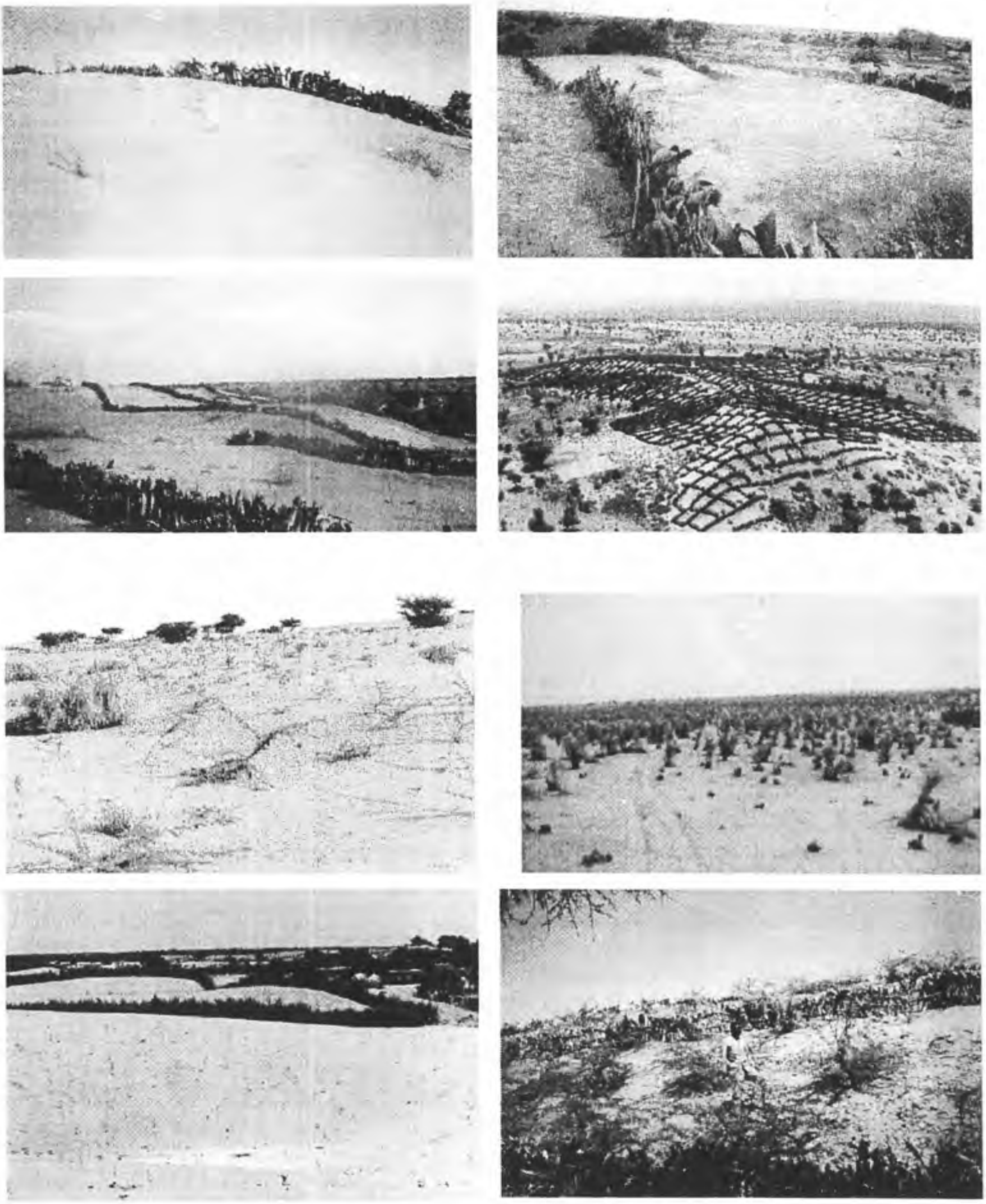

**Figure 2. Examples of mechanical and/or biological fixation of sand dunes in Niger.**

## Sand Dune Fixation

The following techniques are used for sand dune fixation:

- Mechanical and biological techniques (Fig. 2): consisting of installing closely-netted palisades on top of the dune and planting species inside to permanently fix the dune. Fast-growing species are chosen to quickly cover the dune. These are usually *Prosopis juliflora, Prosopis chilensis, Parkinsonia aculaeta,* and *Acacia holoceracia*. Local species such as *Acacia, Leptadenia pyrotechnica, Balanites aegyptia,* etc., are also used, mostly in between the dunes.
- Straw spraying: trash is sprayed over light dunes and *nebkas*. On top of moving dunes agricultural residues are often used successfully.

## Diffa and Zinder Project

During the five years of the project to combat sand encroachment of agricultural areas in Diffa and Zinder, the local population produced 1,274,000 seedings, built over 300,000 linear square meters of palisades, and planted a total of 842,223 trees on 912 ha of moving dunes. In addition, 197 ha was also protected and planted. Agroforestry activities were carried out on 130 ha. Participation totaled 426,532 man-days, and, as a result of the project, 28 village communities were created to manage the protected areas. Women's participation was crucial and contributed in a decisive way to accomplishments.

The project shed light on the psycho-sociological impact of fatalism on the local population, the technological impact of local technology and know-how to fix dunes, and the economic impact of tourism in terms of the reappearance of wildlife, and increased yield of agricultural products and forestry.

Cultural and psychological difficulties (social mores and customs demand division of duties according to sex) were overcome with appropriate measures to influence the local populations and by direct contact. The major result of such projects is the knowledge gained on utilization of local species for dune fixation, association of trees according to dune pattern, and protection measures for the trees.

## Keita Integrated Project

Initiated in 1984, this project covers a priority implementation area of 2,250 $km^2$, including a set of drainage basins for the three valleys located in the area. There are also 153 $km^2$ of plateaux, 2,165 $km^2$ of watersheds and 252 $km^2$ of alluvial plains (Carucci 1989).

The techniques used for windbreaks were:

- Three-row planting at 60 m intervals on sand dunes, alternating rows of *Acacia nilotica* var *adansoni* (facing the wind), with two rows of *Prosopis chilensis* and *Acacia oloricea*. A total of 420 km was planted.
- On active dunes, *Acacia senegal* and *Prosopis chilensis*, sometimes doubled with *Ziziphus mauritiaca* or *Bauhinia rufescens* were densely planted (4×4m). These plantations were generally protected by rows of millet. Approximately 600 ha of active dunes were fixed this way.
- In valleys, *Azadirachta indica* and *Prosopis juliflora* at 60 m intervals covering a total of 170 km were double-row planted.

In production systems, straw is used for wind-erosion control, although this technique depends heavily on biomass availability. The residue is often used for other purposes.

## Research Proposals

In Niger, most soils are sources and sinks of fine dust particles (aerosols). Hence, it is important to establish a method for dust mobilization. This can be done as a regular activity of the African Center of Meteorological Applications for Development (ACMAD) in Niamey, Niger. It will be very useful to quantify outputs and inputs in relation to soil fertility. Follow-up can be carried out by means of remote sensing for spatial integration and checking results in the field.

The following cooperative activities are necessary to tackle wind erosion in terms of particle mobilization, transport, sedimentation, and control measures.

### Study of Wind Erosion

The goal is to calculate, in a realistic manner, soil loss by wind erosion by means of the following equation:

$$Ep = f(P, C, R, L, V)$$

where Ep is soil loss in t/ha per year; P is soil erodibility; C takes into account atmospheric factors (i.e. wind speed and turbulence, thermal instability of lower atmospheric layers); R is the surface roughness; L is the length of the area subject to wind erosion in the direction of the wind; and V is the vegetative cover which influences erodibility and roughness.

This equation should be applied on different scales, hence it is important to determine the various parameters. On a large scale, remote sensing should play an important role in the determination of surface parameters and in estimating quantities of transported material (dust). To achieve this, it is important to obtain ground truth data, mainly atmospheric optical parameters, by means of an adequate area network.

### Study of Sedimentation

It will be necessary for such studies to have a network of dust-collecting devices to determine the quantities of dry and humid deposits, the elemental and mineralogical composition of deposited material, and the size distribution of the particles. The relationships among these parameters must be studied.

### Remote Sensing

First, it will be necessary to establish a specific methodology, as in the case of precipitation studies, by establishing a satellite image routine analysis scheme which will provide tools for characterization of the suspended dust. This in return will allow correction of satellite images, taking into account the change in optical properties of the atmosphere due to high dust concentration (typically around 800 $\mu g$ per $m^3$) when retrieving surface parameters. Another challenge is to forecast dust mobilization using pressure fields, surface wind fields, and soil surface parameters. These two approaches should help locate potential source areas and hence, areas for which wind-erosion control measures should be a priority.

### Wind-erosion Control Actions

#### Combating sand encroachment

Quite a number of studies in this area have been conducted in the region with satisfactory results. As a first step, an inventory of all these studies should be taken, with the results for different socioeconomic and climatic conditions published.

#### Combating agricultural land degradation

In order to achieve self-sufficiency in food production in the Sahelian region, this activity should be given the highest priority. It should directly benefit from the output of the research activities described above. However, success will depend upon their integration with the knowledge of local farmers.

## Conclusions

It is clear that wind erosion should be given the highest priority among the environmental problems in Niger. Besides scientific research that must be conducted to better understand the various mechanisms involved, sensibilization and organization of the local population on specific actions should also be carried out. The key challenge is to rationally manage environmental resources in this area to achieve sustainable economic and social development.

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# Understanding Major Processes and Socioeconomic Constraints

# Wind Erosion Processes

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## Abstract

Research aimed at developing a processed-based Wind Erosion Prediction System, the purpose of which was to improve wind-erosion technology for sustaining agriculture, protecting the environment, and conserving natural resources against the ravages of wind erosion. This emerging processed-based technology includes the capability of simulating weather, field soil and crop conditions, and wind erosion on a daily basis. It provides new capabilities for assessing plant damage, calculating suspension loss, and estimating pm-10 emissions from the field. This paper gives an overview and identification of some of the associated processes.

## Developing a Prediction System

Soil erosion by wind is essentially a flow process where soil is detached from an erodible surface and transported by various modes (creep, saltation, and suspension) in response to wind-shear stress and bombardment of soil particles already entrained in the wind, followed by the redeposition of wind-borne sediments. The rate of erosion for many conditions has been observed to be proportional to wind speed cubed (Bagnold 1943; Lettau and Lettau 1978; Skidmore 1986; Greeley and Iverson 1985). Wind speed cubed multiplied by air density gives units of power. Wind power multiplied by time and integrated over the distribution of wind speeds, exceeding the threshold during the accounting period, gives total erosive wind energy. Wind erosion is thus proportional to wind energy.

The relationship between mass flow rate and the driving force of wind-power density is illustrated by the results of a study now being analyzed (Skidmore and Fryrear, personal communication). Data were obtained from a modification of the Fryrear et al. (1991) field measurement procedure. Measurements include: particle impacts on a pizeo-electric quartz crystal near the surface (Gillette and Stockton 1986), wind speed at four heights, and total mass movement at five heights (Fryrear 1986).

The threshold wind-speed was determined by fitting a linear equation to the rate-of-particle count greater than background vs wind speed cubed, then solving for wind speed at a count rate equal to zero. Wind-power density was found using the following equation:

$$WPD = \rho\ (u_i^2 - u_t^2)^{3/2}$$

where *WPD* is wind-power density (watts/m$^2$); $\rho$ is air density (kg/m$^2$); $u_t$ is threshold wind-speed (9.8 m/s); and $u_i$ is observed wind speed (m/s) at the reference height.

The relationship between particle count rate, which closely approximates mass flow rate, and wind-power density (Fig. 1) illustrates the near-linear dependence of wind erosion on wind speed cubed after the threshold wind-speed is reached.

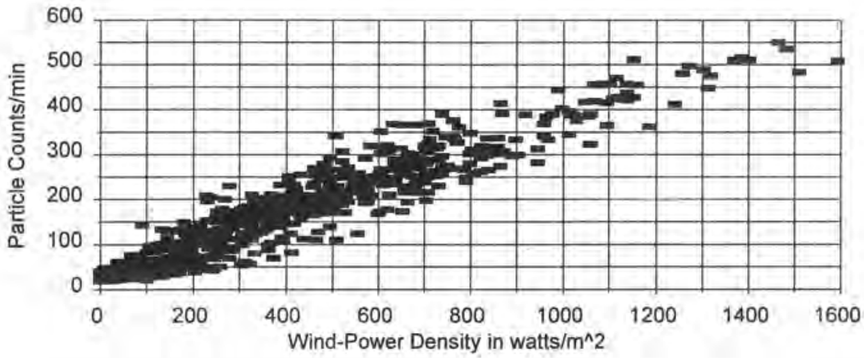


**Fig. 1. Particle count (mass flow rate) as influenced by wind-power density. The wind erosion event took place on 1 April 1996, in Meade County, Kansas.**

The many factors that influence not only the threshold wind-speed but also the sensitivity of mass flow rate to wind-power density change frequently in time and space. Hence we need to understand the processes, their driving forces, and how they change to better predict erosion and develop appropriate control practices (Skidmore et al. 1994).

Changing factors include distance from a non-erodible boundary (Woodruff and Sidoway 1965; Stout 1990) and wetness of the surface material (Chepil 1956; Saleh and Fryrear 1995; Durar et al. 1995). Obstacles that shield the erodible particles from experiencing the full brunt of the wind forces include: crop, flat and standing crop residues, non-erodible soil aggregates and crusts, wind barriers, snow cover, and miscellaneous non-erodible elements. Similarly, the susceptibility of the surface to erosion is subject to change from tillage, compaction, wetting/drying, freezing/thawing, freeze-drying, etc.

## Submodels

To properly account for the various factors influencing wind erosion, the prediction system was divided into the submodels of WEATHER, HYDROLOGY, SOIL, CROP, DECOMPOSITION, MANAGEMENT, and EROSION (Hagen 1991; Wagner 1996). For each of these submodels, theories were developed and field and laboratory experiments conducted to confirm theories, determine function coefficients, calibrate between observed and simulated variables, and evaluate empirical adequacy.

WEATHER generates variables necessary not only to drive EROSION *per se* but also processes within other submodels. Wind speed and direction distribution parameters are determined from historical weather summaries according to procedures outlined elsewhere (Skidmore 1965, 1987; Skidmore and Tatarko 1990; Skidmore et al. 1997). These are used in conjunction with weather variables generated by CLIGEN (Nicks et al. 1987).

HYDROLOGY predicts soil water status and how it changes in time and space as a function of soil hydraulic properties, potential evaporation, and precipitation (Durar and Skidmore 1995; Dural et al. 1995). Special emphasis is given to predicting the wetness of soil particles at the soil-atmosphere interface because of its large influence on detachment of soil particles. Soil hydraulic properties are either measured or estimated from basic soil properties. Potential evaporation is calculated from solar radiation, wind speed, temperature, and humidity furnished by WEATHER. Rainfall information is also obtained from WEATHER. A finite-difference technique redistributes soil water with the Darcy equation for water flow.

SOIL simulates temporal soil properties, which control wind erodibility of soil in response to various driving processes and intrinsic soil properties (Hagen et al. 1995). Temporal soil properties affected by tillage, wetting/drying, freezing/thawing, freezing/freeze-drying, precipitation, etc. include: roughness (both oriented and random), crust (Zobeck 1991; Zobeck and Popham 1990; Zobeck and Popham 1992), and aggregate status (Hagen et al. 1992; Skidmore and Layton 1992).

CROP was adapted from the EPIC crop growth model (Williams et al. 1989). Additional capabilities and modifications were developed and incorporated to meet the need to predict effects of a growing crop on wind erosion (Retta and Armbrust 1995). It calculates daily production of roots, leaves, stems, reproductive organs, and leaf and stem areas. Crop growth variables are adjusted for water and nutrient stresses.

DECOMPOSITION accounts for the biomass residues in standing, flat, and buried categories (Steiner et al. 1995). Carbon–nitrogen ratios, temperature, and moisture drive the rates of decomposition.

MANAGEMENT reflects the effect of various practices upon wind erosion (Wagner and Ding 1995). All major classes are represented, such as primary and secondary tillage, cultivation, planting/seeding, harvesting, irrigation, burning, and grazing. Each operation is simulated as a physical process. These processes include: soil mass manipulation (changes in aggregate size distribution and layer inversion); surface modification; biomass manipulation (burying, flattening standing residues, cutting, and removal); and soil amendments.

EROSION predicts the distribution of soil loss and deposition on a daily basis over a simulation region (Hagen 1995). It determines: threshold friction velocity based on surface conditions; random and oriented roughness; flat biomass, crust, and rock cover; loose, erodible grains resting on the crust; aggregate size distribution and density; and surface wetness. For each sub-hourly period when friction velocity exceeds the threshold, soil loss and deposition are calculated. To aid in the evaluation of off-site impacts, soil losses are further subdivided into components, and the loss reported as saltation/creep, total suspension, and fine particle matter (pm-10).

Work needs to continue to further our understanding of the many processes contributing to a science-based wind erosion technology and to create supporting databases for combating the ravages of wind erosion and developing a more environmentally, economically, and socially sustainable agriculture.

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# Modeling Wind Erosion

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## Abstract

Humanity has lived with the hazards of wind erosion for centuries. Efforts to accurately model wind erosion span almost 40 years. Field-erosion measuring equipment was developed to test a new wind-erosion model on a variety of weather, crop, soil, and farming systems. With the measurement of field erosion, establishing base-line conditions for future comparisons is possible. Field measurements verified that mass transport varies as the cube of the wind velocity. Mass transport increases with field length until the wind stream cannot transport additional material. Maximum transport is sufficient to destroy most crop seedlings within 15 minutes. Soil loss from a single storm was 8.03 $kg/m^2$ from a 2.5 ha circular field. Soil loss from an entire erosion season varied from 0.1 to 30.9 $kg/m^2$. Field size ranged from 2.5 to 145 ha. Effective and efficient wind erosion control systems can be evaluated with RWEQ because of its flexibility. More complex models, including WEAM and TEAM, are available, but may require input data not readily available. Attempts to improve wind erosion predictions are underway in the WEPS, WEAM, and TEAM efforts.

## Introduction

When the soil surface is bare and dry and wind velocities are high, wind erosion can be a major problem. Clouds of dust generated from eroding soil may obscure the sun, damage crops, abrade paint, and impede air and automotive traffic. Wind erosion is one of the basic geomorphological processes that have shaped aeolian features on every continent. Deep deposits of loess soils are evidence that wind has played a major role in shaping the landscape of the earth.

The severity of wind erosion is more pronounced in arid regions, which constitute 31.5% (46.1 million ha) of the total land of this world (Dregne 1976). Africa has the highest concentration of arid soil (17.7 million ha or 59.2% of total land area). The highest percentage of arid land (82.1%) is in Australia. Asia has 14.4 million ha and North America 4.4 million ha of arid lands.

## Processes

Wind is the basic driving force in the wind-erosion process. To model wind erosion, the interaction between air flow over rough soil surfaces and forces on soil particles must be described. Non-erodible elements reduce wind velocity at the soil surface. Wind erosion is possible when the wind velocity at the soil surface exceeds the threshold velocity required to move the least stable soil particle. The detached particle may move a few millimeters before finding a more protected site on the landscape. The wind velocity required to move this least stable particle is called the static threshold (Bagnold 1941). If wind velocity increases, soil movement begins, and if the velocity is sufficient, soil movement is sustained. This velocity is called the dynamic threshold.

The larger the soil particle, the greater the wind velocity required to dislodge and transport the particle. The velocity and turbulence of the wind dictate the largest soil particle that can be eroded (Chepil and Woodruff 1963). The cohesive forces between micron and submicron particles cause them to coalesce into larger, less erodible, particles.

When soil movement is sustained, the quantity of soil that can be transported by the wind varies as the cube of the velocity (Bagnold 1941; Chepil and Woodruff 1963). Many transport equations have been reported that include a term for wind velocity or friction velocity (Greeley and Iverson 1985; Sorensen 1991). Soil roughness, soil erodibility, soil wetness, and quantity and orientation of crop residues are some of the parameters that impact transport of eroded soil. If the erodible soil surface is covered with vegetation, or residues from a previous crop, the surface is protected from the force of the wind and erosion is controlled. Unfortunately, rainfall in arid and semiarid regions may not be sufficient to grow enough vegetation to protect the soil. Soil in these regions may erode until a desert pavement is formed. With deep sand, the surface may never stabilize, and active sand dunes will dominate the landscape.

As the wind velocity, or any of the above factors are modified, soil erosion may increase or be controlled. Field measurements of wind velocity during severe wind erosion events indicate that computing friction velocity from wind profiles is difficult because of the influence of airborne soil material in the saltation zone. Anderson et al. (1991) also reports that the presence of sediment transport influences near-bed wind velocity.

## Wind Erosion Models

To describe the interactions between the numerous factors involved in the wind erosion process requires the development of functional models. Wind erosion models can be physically, empirically, or theoretically based. Physically-based models require expressions for all the processes involved; therefore, many physically-based models have some empirically-derived coefficients. Describing air flow over a rough soil surface presents a challenge to scientists. Many air flow and detachment processes are dynamic and complex during an erosion event. The application of empirically-based models is limited to the range of conditions under which the model was developed. Also, empirically-based models require carefully controlled experiments to develop the essential coefficients. Theoretically-based models may be widely adapted but depend upon the fact that the theory and assumptions imbedded within the model are correct. For example, an analytical model developed by Sorensen (1991) utilizes processes for particle trajectory, wind modification, and grain-bed collision. Formulae were derived for transport rate and sand grain flux from the surface into the air. McEwan and Willetts (1993) caution wind-erosion scientists that extrapolating sand-transport-rate formulae from laboratory wind-tunnel conditions to field conditions may not be justified.

An empirically derived differential equation of dust concentrations in a thin layer near the ground to predict dust concentrations at the top of the surface layer was developed by Berkofsky and McEwan (1994). Unfortunately, it neglects horizontal transport, which is a major component of the wind erosion process. However, they did recognize that detachment plus a source term was inversely proportional to surface roughness. This relationship has been reported from field studies (Fryrear 1984).

While the above studies provide a solid foundation of information on the wind erosion process, they have not been combined with other input parameters to develop a complete wind-erosion model. Essentially, all the models developed to date are combinations of all three approaches. The user must determine which model will produce the desired output with the available input data.

## Wind Erosion Equation

The Wind Erosion Equation (WEQ; Woodruff and Siddoway 1965) has been widely used to plan conservation systems and estimate annual soil erosion. This model assumes that the wind erosion process is similar to an avalanche of snow and debris rolling down a mountain (Chepil 1957). As an avalanche rolls down the side of a mountain the quantity of moving snow may increase as long as there is a source of snow and the slope is long and uniform. Unlike the mass in the avalanche, the quantity of material being transported by the wind can increase until the total capacity of the wind to detach and transport soil has been reached. WEQ was one of the first models to estimate soil erosion in the field using single-input values for weather, soil erodibility, soil roughness, field length, and crop residue. The WEQ was developed from wind tunnel studies with limited field erosion measurements. Concerns that the climatic factor did not describe wind erosion in high or low rainfall regions were addressed, and a new climatic factor was developed (Skidmore 1986).

The WEQ consists of a functional relationship among five factors:

$$E = f(IKCLV) \quad [1]$$

where $E$=annual soil erosion in t/acre; $f$=functional relationship; $I$=soil erodibility in t/acre; $K$=soil roughness factor; $C$=climatic factor; $L$=unprotected field length in feet; and $V$=small grain equivalent.

WEQ estimates soil loss (note units of $E$ and $I$) for an unprotected field length ($L$). If soil loss is divided by field length, the unit is mass per unit width or an expression of transport mass.

The WEQ was modified for shorter time periods (Woodruff and Armburst 1968; Bondy et al. 1980), but concerns remain. As stated by Bondy et al. (1980 p. 176): "No experimental data base exists for using the wind erosion equation for periods of less than one year."

WEQ was coupled with the Erosion Productivity Impact Calculator (EPIC; (Williams et al. 1984) to estimate daily wind erosion soil loss (Cole et al. 1983). The C, I, K, and V factors in WEQ are annual values, but in the EPIC daily wind erosion model they are considered constant for a single day. Limited comparisons were made assuming WEQ was correct. With field erosion measuring equipment to measure mass being transported, it is possible to describe the wind erosion process correctly. Field measurements of transport mass and a critical assessment of the physics of WEQ reveal that the avalanching principle does not describe the wind erosion process in fields hundreds of meters long.

## Pasak

A soil loss model reported by Pasak (1973) was intended as a single event model:

$$E = 22.02 - 0.72P - 1.69V = 2.64Rr \qquad [2]$$

where $E$=erodibility in kg/ha; $P$=percent of nonerodible particles; $V$=relative soil moisture; and $Rr$=wind velocity in km/hr.

The lack of inputs for crop residue and soil roughness limits the use of this model. Also, wind velocity and soil moisture are not constant during an erosion event.

## Texas Erosion Analysis Model (TEAM)

TEAM, developed by Gregory et al. (1988) is a computer program developed to simulate wind profile development and soil movement over multiple field lengths. The basic equation is:

$$X = C\left( SU_*^2 - U_{*t}^2 \right) U_* \left( I - e^{-0.000169 A_a I L_f} \right) \qquad [3]$$

where $X$=rate of soil movement at length $L_f$ (M/LT); $C(SU_*^2 - U_{*t}^2)U_*$=maximum rate of soil movement which occurs when the surface is covered with fine non-cohesive material; $C$=a constant which depends on width sampled and units used for $U_*$; $L_f$ =length of unprotected field in the wind direction; $A_a$=abrasion adjustment factor; $I$=soil erodibilitiy factor involving soil shear strength and angle; $S$=surface cover factor which expresses the amount of detachment energy at the top of the cover which is transferred to the soil; $U_*$=shear velocity; and $U_{*t}$=threshold shear velocity. The abrasion adjustment factor is computed using the equation:

$$A_a = (1 - A_l)\left(1 - e^{-0.0072 e^{0.00079 U_{*t}}}\right) + A_l \quad [4]$$

where $A_l$=lower limit of abrasion effect (assumed 0.23).

The output from TEAM was compared with the output from WEQ.

## Wind Erosion Assessment Model (WEAM)

This process-based model, developed in Australia, is a combination of established and theoretical results (Shao et al. 1996). It synthesizes research results on sand drift and dust entrainment, approximated quantitative assessment of wind erosion, and evaluates the current limits to our knowledge of wind erosion processes. The WEAM model does not predict the evolution of soil surface properties due to wind erosion, natural weathering processes, or management interventions. WEAM treats erosion of a dry, bare soil in a given wind. To model total erosion from an entire erosion period, it is essential that the model reflects the impact of weathering and management practices. When coupled with large computers, WEAM does have the capability of estimating the movement of large dust clouds across complex landscapes. Input requirements are such that GIS or other information databases are essential to utilize this model effectively.

## Wind Erosion Prediction System (WEPS)

WEPS is designed to use a weather generator with submodels that simulate soil, crop, and field conditions using a daily time step (Hagen 1991). During high wind conditions, erosion may be calculated on a sub-hourly basis. Describing changes in soil surface and residue conditions on a daily time step is challenging. Describing changes during erosion events is a formidable task. Development of WEPS is continuing.

## Revised Wind Erosion Equation (RWEQ)

The WEQ did not describe wind erosion in high rainfall areas or in extremely dry regions. As erosion-measuring equipment and procedures were developed it became apparent that there were serious problems with WEQ, and new technology was needed for incorporation into a different model. To expedite the use of new technology, the RWEQ effort was suggested. The RWEQ model uses simple inputs to compute soil loss from agricultural land. RWEQ has been field tested against measured wind erosion for a broad range of conditions.

A physically-based mass transport equation was derived by Stout (1990). This equation is based on the concept that a self-balancing mechanism controls wind erosion and is the major relationship in RWEQ. With the self-balancing concept, momentum is transferred from the wind to the soil surface (Owens 1964). The equation derived by Stout (1990) is:

$$\frac{Q_x}{Q_{max}} = 1 - e^{-\left(\frac{x}{b}\right)} \quad [5]$$

where $Q_x$=mass being transported by wind at field length $x$ in kg/m; $Q_{max}$= maximum transport capacity of wind over that field surface in kg/m; $x$=field length in m; $b$= field length where wind attains 63.2% of $Q_{max}$ in m.

Equation 5 assumes if the wind velocity is above threshold, the erosion process detaches and picks up soil particles at an increasing rate until the wind has attained 63.2% of its capacity. Equation 5 is a negative exponential decay curve with the highest soil loss per unit area immediately downwind of the non-erodible upwind boundary, assuming $Q_x = 0$ at $x = 0$. The exponential decay does not describe conditions observed in fields where little or no erosion occurs for a distance downwind from the upwind edge of the field. Equation 5 was modified to the form:

$$Q_x = Q_{max}\left(1 - e^{-\left(\frac{x}{s}\right)^2}\right) \quad [6]$$

where $s$=inflection point where the slope changes from positive to negative.

This assumes that at $s$, $Q_x$ is 63.2% of $Q_{max}$ in Equation 6. While developed for flow layers close to the soil surface, this mass transport equation is used to describe the total mass being transported from the soil surface to a height of 2 meters. The input data required by RWEQ include factors for weather, soil, crop, field, tillage, and, where applicable, irrigation.

Least square analysis was used to determine the regression coefficients $Q_{max}$ and $s$ values for each erosion event. Equation 6 is a sigmoid curve where the mass being transported is zero at the upwind boundary, then rapidly increases until the wind attains 63.2% of its capacity. Beyond field length $s$ the rate of increase in soil mass is limited by the capacity of the wind to detach and transport additional soil. Therefore, beyond the critical field length the capacity of the wind to transport additional material diminishes until the maximum transport capacity has been achieved.

Collecting samples of mass being transported from natural wind events is possible with the BSNE field sampling equipment (Fryrear 1986). With the BSNE sampler daily soil losses as small as 0.001 kg/m$^2$ have been measured. These data are used to verify Equation 6 and test complete wind erosion models. Procedures have been developed to analyze the data (Fryrear and Saleh 1993) and interpret the results (Fryrear et al. 1991).

Unlike WEQ, the basic relationship between field length and transport mass in RWEQ reflects that as the wind becomes saturated, any additional material picked up by the wind results in the deposition of a portion of the original load. The rate of increase in suspension is a function of wind velocity, turbulence, soil texture, and field length. The field length required for the wind to become saturated varies with soil surface conditions and wind velocity. Rarely does the wind become totally saturated before surface conditions or wind velocity changes.

Empirical equations for estimating $Q_{max}$ and $s$ were developed using selected erosion events (Table 1). This analysis shows that the relationship between the input parameters and $Q_{max}$ are:

$$Q_{max} = 107.8(WF \times EF \times SCF \times K' \times COG) \quad [7]$$

where $Q_{max}$=maximum transport capacity in kg/m; $WF$=weather factor in kg; $EF$=soil erodible fraction; $SCF$=soil crust factor; $K'$=soil roughness; and $COG$=vegetation factor including flat residues, standing residues, and canopy.

The slope $s$ of the empirical relationship in Equation 6 is also computed from the input factor using the equation:

$$s = 146.86(WF \times EF \times SCF \times K' \times COG)^{-0.413} \quad [8]$$

where $s$ = critical field length where $Q_x$ is 63.2% of $Q_{max}$ in m.

When good input data are available, the estimated erosion for single storms is close to the measured values (Table 1). With the coefficients from Equations 7 and 8 as input for Equation 6, soil erosion can be computed for circular fields up to 60 ha and for square or rectangular fields up to 145 ha. The $WF$ is time-based, so erosion can be computed for any time interval when the remaining parameters are constant. Within the RWEQ computer program, the $WF$ is adjusted for rainfall and snow cover, crop residues are decomposed by water and temperatures (Steiner and Shomberg 1994), and soil roughness is decayed by rainfall amount and intensity (Saleh 1997).

The same coefficients used to estimate soil erosion for a single event are also used to estimate erosion from the entire erosion season. With the RWEQ computer program, erosion is computed for field length along the dominant wind direction. The transport mass from Equation 7 is important in evaluating potential plant injury from blowing sand. The critical field length from Equation 8 is used to plan field-barrier systems or field widths that will minimize soil erosion.

**Table 1. Maximum transport capacity and critical field length for 10 sites.**

| Site | Date | Factors | | | | | Soil loss (kg/m²) | | $Q_{max}$ | s |
|---|---|---|---|---|---|---|---|---|---|---|
| | | WF | EF | SCF | K′ | COG | MSL | EST | (kg/m) | (m) |
| BS | 04/17/95 | 14.2 | 0.72 | 0.77 | 1.00 | 0.80 | 4.43 | 5.32 | 644 | 33 |
| BS | 01/27/90† | 2.3 | 0.64 | 0.77 | 0.95 | 0.90 | 0.55 | 0.59 | 112 | 123 |
| BS | 01/29/90 | 2.8 | 0.64 | 0.77 | 0.95 | 0.90 | 0.80 | 0.71 | 133 | 88 |
| BS | 02/08/90 | 0.6 | 0.64 | 0.77 | 0.95 | 0.90 | 0.15 | 0.15 | 96 | 289 |
| BS | 03/06/90 | 2.8 | 0.64 | 0.77 | 0.95 | 0.90 | 0.93 | 0.71 | 226 | 149 |
| BS | 03/29/93‡ | 3.6 | 0.77 | 0.77 | 1.00 | 0.96 | 2.46 | 1.24 | 402 | 84 |
| MW | 04/02/91 | 8.4 | 0.79 | 0.91 | 0.82 | 0.43 | 1.14 | 1.29 | 168 | 43 |
| EK | 03/09/92 | 41.9 | 0.70 | 0.65 | 0.91 | 0.65 | 8.03 | 6.82 | 1,403 | 98 |
| KM | 03/13/93 | 15.3 | 0.85 | 0.90 | 0.85 | 1.00 | 4.05 | 6.02 | 751 | 109 |
| EC | 03/12/91 | 179.9 | 0.26 | 0.21 | 0.80 | 0.48 | 2.14 | 2.28 | 648 | 179 |

† Includes 27, 28 January 1993 wind data.

‡ Includes 28, 29 March 1993 wind data.

s=critical field length. WF=wind factor; EF=soil erodible fraction; SCF=soil crust factor; K′ soil roughness; COG=flat and standing residues; MSL=measured soil loss; EST=estimated soil loss; $Q_{max}$=maximum transport capacity; s= critical field length for selected erosion events. Sites are coded Big Spring, Texas, (BS); Mabton, Washington, (MW); Elkhart, Kansas, (EK); Kennett, Missouri, (KM); and Eads, Colorado, (EC)

RWEQ estimates of erosion were tested against measured erosion data from fields much larger than the original test sites and for different shapes. Agreement between measured and estimated soil losses in Table 2 illustrates that RWEQ can provide accurate estimates of soil erosion from time intervals of 2.5 months to one year. The data in Table 2 are from soil textures that include sand and clay loam soil, average rainfall amounts of 100–1200 mm, and crops including cotton, corn, small grains, vegetables, peanuts and sorghum. All soils, crops, weather, and management systems used by farmers are not represented. The data do represent typical conditions in the major wind-erosion regions in the United States. Total soil loss during the entire erosion period varied from zero at Fargo, North Dakota to 30.94 kg/m$^2$ at Crown Point, Indiana. At Big Spring, Texas the same field is instrumented between January and June. Soil losses from a flat smooth surface of sandy loam soil varied from 26.29 in 1995 to 3.99 kg/m$^2$ in 1996. In 1991 the field was roughened at the beginning of the erosion period and soil loss was 0.10 kg/m$^2$. Comparison of both measured and estimated erosion were highly significant ($r^2$=0.95).

This analysis supports the view that when RWEQ is used with good weather, soil, crop, and management input data, accurate estimates of erosion are possible. For single events, average soil loss of 9.44 kg/m$^2$ from a 2.5 ha field was measured. Soil loss of 30.9 kg/m$^2$ was measured for the entire erosion season.

**Table 2. Comparison of measured and estimated soil erosion.**

| Site | Start time | Stop time | Soil erosion (kg/m$^2$) | |
|---|---|---|---|---|
| | | | Measured | Estimated |
| Mabton, WA | 12/12/90 | 04/28/91 | 3.72 | 2.60 |
| Prosser, WA #1 | 12/03/91 | 03/25/92 | 0.004 | 0.29 |
| Prosser, WA #2 | 06/10/92 | 10/01/92 | 0.33 | 0.74 |
| Sidney, NE | 10/25/88 | 05/24/89 | 0.52 | 1.46 |
| Sidney, NE | 10/25/89 | 04/24/90 | 0.37 | 0.54 |
| Sidney, NE | 10/31/90 | 05/07/91 | 1.68 | 4.68 |
| Elkhart, KS | 02/27/90 | 12/30/90 | 0.29 | 1.12 |
| Elkhart, KS | 01/01/91 | 12/31/91 | 1.32 | 5.15 |
| Elkhart, KS | 01/01/92 | 12/30/62 | 12.86 | 14.66 |
| Elkhart, KS | 01/01/93 | 05/25/93 | 2.06 | 5.83 |
| Lindsey, MT | 10/18/90 | 05/21/91 | 0.03 | 3.48 |
| Lindsey, MT | 10/08/91 | 04/07/92 | 0.08 | 3.02 |
| Eads, CO | 10/30/90 | 05/21/91 | 2.45 | 1.86 |
| Eads, CO | 12/05/91 | 04/13/92 | 0.74 | 0.07 |
| Akron, CO | 10/27/88 | 05/26/89 | 0.83 | 4.72 |
| Akron, CO | 10/25/89 | 04/29/90 | 1.08 | 1.27 |
| Portales, NM | 11/24/94 | 04/06/95 | 0.19 | 0.11 |
| Martin-C, TX #1 | 01/24/95 | 07/05/95 | 0.30 | 0.43 |
| Martin-C, TX #2 | 01/24/95 | 07/05/95 | 0.80 | 0.63 |
| Martin-C, TX #3 | 01/24/95 | 04/05/95 | 0.30 | 1.10 |
| Plains E, TX | 12/13/94 | 05/24/95 | 2.20 | 2.85 |
| Plains YB, TX | 12/13/94 | 05/24/95 | 1.60 | 2.26 |
| Fargo, ND | 12/06/94 | 04/22/95 | 0.00 | 0.00 |
| Fargo, ND | 10/24/95 | 05/06/96 | 0.00 | 0.00 |
| Big Spring, TX | 01/12/89 | 05/02/89 | 21.54 | 18.40 |
| Big Spring, TX | 01/10/90 | 06/04/90 | 20.96 | 18.04 |
| Big Spring, TX | 01/28/91 | 05/13/91 | 0.10 | 1.82 |
| Big Spring, TX | 03/16/93 | 06/01/93 | 28.78 | 26.90 |
| Big Spring, TX | 01/06/94 | 06/18/94 | 17.16 | 13.00 |
| Big Spring, TX | 01/11/95 | 05/15/95 | 26.29 | 24.29 |
| Big Spring, TX | 01/12/96 | 05/21/96 | 3.99 | 8.40 |
| Crown Point, IN | 01/10/90 | 12/31/90 | 30.94 | 32.00 |
| Crown Point, IN | 01/01/91 | 12/30/91 | 23.41 | 24.70 |
| Crown Point, IN | 01/01/92 | 06/04/92 | 0.35 | 2.89 |
| Havre, MT | 10/28/92 | 05/05/93 | 0.02 | 0.19 |
| Havre, MT | 10/19/93 | 03/30/94 | 0.01 | 0.12 |
| Kennett, MO | 12/02/92 | 06/15/93 | 13.56 | 10.82 |
| Kennett, MO | 11/18/93 | 05/03/94 | 0.64 | 2.80 |
| Scobey, MT | 10/03/88 | 04/17/89 | 5.47 | 5.09 |
| Scobey, MT F | 10/04/89 | 05/04/90 | 1.34 | 2.50 |
| Scobey, MT S | 10/04/89 | 05/04/90 | 0.39 | 1.68 |
| Plains, TX E | 12/12/95 | 06/04/96 | 3.83 | 3.29 |
| Plains, TX B (800m) | 12/12/95 | 06/04/96 | 2.02 | 1.94 |
| Plains, TX B (1600m) | 12/12/95 | 06/04/96 | 1.55 | 0.66 |

## Conclusions

Field erosion measuring equipment has been developed to test a new wind erosion model on a variety of weather, crop, soil, and farming systems. With the measurement of field erosion, establishing base-line conditions for future comparisons is possible. Field measurements verify that mass transport varies as the cube of the wind velocity. Transport mass increases with field length until the wind cannot transport additional material. Maximum transport rates of 1,403 kg/m-width have been measured at field sites. This level of transport is sufficient to destroy most crop seedlings within 15 minutes. Soil loss from a single storm was 8.03 kg/m$^2$ from a 2.5 ha circular field. Soil loss from an entire erosion season varied from 0.1 to 30.9 kg/m$^2$. Field size ranged from 2.5 to 145 ha.

Field measurements of wind erosion from 43 site/erosion periods verify that RWEQ is suitable for a variety of soil, weather, crop and management conditions. Because of its flexibility, effective and efficient wind-erosion control systems can be evaluated with RWEQ. More complex models including WEAM and TEAM are available, but may require input data not readily available. Efforts to improve wind erosion prediction are underway in the WEPS, WEAM, and TEAM efforts.

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# Quantification of Aeolian Sediment Balances from Soil Particle Transport Measurements

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## Abstract

Quantification of aeolian sediment balance requires detailed measurements of soil particle transport. For that purpose, several techniques and instruments exist that work on different spatial and temporal scales. The objectives of this paper are: 1) to describe two different devices for soil particle transport measurement, the saltiphone and the Modified Wilson and Cooke (MWAC) sediment catcher; and 2) to show how sediment balance can be quantified on different spatial scales. The saltiphone is an acoustic saltation sampler that continuously records the impact of saltating sand grains with a microphone. The output, in counts per unit of time, shows the temporal variability in saltation flux, and can be used to asses the number, duration, and intensity of storms. The MWAC sediment catcher traps aeolian material at seven heights between 0.05 and 1.00 m. For each storm, the MWAC catcher provides the total particle mass transport value at the point of observation. During a Sahelian field experiment, 21 of these catchers were installed in one 40 × 60 m plot, and four storms were sampled. Storm-based maps of particle mass transport were produced by applying geostatistics. These maps were used to calculate the sediment balance for the plot. Quantification of sediment balance on larger scales than the plot or field scale requires integration of different techniques in the same area. A method is described that combines ground-based experiments, wind-erosion modeling, remote sensing, and a geographical information system to quantify sediment balances on scales of tens to hundreds of square kilometers.

## Introduction

Wind erosion and sedimentation are the result of aeolian transport processes. Wind erosion is the removal of soil material (soil particles, nutrients, and organic matter), whereas sedimentation is the deposition of wind-blown material. Between erosion and sedimentation, the material is transported by three different transport processes: saltation, creep, and suspension. Saltating particles jump and bounce over the surface, reaching a maximum height of approximately 1 m, but the main particle mass moves just above the soil surface. Saltation transports soil particles with sizes roughly between 50 and 500 μm. When saltating particles fall to the soil surface they not only eject other saltating particles but also induce creep, the rolling and sliding of larger particles (>500 μm), and suspension, the raising and transport of dust particles (<100 μm). The overlap in diameters for suspension and saltation indicates that certain particles may be moved by different transport modes, depending on particle density and wind speed. The three transport processes move particles over a wide range of distances. During a storm, creep can move particles over distances from a few centimeters to several meters; saltating particles travel from a few meters to a few hundred meters; and suspension transport ranges from tens of meters to thousands of kilometers.

Quantification of wind-blown-particle transport in the field is difficult because of large temporal and spatial variability in particle mass flux (Wilson and Cooke 1980). At a certain location, the number of wind erosion events differs from year to year, and during a particular year, storms are different in duration, wind speed, and wind direction. This results in a wide range of particle mass fluxes. Moreover, soil erodibility is determined by several variables like soil texture, surface roughness, and topography. These variables usually show spatial variability, resulting in spatial variability in soil erodibility and thus in particle mass flux as well (Sterk and Stein 1997).

Measurement techniques of wind-blown-particle transport can be divided roughly into direct and indirect techniques, and are scale-dependent. Indirect techniques such as repeatedly measuring soil-surface elevation (e.g., Wilson and Cooke 1980; Gibbens et al. 1983) or the $^{137}Cs$ isotope technique (e.g., Chappell et al. 1996) do not quantify soil-particle transport itself, but determine the erosion or sedimentation rate from changes in soil surface elevation or $^{137}Cs$ concentration. These techniques provide point observations with a temporal resolution varying from days to several decades. A problem, however, is that in many areas where wind erosion occurs, the soil is also subject to water erosion, which makes it difficult to determine the rate of wind erosion only. Other indirect techniques that work on larger spatial scales and on similar or larger temporal scales are the use of remote sensing, for instance tracing sand and dust movement in the Saharan desert (e.g., Mainguet 1984), and the description of wind erosion features in geomorphological studies (e.g., Cornish 1900; Jawad Ali and Al-Ani 1983).

Direct measurement techniques sample fluxes of wind-blown particles at a fixed position. Erosion and sedimentation in a certain area can only be determined from the spatial distribution of a number of these transport observations by calculating a sediment balance, which is the mass balance between input and output of soil particles (Mainguet 1996).

The different devices can roughly be divided into two groups. The first group consists of catcher-type and filter-type samplers, which are characterized by a relatively low temporal resolution. For instance, sediment catchers continuously trap particles during storms, but the total particle mass flux can only be determined after the storm by weighing the trapped material. The same holds for filter-type dust samplers (e.g., Rajot et al. 1996), which suck dustladen air through a filter. After a period of operation, the filter is replaced and, hence, the mass of dust on the filter represents the total mass flux for that period.

The second group of direct samplers is characterized by a high temporal resolution. These samplers continuously record soil-particle transport. Two devices have been developed that measure saltation transport by detecting particle impacts, with a microphone (Spaan and Van den Abeele 1991), or a piezoelectric crystal (Stockton and Gillette 1990). A slightly different technique was used by Janssen and Tetzlaff (1990), who developed a catcher that continuously weighs the mass of trapped saltation particles. Several instruments exist for continuous recording of dust transport. For instance, Koch et al. (1997) developed a device that monitors continuously the light scattered by three dust-size fractions. It also collects the material on a filter for final gravimetric analysis.

The purpose of this paper is to describe the use of the two samplers, a continuous recording saltation sampler and a sediment catcher, for the study of soil particle transport in the field. These devices operate at heights between 0 and 1 m, and therefore, fine suspended dust moving above 1 m is not considered here. In particular, the issue of upscaling is discussed. First, it is shown how maps of particle mass transport are created and used to calculate the sediment balance for the experimental plot. Finally, a method is presented that can be applied to quantify aeolian sediment balances at spatial scales of tens to hundreds of square kilometers.

## Materials and Methods

### Site Description

A field experiment was conducted in the West African Sahel, at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center. The site is located at Sadoré in southwest Niger, 45 km south of the capital, Niamey. In this region, farming practices, soil, and climate are favorable for wind erosion. Except for a few months in the growing season, the soil surface is mostly bare, and no adequate soil conservation measures are taken. Moreover, the sandy textures and dry climatic conditions make the soil erodible for most of the year. Winds that exceed the threshold wind-speed for soil-particle movement may occur during two distinct seasons. During the dry season (October–April), the area is invaded by dry and rather strong northeasterly winds, locally known as harmattan, that may result in moderate soil-particle transport. These winds originate over the Sahara desert, and from January to March they usually carry much dust from remote sources. Part of the transported dust is deposited in the Sahel, enriching soils with fine particles and nutrients (Drees et al. 1993).

The second and most important wind erosion period is the early rainy season (May–July), when rainfall comes with heavy thunderstorms that move westward through the Sahel. Within a fully-developed thunderstorm, strong vertical down drafts occur, causing a forward outflow of cold air that results in intense soil particle movement. The wind storms are often followed by high-intensity rainfall that usually creates much splash erosion.

## Quantification of Soil Particle Transport

Wind characteristics and soil particle transport were measured during the rainy seasons of 1993, 1994, and 1995. The equipment was installed in a field of 170 × 90 m on a sandy alfisol with 92.2% sand, 3.0% silt, and 4.8% clay. Wind speed was measured at a height of 2 m with an ordinary cup anemometer during the 1993 season, and with a fast response cup anemometer during in 1994 and 1995 seasons. Wind direction was measured with a wind vane. The measurements of horizontal particle mass transport were made with two devices, the saltiphone and the MWAC sediment catcher.

The saltiphone (Spaan and Van den Abeele 1991) is an acoustic saltation sensor that records the impact of saltating sand grains with a microphone (Fig. 1). The microphone is placed inside a steel tube (0.05 m in diameter, 0.13 m long) that protects it from severe weather conditions. The tube is mounted on a ball bearing and has two vanes at the back to keep it oriented into the wind.

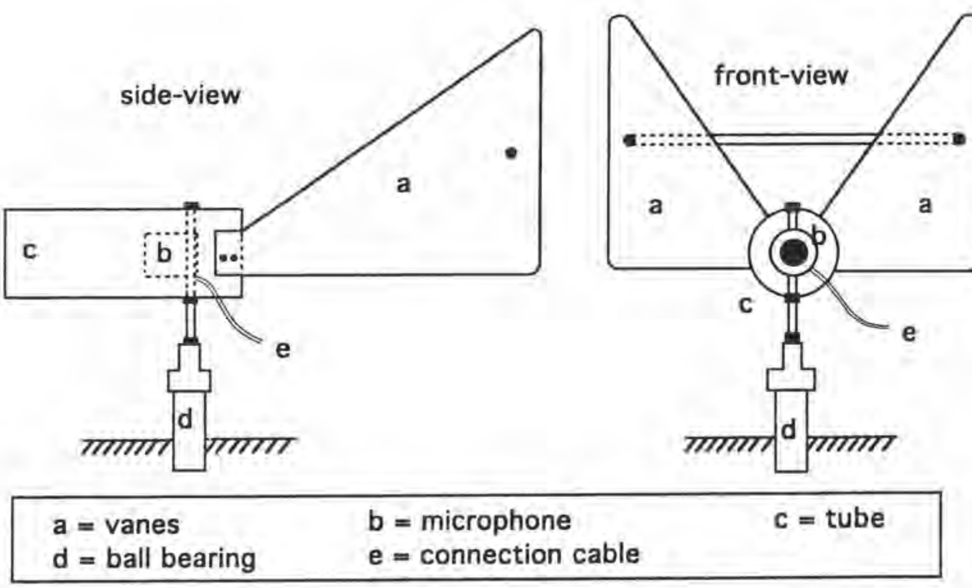


**Figure 1. The saltiphone.**

During a storm, some of the saltating sand grains moving through the tube hit the microphone and create high frequency signals. By amplifying these signals and filtering low-frequency signals, saltating sand can be distinguished from other noise such as that created by wind and rain. Every amplified signal, or pulse, is cut off after 1 ms, so, theoretically, a maximum of 1,000 grains per second can be recorded. The actual number of impacts may be higher due to the overlap of particle impacts during the 1 ms pulse.

The saltiphones were installed with the center of the microphones positioned at a height of 0.10 m. Pulses were recorded with a data logger. A one minute sampling period was used in 1993 season, and one second period in 1994 and 1995. The output, in counts per unit of time, was used to determine the number, duration, and intensity of storms. The threshold wind-speed for soil-particle movement was also determined.

The MWAC sediment catcher (Sterk and Raats 1996) has seven sediment traps attached at heights between 0.05 and 1.00 m (Fig. 2), which means that trapped material is a mixture of saltation and suspension particles. Creep particles are not trapped. After a storm, the sediment in each trap is collected and weighed. For each catcher and storm, a model is fitted through seven observations of the horizontal particle mass flux (Sterk and Raats 1996):

$$q(z) = a\left(\frac{z}{\alpha}+1\right)^{-b} + c\exp\left(-\frac{z}{\beta}\right) \qquad [1]$$

where $q(z)$ is the horizontal particle mass flux (kg/m$^2$ per second) at height $z$ (m), and $a$, $\alpha$, $b$, $c$, and $\beta$ are regression coefficients. The model describes the vertical profile of horizontal mass flux from the soil surface ($z$=0) to any height $z$, but is usually not extended to heights >1 m, since it cannot be calibrated at that height.

Integration of the mass flux profile over heights from $z$=0 to 1 m and correction for the trapping efficiency of the MWAC catcher (0.49) result in a total particle mass transport rate (kg/m per second) at the point of sampling. When multiplied by the storm duration, a total particle mass transport value (kg/m) is obtained. This value represents the total mass of sediment below 1 m that passes a strip 1 m wide perpendicular to the mean wind direction of the storm. It is assumed that the contribution of the sediment moving above 1 m to the total mass transport can be ignored.

During the 1993 season, 21 MWAC catchers were used to study the spatial variability in wind-blown mass transport by applying geostatistics (Sterk and Stein 1997). The catchers were installed in an experimental plot (40 × 60 m) within the measurement field. They were regularly distributed over the plot in three rows of six catchers, with the three remaining catchers placed between two rows. Four storms were sampled during the 1993 rainy season.

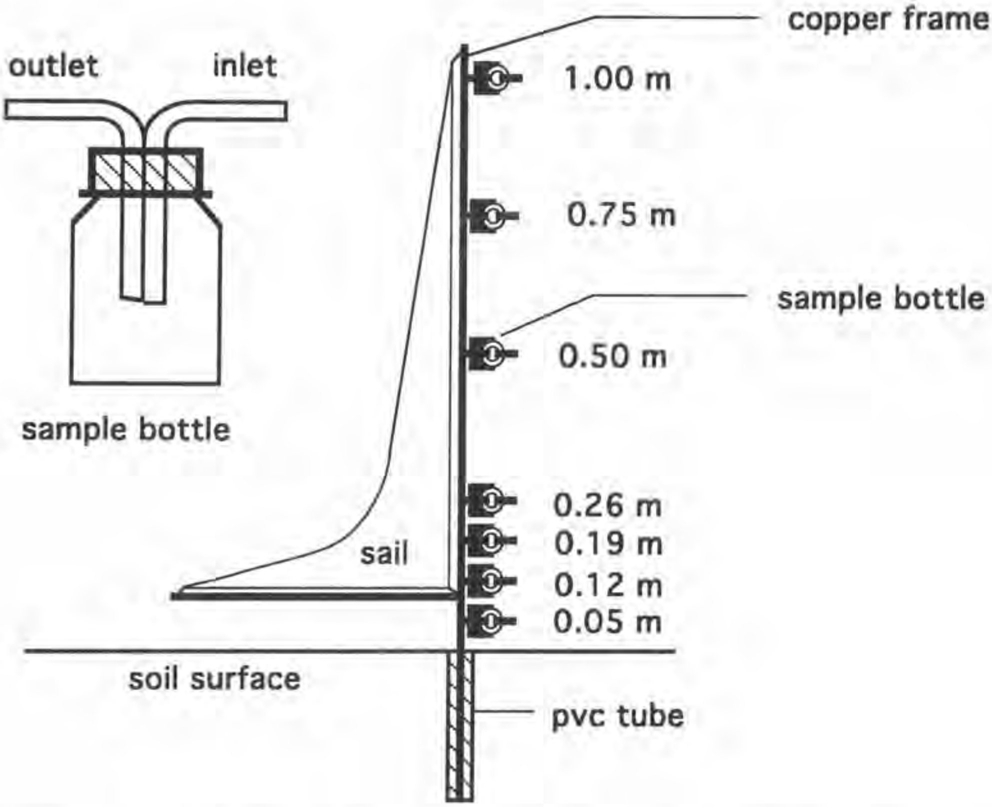


**Figure 2. The Modified Wilson and Cooke sediment catcher.**

Observations of total particle mass transport were used for geostatistical analysis. Geostatistical theory uses the concept of spatial correlation, which means that observations of a spatially distributed variable at any two points close to each other are more similar than observations at two points at a larger distance (Journel and Huijbregts 1978). By modeling the spatial correlation between observations as a function of distance (variogram), good quality maps of the variable are made with the spatial interpolation technique of kriging.

Since 21 observations are not sufficient to reliably estimate a variogram for each storm, the analysis was extended from the space domain into the space-time domain by pooling the four storms. Full details about this procedure are not given here, but can be found in Sterk and Stein (1997). The data and results of this study are briefly described in this paper. During the 1994 and 1995 seasons, 20 MWAC catchers were used to test the effectiveness of different mulch application rates in reducing soil particle transport (Sterk and Spaan 1997). Two plots of 55 × 70 m were both equipped with 10 catchers. One plot was covered with mulch, while the other remained bare during the two seasons. Only the meteorological and particle mass transport data from the plot without mulch are presented here.

## Results and Discussion

### Temporal Variability in Soil Particle Transport

In total, 24 wind storms were recorded during three field seasons (Table 1). Only four storms were recorded during the first, which is an exceptionally small number for this region. During the previous three seasons, 21, 13, and 15 events, respectively, were recorded at the ICRISAT Sahelian Center (Michels 1994). The average number of wind storms per season during six years was 12.

**Table 1. Characteristics of wind storms during the 1993, 1994, and 1995 rainy seasons at the ICRISAT Sahelian Center, Sadoré.**

| Year | Date | $\overline{u}$ (m/s) | W dir (°) | Dur (s) | $\overline{M}$ kg/m | CV (%) | n |
|---|---|---|---|---|---|---|---|
| 1993 | 13 June | 10.3 | 135.0 | 1481 | 102.7 | 35.9 | 20 |
| | 27 June | 7.6 | 179.9 | 1320 | 15.5 | 33.5 | 21 |
| | 30 June | 8.9 | 123.4 | 1321 | 31.8 | 46.6 | 21 |
| | 1 July | 9.2 | 159.3 | 3004 | 149.8 | 34.5 | 21 |
| 1994 | 7 June | 7.7 | 180.0 | 3835 | 67.5 | 39.1 | 10 |
| | 10 June | 12.3 | 37.8 | 464 | 71.4 | 25.2 | 10 |
| | 14 June | 7.4 | 107.5 | 2007 | 14.0 | 29.2 | 10 |
| | 15 June | 15.8 | 47.4 | 942 | nd | nd | 10 |
| | 18 June | 10.7 | 94.4 | 1209 | 61.4 | 21.0 | 10 |
| | 27 June | 9.4 | 118.1 | 515 | 37.0 | 24.8 | 10 |
| | 1 July | 8.4 | 150.9 | 584 | 41.9 | 27.7 | 10 |
| | 4 July | 10.6 | 81.2 | 838 | 65.4 | 16.5 | 10 |
| | 9 July | 8.3 | 94.5 | 822 | 17.8 | 27.2 | 10 |
| | 12 July | 9.4 | 75.7 | 902 | 36.4 | 18.5 | 10 |
| 1995 | 28 May | 8.6 | 160.4 | 1983 | 271.9 | 16.4 | 10 |
| | 5 June | 9.0 | 175.2 | 2157 | 113.7 | 15.1 | 10 |
| | 13 June | 9.1 | 153.8 | 600 | 71.7 | 14.4 | 10 |
| | 14 June | 11.1 | 37.6 | 1086 | 117.1 | 14.1 | 10 |
| | 17 June | 9.4 | 173.3 | 1893 | 187.4 | 18.4 | 10 |
| | 20 June | 8.8 | 160.4 | 1662 | 174.3 | 18.3 | 10 |
| | 25 June | 9.6 | 86.9 | 415 | 30.7 | 22.7 | 10 |
| | 8 July | 9.3 | 131.1 | 1092 | 71.0 | 16.8 | 10 |
| | 13 July | 11.3 | 91.7 | 723 | 89.5 | 16.1 | 10 |
| | 16 July | 8.9 | 175.6 | 1034 | 55.8 | 28.6 | 10 |

$\overline{u}$=average wind speed; Wdir=average wind direction (0°=north); Dur=storm duration; $\overline{M}$=average total mass transport value; CV=coefficient of variation; n=number of MWAC catchers; nd=not determined.

The storms were very different in terms of wind speed, wind direction, and duration (Table 1). This variability can be explained by the local character of the thunderstorms. The most severe conditions are expected near the center of the thunderstorm, where a forward, i.e. easterly, outflow of cold air occurs. Away from the center, conditions are less severe, with lower wind speeds and wind direction shifted either northward or southward. Furthermore, the duration of wind storms is likely to change position relative to the center of the cloud. The probability of rain decreases away from the center, which may cause a longer duration at the northern and southern limits (compared with the center). Hence, the characteristics of a storm at a certain location depend on the distance to the center of the cloud.

The simultaneous recording of wind speed and saltation flux with one saltiphone during a typical Sahelian storm (Fig. 3) clearly illustrates the temporal variability in saltation transport. Quiet periods, with little activity, alternate with intense bursts of saltation transport. A good correlation between instantaneous wind speed and saltation flux exists (r=0.65). The best correlation, however, is obtained if a time lag of one second between saltation flux and wind speed (r=0.71) is assumed, indicating that the response time of saltating sand grains to wind speed fluctuation is in the order of one second (Sterk et al. 1997).

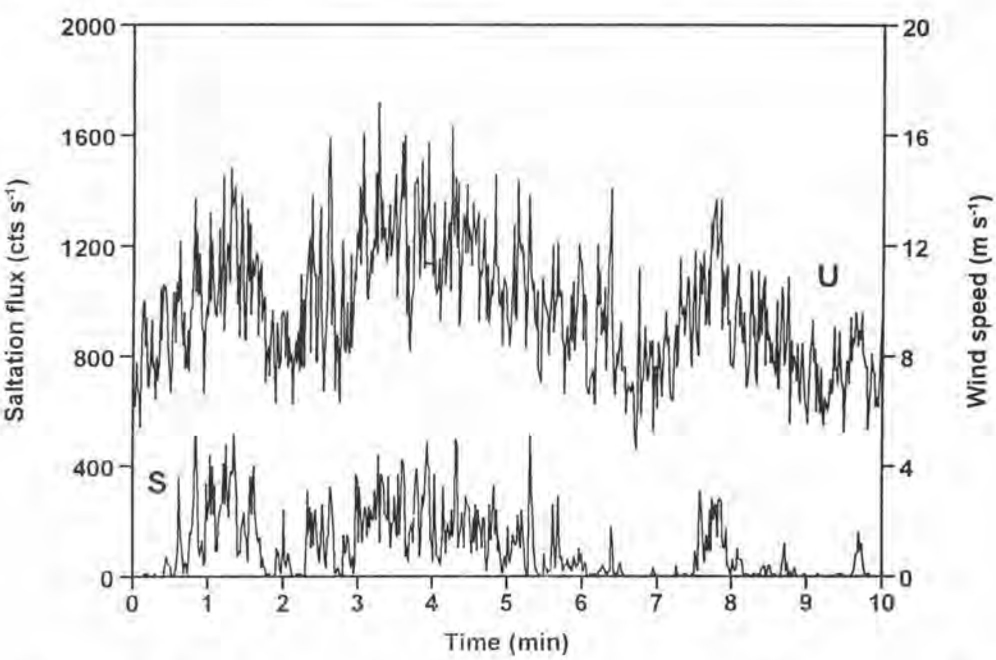


**Figure 3. Graph of instantaneous wind speed (U) and saltation flux (S) vs time for a typical Sahelian wind storm (27 June 1994).**

By plotting the saltation count rate as a function of wind speed, the threshold wind-speed for soil particle movement can be determined. This was done for the four storms in 1993 (Fig. 4), when saltation transport and wind speed were recorded at one minute intervals. The threshold wind-speed at a height of 2 m was approximately 8 m/s for this sandy Sahelian soil.

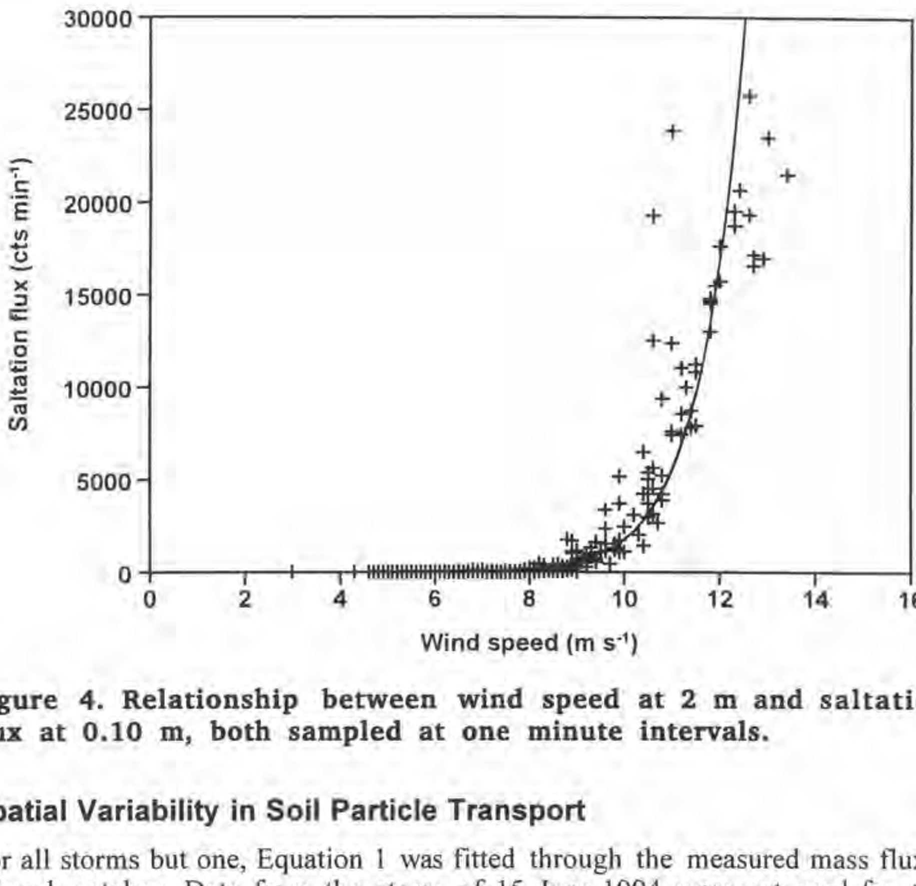


**Figure 4. Relationship between wind speed at 2 m and saltation flux at 0.10 m, both sampled at one minute intervals.**

## Spatial Variability in Soil Particle Transport

For all storms but one, Equation 1 was fitted through the measured mass fluxes of each catcher. Data from the storm of 15 June 1994 were not used for the analysis. This storm was immediately followed by 25 mm of rain in only 35 min. Although the average rain intensity was moderately high (42.9 mm/h), the instantaneous value exceeded 100 mm/h several times, and created much splash erosion, while the instantaneous wind speed exceeded 20 m/s. Part of the splash material entered the sediment traps and got mixed with wind-blown material. This problem did not occur during the other events, although several wind storms were immediately followed by rain. During some of those events, splash material clogged the inlet tubes of the lowest traps, but it was not observed to have entered the bottles (Sterk and Spaan 1997).

This relative insensitivity to splash erosion is an important advantage of the MWAC catcher compared with other sediment catchers. For instance, in 1993, 10 Big Spring Number Eight (BSNE) traps (Fryrear 1986) were installed in the field at a height of 10 cm. During one storm, without any wind-blown-particle transport prior to rain, between 17 and 50 g of splash material was collected by the BSNE traps, whereas the MWAC traps were still empty (Sterk, unpublished data). Therefore, traps like the BSNE may cause severe overestimation of wind-blown particle transport during early rainy season storms, and should not be used.

Figure 5 shows a fitted particle mass flux profile for one sediment catcher during the storm of 1 July 1993. The profile has a maximum at the soil surface and decreases sharply with increasing height. In general, the fitted profiles show good agreement with observations. Average deviations between measured and calculated mass flux for the four storms of 1993 increased from 0.1% at the lowest sampling level to 38.0% at the highest. The larger deviations at the higher sampling levels were caused by bigger measurement errors due to the very small quantities trapped at those heights (Sterk and Raats 1996).

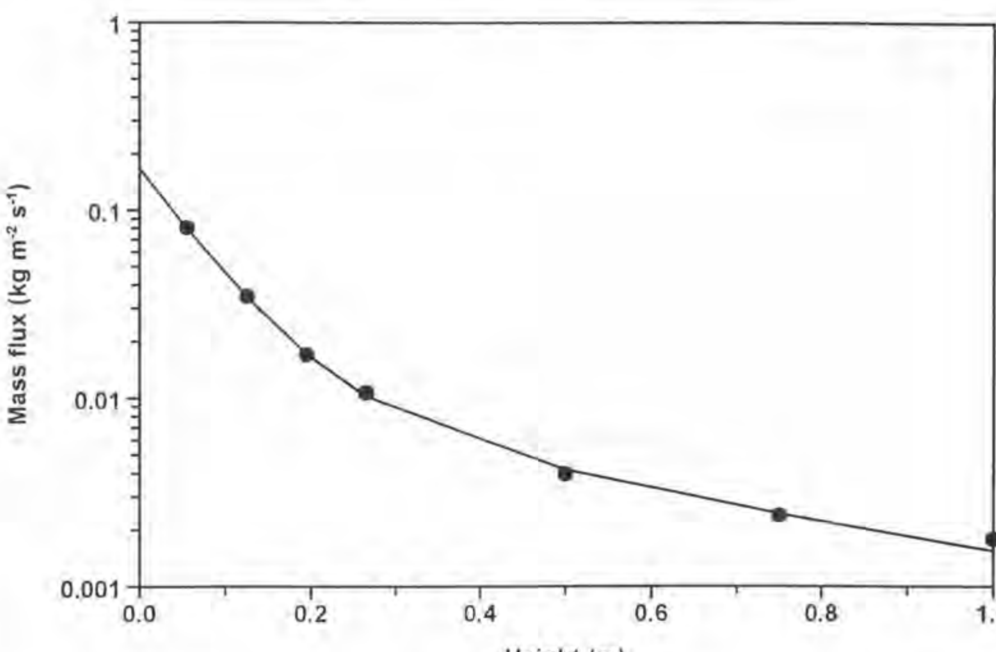


**Figure 5. A fitted profile through measured particle mass flux with one MWAC sediment catcher during the storm of 13 June 1993.**

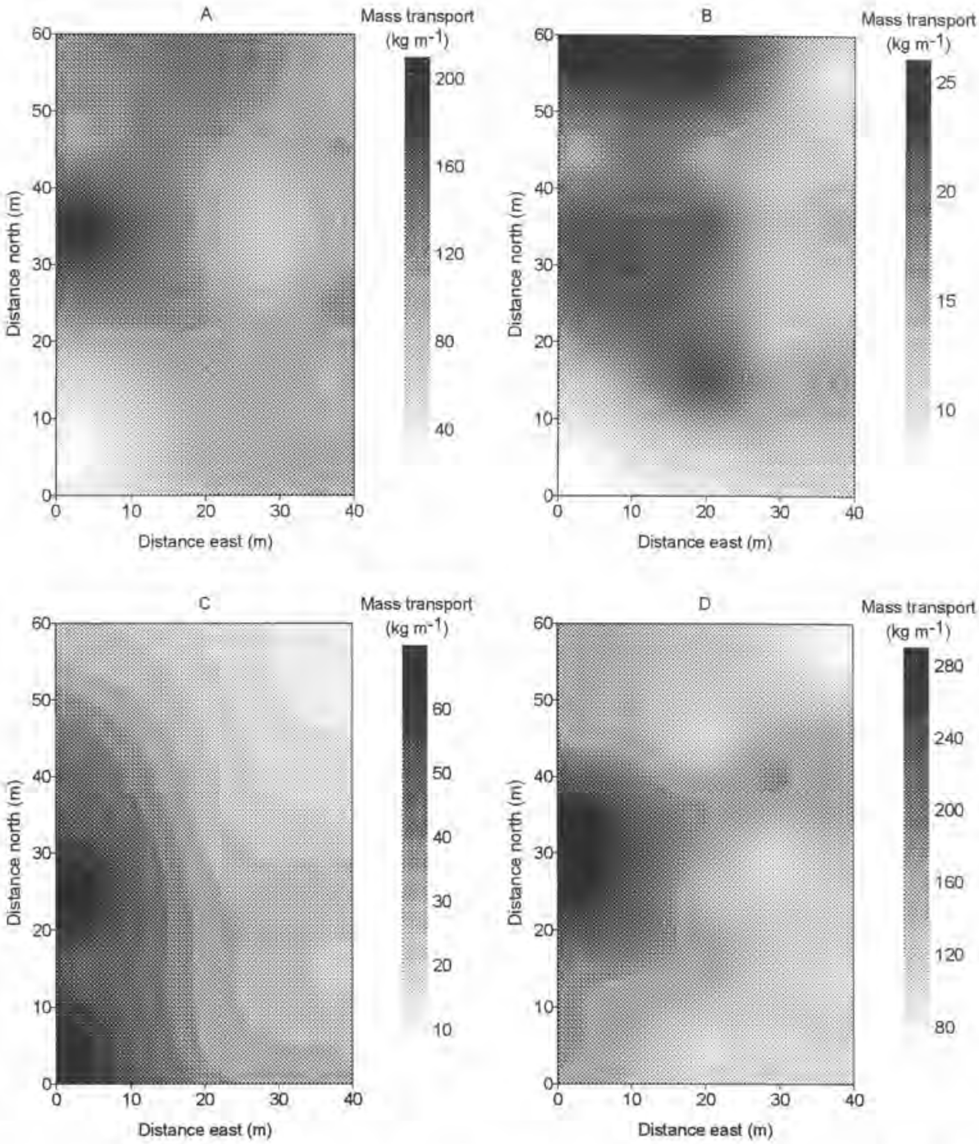


**Figure 6. Maps of total particle mass transport produced by kriging. Storm dates are (A) 13 June, (B) 27 June, (C) 30 June, and (D) 1 July 1993.**

Total mass transport values were calculated for each catcher and storm from the vertical mass flux profiles. In Table 1 the average values and coefficients of variation are given. Individual point observations of particle mass transport do not give any information about erosion or sedimentation. For that purpose, the sediment balance for a defined area needs to be determined. A negative balance indicates erosion, a positive balance indicates sedimentation, and a zero balance indicates transport only (Mainguet 1996).

Data from the four storms in 1993 were used to produce storm-based maps of wind-blown-particle mass transport with kriging (Sterk and Stein 1997). The maps (Fig. 6) provide the best linear unbiased predictions (Stein and Corsten 1991) of total particle mass transport at each unsampled location, and are therefore well suited for calculating net soil losses from the experimental plot. For all four storms, sediment balances (Table 2) were determined by averaging the kriging predictions along the four plot boundaries (Sterk and Stein 1997). Two boundaries contributed to input and two to output of sediment, respectively. During the first, third, and fourth storms, the material moved into the plot across the southern and eastern boundaries and left the plot via the northern and western boundaries. During the second storm, when the wind direction was from the south, only the southern and northern boundaries contributed to input and output, respectively.

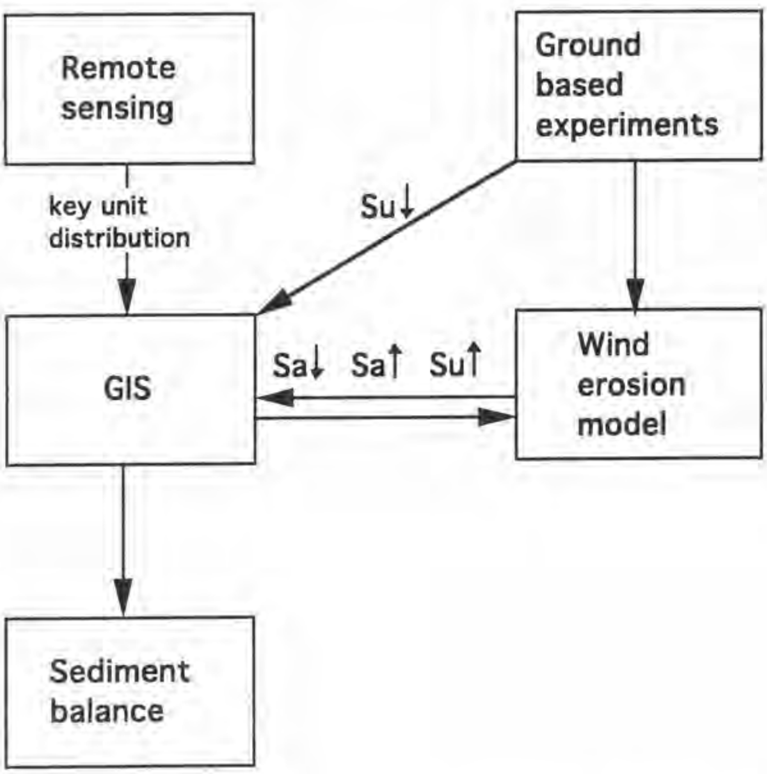


**Figure 7. Integrated system for the quantification of aeolian sediment balances at spatial scales varying from tens to hundreds of square kilometers.**

**Table 2. Sediment balances for the experimental plot during four storms at the ICRISAT Sahelian Center, 1993 rainy season.**

| Storm date | Input (kg/m$^2$) | Output (kg/m$^2$) | Balance (kg/m$^2$) |
|---|---|---|---|
| 13 June | 4.7 | 5.9 | -1.2 |
| 27 June | 0.2 | 0.4 | -0.2 |
| 30 June | 1.4 | 1.9 | -0.5 |
| 1 July | 6.2 | 8.9 | -2.7 |
| Total | 12.5 | 17.1 | -4.6 |

Sediment balance=sediment input–sediment output.

The maps clearly show that particle mass transport is characterized by a large spatial variability. Because of this variation, the traditional method of describing soil loss per unit area (Table 2) is not the best erosion indicator (Wilson and Cooke 1980). It is more useful to distinguish erosion and deposition areas in the plot from downwind gradients in gray values. Positive gradients (from light to dark) are associated with erosion, negative gradients (from dark to light) with deposition, and zero gradients with transport only. Combining this information with maps for soil characteristics, surface roughness, crop characteristics, and topography may lead to a better understanding of soil particle transport processes.

The pattern of particle mass transport is not constant, but rather changes from storm to storm. Prediction of these patterns with a wind erosion model requires detailed input of soil characteristics, crop characteristics, and wind field in many positions, which makes modeling at such a level virtually impossible.

## Upscaling

The application of geostatistics is, in fact, an example of upscaling. A limited number of point observations of particle mass transport was used to determine mass transport at every point in the experimental plot, hence the geostatistical analysis involved an upscaling from point scale to plot scale. The maps produced are useful to distinguish erosion and deposition areas within the plot, and to calculate soil loss from the plot (Table 2). Although this loss is dramatic, it is from one small and unprotected plot only. Since the main mass of material was moved by saltation, which is a short-range transport process, much of this material may be trapped again in nearby fields with soil conservation measures or good vegetation cover (Sterk et al. 1996). So, when studying the effects of wind erosion on entire farming systems, it is necessary to quantify soil particle transport on scales larger than that of an individual field.

Herrmann and Sterk (1996) propose a method for quantifying storm-based sediment balances of wind-blown material at spatial scales on the order of 100 km$^2$. This method consists of: 1) selection of key units; 2) quantification of the sediment balance in each key unit, and 3) quantification of the sediment balance for the total area based on the contributions of separate key units.

### Selection of key units

Key units are areas which are more or less equal in erodibility. Selection of key units is based on surface characteristics like soil type, soil surface roughness, and vegetation.

### Quantification of the sediment balance in each key unit

Soil-particle transport can take place in any one of the three transport modes: creep, saltation, or suspension. It is assumed that creep transport can be included in the saltation component (Fryrear and Saleh 1993). The sediment balance is then equal to:

$$\Delta S = S_a \downarrow - S_u \uparrow \qquad [2]$$

where $\Delta S$ is the sediment balance (kg/m$^2$); the subscripts a and u denote saltation and suspension, and the arrows $\downarrow$ and $\uparrow$ indicate input and output, respectively. For each key unit and storm, the four components need to be determined by experimentation at selected sites. The data are used to develop and calibrate a wind erosion model.

## Quantification of the Sediment Balance for the Total Area

A storm-based sediment balance for the defined region is calculated from the distribution of the key units within the region, meteorological data, and the calibrated wind erosion model.

In Figure 7, a scheme is shown that illustrates how different techniques can be integrated to estimate storm-based sediment balances on spatial scales of several tens to hundreds of square kilometers. Remote sensing provides data on vegetation and soil-surface characteristics. Based on these data, different key units are selected and the boundaries of the single key unit areas determined. The data are stored in a geographical information system (GIS). The ground-based experiments include meteorological measurements for the wind-erosion model, and dust deposition measurements, since input of dust (Su$\downarrow$) from remote areas cannot be calculated with storm-based wind-erosion models. The model calculates the components Sa$\downarrow$, Sa$\uparrow$, and Su$\uparrow$ on the basis of the meteorological data (wind speed, wind direction, rainfall, etc.) and geometrical information of the single key unit areas. Based on the sediment balances for each separate key unit area, the total sediment balance for the region is calculated by the GIS. In addition, the GIS provides the possibility of producing maps that show the spatial distribution of particle mass transport in the region.

## Conclusions

Several instruments and techniques for the measurement of soil-particle transport under natural conditions exist. These techniques quantify soil-particle transport either directly or indirectly, and work on different spatial and temporal scales. Of the two devices used in this study, the saltiphone has the higher temporal resolution. It quantifies the temporal variability in saltation flux at a certain position. The number, duration, and intensity of storms can be determined from the output. When combined with wind-speed measurements, the threshold wind-speed for soil particle movement can also be determined.

The MWAC sediment catcher gives point observations of particle mass transport at a maximum temporal resolution of the storm duration. By installing many of these catchers in one field or plot, a high spatial resolution is obtained, which makes it possible to create storm-based maps of particle mass transport by applying geostatistics. From these maps, sediment balances for the experimental area, which show the spatial variability in particle mass transport, can be calculated. This kind of information is important when the impact of wind-blown particle transport on soils and crops is studied on the field scale.

For studying the impact of wind action on soil and crops at larger spatial scales, it is necessary to integrate different techniques such as a geographical information system, wind-erosion modeling, remote sensing, and field measurements in the same area. However, such a procedure inherently leads to a loss of accuracy, since wind-erosion models are not able to simulate the complicated spatial patterns of particle mass transport derived from the geostatistical analysis.

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# Wind Erosion in Niger: Farmer Perceptions, Traditional Techniques to Prevent and Combat Wind Erosion, and Farmer Adoption of Modern Soil Conservation Technologies

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## Abstract

Farmers in Niger have their own opinions about the causes and problems of wind erosion. Their views are based on experience and observation, gained in their own environment. Farmers mentioned soil loss and plant damage as the most important nuisances of wind erosion. They have their own methods for controlling wind erosion, such as mulching with organic matter, fallow, manure applications (pit holes), herding strategies, and cover cropping. These are based on their available resources. Without additional financial and human resources, local practices cannot be implemented on a large scale. Insufficient resources, and socioeconomic and institutional constraints such as cattle ownership, land tenure, labor requirements, and input prices, restrict the application of wind-erosion-control techniques. New technologies must fit into the socioeconomic environment, because without farmer involvement, wind erosion and soil degradation will not be offset. Subsidiarity and complementarity of local and researcher knowledge demand the development of institutional pluralism within research organizations to the final benefit of farmers and the agricultural sector as a whole. This may first require institutional reform, but, perhaps more important, an attitudinal change in the research community must occur. Future research should include farming systems and analysis of costs and benefits of subsidy levels required to increase the implementation of wind-erosion control.

## Introduction

Most soils in the West African Sahel (WAS) are fragile and deficient in nutrients and organic matter (Sivakumar 1989). In the absence of appropriate conservation practices, the sandy soils are prone to wind erosion and depletion of nutrients (Bationo and Mokwunye 1991). During the last three decades, soil degradation has grown worse because of decreasing rainfall, overstocking of the natural pasture with livestock, and the rapid growth of population to critical levels (Sivakumar 1989). The ongoing process of decreasing soil fertility and advancing soil degradation must be reversed to encourage agricultural development in the WAS. Agricultural research and technology transfer are crucial in this process. This is highlighted by the case of Niger, West Africa.

Wind erosion events and soil degradation in Niger have been observed for several decades (Raulin 1965). Often, wind erosion is most prominent in areas with low biomass production potential (Michels 1994; Sivakumar 1989). Soil-conservation techniques have found little acceptance in Sahelian farming systems (Deuson and Sanders 1990). Frequently, there is a conflict between long-term soil-conservation and short-term production-increasing techniques. In making land-use decisions, farm households need to consider both agro-ecological and economic consequences. Evidence from Africa reveals that the reluctance of farmers to adopt soil conservation technologies has a logical base (Scoones et al. 1996). Promising technologies to control wind erosion in Niger have been studied intensively (Banzhaf et al. 1992; Michels et al. 1995a, 1995b; Renard and Vandenbeldt 1990). A recurring question is whether or not new innovations are acceptable to farmers, for example, if they are superior to local practices.

Sahelian farmers combine a range of exogenously and endogenously developed innovations (Lamers and Feil 1995; Scoones et al. 1996). Most local practices have their origin elsewhere and are not necessarily generated in the region where they are practiced, but they are adapted by and further developed within the community. Knowledge is obtained mostly via traditional communication channels, such as migration, visits during journeys and celebrations of the extended family, and market visits. Furthermore, local knowledge develops over time (Feil 1995; Scoones et al. 1996). Increasing evidence confirms that existing farming systems are a result of experience, knowledge, tradition, available resources, priorities, environment, technology level, political, and economic and market conditions (Feil 1995). Farming systems change not only from region to region, but also from village to village, and between farmer groups within a village. It is not only vital to know what farmers do, but equally enlightening to understand why farmers do not do things. Local knowledge has some analogy with a drifting iceberg: most of it is not directly visible. This paper summarizes various views, current practices, and future potential with respect to wind erosion and its control measures in west Niger.

## Farming Systems in West Niger

The amount of rainfall and its distribution are the farmer's two principal guidelines for cultivation in Niger. Even though this appears straightforward, farmers operate complex production systems and combine subsistence and commercial activities that involve a range of crops and animals under diverse socioeconomic conditions (McIntire et al. 1989). The mixed-farming systems in western Niger, with a mean farm size of about 10 ha (McIntire et al. 1989), are based on limited family labor and low cash inputs. Agriculture is dominated by pearl millet (*Pennisetum glaucum*) and to a lesser extent by sorghum (*Sorghum bicolor*), both of which are usually associated with cowpea (*Vigna unguiculata*). Millet grain yield is 250–400 kg/ha, whereas stover yield is 800–1,500. Most of the cropping budget is spent hiring manpower for weeding.

Additional cash income is earned with off-farm activities, particularly during the dry season (Baidu-Forson 1988). All cropping activities are usually done manually. Most households own sheep, goats, and/or cattle. Hay from pulses and grasses enrich the millet-stover diet of livestock in the dry season (Lamers et al. 1996b). Animal traction is limited to bulky carts. The Sahelian farming systems have many goals and undertake a variety of activities to achieve these goals (Lamers and Bruentrup 1996). Agriculture, livestock, commerce, art, and off-season labor abroad are some of these activities, which are dispersed over the year and may have long-, medium- and short-term effects (Lamers and Feil 1995). Any new technology must fit into these farming systems. The effects of farming practices, livestock overgrazing, ineffective land-use, absence of transparent laws, and population growth have accelerated land degradation at alarming rates. But how do farmers perceive soil degradation caused by wind erosion, since they are often held, in part, responsible for the phenomenon?

## Farmer Perception of Wind Erosion

Household surveys have been conducted in western Niger to learn about the awareness and knowledge farmers have concerning wind erosion and control techniques (Feil and Lamers 1996; Lamers et al. 1995a). Farmers mentioned soil loss and plant damage as the most important nuisances of wind erosion. This occurred on the fields of 66% of the farmers surveyed in 1982–1992 (Fig. 1). Damage was perceived as removal of the top layer by 45% of the farmers, while 21% mentioned the subsequent formation of a surface crust. Farmers observed soil loss due to wind each year and on most fields, but soil erosion is considered harmful on specific patches within a field only. One-third said they had no wind erosion problem on their soils.

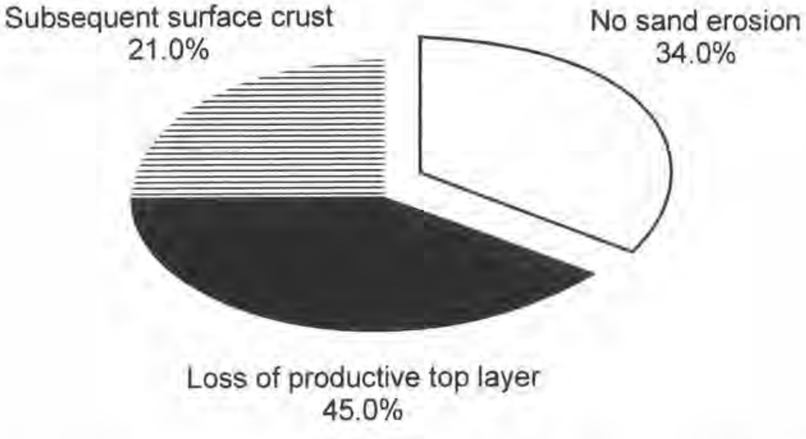


**Figure 1. Wind erosion effects on the soil as mentioned by farmers.**

Concerning crops, most farmers (69%) mentioned a damage to millet caused by high wind speed or by burial (Fig. 2). Within this group, 17% of the farmers were most concerned with air-blown sand burying young seedlings at the onset of the growing season. Mechanical damage of millet development was often observed by the farmers, but the subsequent retarded development was not considered a major concern. More than half of the farmers (52%) mentioned stem lodging as a possible direct effect of intensive winds, especially at the end of the growing season. Lodging retards grain ripening, whereas termites and rodents cause the actual losses. Nearly one third (31%) mentioned no crop damage due to high wind speeds.

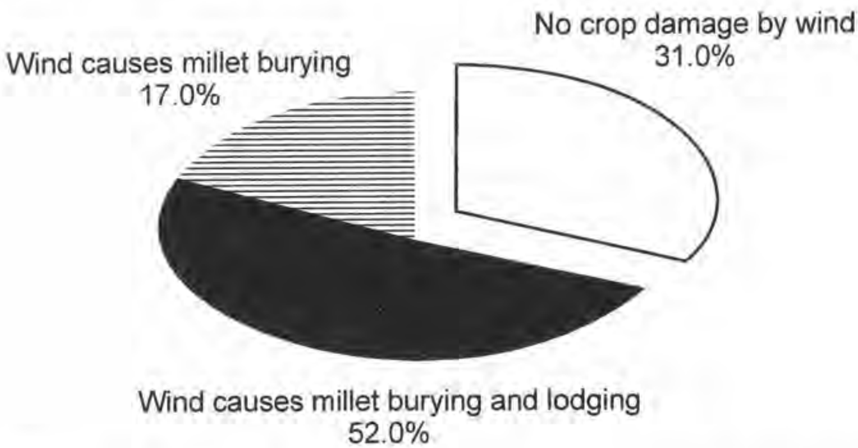


**Figure 2. Wind erosion effects on plants as mentioned by farmers.**

Farmer fields are characterized by small elevations and depressions within short distances. Because of the deposition of air-blown material, farmers consider micro-highs to contain a more sandy top layer than micro-lows with thinner top layers. In addition, farmers observed that micro-highs concur with more intensive plant growth, such as trees and bushes, which continue to trap sand (Feil and Lamers 1996). The decomposition of organic material is considered responsible for the increased fertility on the micro-highs.

Farmers view wind erosion as a vicious cycle originally initiated by decreasing yields due to low soil fertility or inadequate rainfall (Feil and Lamers 1996). Reduced stover yield means less mulching material, which leaves the topsoil layer prone to wind erosion resulting in soil being carried onto the slopes to micro-lows and micro-highs. After 3–4 years, the end stage of the erosion process is a micro-low with a surface crust.

The accuracy of farmer perception of wind erosion and soil and plant damage has been confirmed by on-farm and on-station studies (Lamers and Feil 1995). For instance, farmers know that the surface crust inhibits the infiltration of rain and thus renders these spots unsuitable for plant growth, as was concluded by Hoogmoed and Stroosnijder (1984). Furthermore, the sensitivity of young millet seedlings to burial and the delay of millet growth after exposure to wind and sand has been confirmed by wind-tunnel experiments (Michels 1994). Yet, farmers specified that millet plants would only perish when burial was immediately succeeded by drought and high temperatures. No research results could be found on yield losses due to lodging. Geiger and Manu (1993) report on the relationship between soil fertility and micro-elevation. Millet grain yield in sites with micro-highs was 120% higher than on sites without micro-highs.

Farmers surveyed consider wind erosion a minor problem. They recognize that wind erosion undermines their production capacity, but the degree of this nuisance is considered tolerable. Whereas the farmers' view is based on experience and observations limited to their surrounding, the researchers' knowledge on the degree of wind erosion derives from plot-based measurements which are extrapolated to assess total soil loss per hectare or even per region (Herrmann and Sterk 1994) and aerial photography. The conclusions are consistently dramatic, and call for immediate action. However, recent research results also conclude that wind erosion in one part of the field leads to soil enrichment in another part through deposition (Drees et al. 1993; Herrmann and Sterk 1994). In contrast to K, Ca, and Mg, soil P concentrations cannot be compensated for by dust deposition (Herrmann and Sterk 1994). What evidence bears more truth? Farmers' observation and experience, which makes them conclude that wind erosion is a minor problem (which explains their reaction towards prevention and combat of wind erosion), or researchers' measurements, which indicate on the one hand that soil loss is tremendous and damage to plants severe, but also that much soil is redistributed rather than being lost permanently? The impact of wind erosion on nutrient balance needs to be quantified, particularly on a regional scale.

## Traditional Techniques to Combat Wind Erosion

Farmers comprehend that vegetative cover is most effective to prevent wind erosion. For instance, the perennial grass *Andropogon gayanus* is used to mark borders between fields and, at the same time, functions as a windbreak (Lamers et al. 1996b). Some farmers manage the natural regeneration of scattered tree vegetation, which helps reduce wind erosion and provides food, feed, and wood (Feil and Lamers 1996). Tree species, such as *Combretum glutinosum*, *Piliostigma reticulatum*, *Guiera senegalensis*, and *Annona senegalensis*, are effective against wind erosion and also catch aeolian material, which improves soil fertility. Farmers observe increased wind erosion underneath other tree species, which are nevertheless tolerated because they produce palatable and nutritive fruits and leaves (Feil and Lamers 1996).

Aside from such practices, farmers prefer multipurpose management strategies with the principal aim of maintaining soil fertility, rather than a strategy to prevent wind erosion only. Multipurpose strategies not only reduce wind erosion but also, for example, striga infestation, to mention an additional key problem of Sahelian farmers (Feil and Lamers 1996; Lamers and Feil 1995). To maintain soil fertility, farmers in many WAS countries use techniques such as mulching, cover cropping, incorporation of organic matter, animal manure, crop rotation, leguminous crops, and herding strategies (Hailu and Runge-Metzger 1992; Vlaar 1992). Although these practices are not effective in establishing sustainable agro-ecosystems on a large scale (Hailu and Runge-Metzger 1992), they do show farmer awareness of problems and possible solutions. The principal problem of most farmers is that they are unable to implement these technologies on a large scale. This is due to insufficient resources, and socioeconomic and institutional constraints such as cattle ownership, land tenure, labor requirements, and input prices. For instance, the traditional methods for soil fertility management are fallow and manuring (Feil and Lamers 1995). The duration of fallow periods is declining under increasing demographic pressure. A drop in manuring is caused by declining stocks and reduced access to nomadic herds.

Farmer remedies to restore wind-erosion damage are based on the limited resources available (Lamers et al. 1994a; Lamers et al. 1995a). For instance, surface crusts created by wind erosion can be tilled with hoes, but farmers prefer an alternative solution over this labor-intensive activity. They know that a mulch protects the soil against wind erosion and improves soil fertility at the same time because it is decomposed by termites. They restore crusted spots by transferring millet stalks from more producted sites (Lamers and Feil 1995), twigs from trees and shrubs (Baidu-Forson and Igbo 1996), household refuse, and any other mulching material (Lamers et al. 1995b) to such patches. After 1–2 years, a sandy topsoil is regained and soil structure and soil fertility are improved (Chase and Boudouresque 1987). Geiger and Manu (1993) conclude that the management of micro-sites should be adapted to their production potentials.

Other soil conservation practices in Niger and Burkina Faso, such as by the use of zays (planted pit-holes), half-moons, and earth or rock bunds, are also based on traditional knowledge (Scoones et al. 1996; Vlaar 1992). These technologies are implemented on degraded (laterite) soils. Most preferred is the use of zays in combination with manure or P fertilizers, which ensures short-term improvement, and, when used with stone bunds, long-term effects.

Characteristics of indigenous knowledge of soil conservation technologies are summarized in Table 1. Local practices often have multiple functions: they are adapted to the environment and the farming systems, flexible, and have short-term returns to labor (Scoones et al. 1996).

**Table 1. Characteristics of externally and locally derived soil and water conservation technologies.**

| Characteristics of technology | Externally developed | Locally developed |
|---|---|---|
| Designer | Researchers and engineers | Local farmers |
| Purpose | Soil conservation | Multiple, depending on setting |
| Design features | Standardized | Flexible and adapted to local micro-variation |
| Construction | One-time | Incremental (fitting with household labor supply) |
| Labor demand | High | Variable, generally low |
| Return | Long-term (environmental investment) | Immediate return, particularly to labor |

After Scoones et al. (1996).

## Farmer Adoption of Modern Soil Conservation Technologies

Wind erosion in the Sahel can be controlled by soil cover such as cover crops or crop residue (Michels et al. 1995a, 1995b), soil roughening through tillage (Banzhaf et al 1992; Leihner et al. 1993), and the reduction of wind speed through annual or perennial grass barriers (Renard and Vandenbeldt 1990) or windbreaks (Lamers et al. 1994a, 1994b, 1994c; Michels 1994). Such control measures have the potential to establish sustainable agro-ecosystems, but they have found little acceptance in local farming systems on a large scale. Several studies indicate that improved soil conservation technologies, including wind-erosion control, are only profitable under specific conditions (Bruentrup et al. 1996; Lamers and Bruentrup 1996; Vlaar 1992). Controversially discussed during the debate on adoption of soil conservation innovations are population density, access to capital markets, financial returns to investments, the presence of functioning input-outputs markets, land tenure, and access to information and technology (Table 2).

The most appropriate technology is the one that best fits the farming system. Erosion-control technologies adopted in the past were simple, inexpensive, often based on local practices, and demanded few external inputs (Baidu-Forson and Ibro, 1995; Lamers and Feil 1995). They produced short-term benefits and required a minimum of community organization. Thus, for the purpose of adoption, it is imperative to pre-examine the consequences for the farming system, socio-cultural compatibility, and labor input, as well as costs for environmental innovations (Table 3).

**Table 2. Most mentioned characteristics influencing the adoption of environmental innovations.**

| Characteristic | Pros | Cons |
|---|---|---|
| Population density | High population density provokes land shortages and motivates the use of technology | High population density is also associated with low investment in soil conservation measures |
| Investment and access to capital | Without access to capital markets, limited investment incentives | Non-farm income is a key-substitute for credit |
| Return to soil conservation investment | Capital return to soil conservation methods is low | Short-term return is unimportant, but long-term return off-sets increasing costs |
| Market and infrastructure | Farmers' investment motivation rises with the rise in value of outputs | Higher output prices will encourage soil mining |
| Security and land tenure | Farmers will invest if benefits are obtained in the future | Land ownership does not automatically guarantee investment. Land-user rights should be assured |
| Access to information and technology | Increasing knowledge on innovations and their availability will increase adoption of new innovations | New innovations should be based on local practices and existing knowledge |

After Scoones et al. (1996).

The results illustrate that many of these technologies ingrain constraints for spontaneous adoption (Table 3). A controversial issue in relation to soil conservation is land ownership, which in Niger is regulated by both customary laws and state legislation. Customary tenure does not allow non-land-owners to plant trees, which constrains the development of agroforestry systems, whereas forest legislation limits the land owners' right to plant trees on their own land (Neef et al. 1995). However, general statements concerning land ownership should be made cautiously, because individual ownership does not automatically mean that soil improvement measures are implemented (Napier 1994). The low reputation of agricultural work, low return to additional invested labor, and more profitable off-farm activities play a role as well (Lamers and Feil 1995).

Many resources have been expended to generate technical knowledge and develop environmental innovations with the emphasis on details such as dimension, design, and implementation procedures, as well as monitoring, maintenance, and evaluation schedules (Scoones et al. 1996; Vlaar 1992). This has resulted in standardized solutions that can be transferred into extension messages suitable for extension manuals and training. The research community used to focus on soil loss as one in a series of major issues. Other important production constraints received separate attention and did, sometimes, lead to contradicting recommendations (Feil et al. 1995). Yet Sahelian farmers have to cope concurrently with short growing seasons, low inherent soil fertility (particularly phosphorus), limited and erratic rainfall, deep groundwater levels, frequent drought, and wind erosion (Bationo and Mokwunye 1991; Sivakumar 1987). Obviously, the development of standardized technologies for a single component of the cropping system without affect on other parts is virtually impossible. It is not enough to know the increase in yield or the decrease in soil loss if, for instance, the economic and social significance of the technologies are unknown.

**Table 3. Assessment of the most important research and extension recommendations for soil conservation in Niger.**

| Technology | Consequences for the farming system | Socio-cultural compatibility | Labor inputs and costs |
|---|---|---|---|
| Broadcast (2,000 kg CR/ha) | ++ | – | ++ |
| Banded (1,000 kg CR/ha) | – | 0 | ++ |
| Ridging | + | + | ++ |
| Breaking up crusts | 0 | 0 | ++ |
| Planted/natural windbreaks, vegetation strips | + | – | ++ |
| Managed natural regeneration, parkland, fallow | – – | ++ | – |
| Half-moon, earth/rock bunds | + | 0/– | ++ |

CR=millet crop residue; (--) very low; (-) low; (0) indifferent; (+) medium; and (++) high.

*Consequences for the farming system* indicates if the technology fits the current farming practices. "High" means a profound change can be awaited. *Socio-cultural compatibility* indicates if use of the technology fits the existing socio-cultural norms and rules. "High" means that it fits well with land tenure, ranging practices, work distribution, or goal setting. *Labor inputs and costs* comprise the direct as well as indirect costs and the need for liquidity. "High" signifies that the use of the technology is associated with important additional investments.

Because agronomic research aims to transfer its outcome into recommendations for users, solutions should be agronomically and economically superior to local practices, fit the socioeconomic environment of the farming systems, and be sustainable. This requires not one single, standardized technology, but recommendations that are flexible enough to deal with the diversity and variability of the farming community. Thus, any research concept requires a perspective of the whole farming system and a broader view than that of any single discipline. Experience from extension services in Africa shows that it is easier to bring different messages to one community than it is to bring different communities to one message (Duevel 1995).

Millet grain prices in Niger are fixed by the government in favor of urban households. Consequently, the low short-term return to millet production limits investment in technology. For instance, the need for land, as well as soil degradation, can be reduced by the use of mineral fertilizers (Bruentrup et al. 1996). The unattractive price ratio between crop and fertilizer, the liquidity constraints of farmers, and the unpredictable agro-climatic conditions do not motivate Nigerian farmers to invest in millet production. In the short-run, the economic feasibility of several soil-conservation technologies is not ensured (Lamers and Bruentrup 1996; Vlaar 1992). Moreover, recommending soil conservation techniques alone is not sufficient to sustain productivity. To obtain maximum benefit, soil conservation techniques need to be supplemented with plant nutrient inputs (Lamers 1995; Vlaar 1992). The additional cost comes on top of the initial investment farmers need to pay, and this reduces the chances of adoption (Lamers 1995; Lamers et al. 1996a).

## Conclusion

Sahelian farmers face increasing wind erosion and are aware that their local technologies to prevent and combat erosion are becoming increasingly inadequate. However, they cannot implement developed technologies because of overwhelming constraints. Evidence from the African continent reveals that the reluctance of farmers to adopt environmental innovations has a logical base. Aside from site-specific conditions, the farmer's choice is influenced by management, high initial cost, and labor demands, as well as land ownership, social, and perceptional aspects. Furthermore, on-station research focuses on the generation of knowledge about a specific component of a farming system with wide adaptability across a broad range of environments. The disadvantages of these standardized innovations outweigh the advantages. The development of environmental innovations for Sahelian farming systems requires that agronomic research be re-oriented towards greater interaction with farmers. This farmer-oriented, demand-driven research approach should focus on technology development that improves the overall productivity of a farming system within a specific environment.

Future research strategies on soil conservation should take into account local knowledge. It is less a question of choosing between local and researcher knowledge, and more of ensuring that researchers consider local knowledge while continuing to proceed with their objectives. There is no myth involved in local knowledge, neither will it provide the solution for the future, but it should be part of it. Subsidiarity and complementarity of local and researcher knowledge demand the development of institutional pluralism within research organizations to the final benefit of farmers and the agricultural sector as a whole. This will require institutional reform, and, perhaps more importantly, an attitudinal change within the research community.

It is necessary to convince decision makers that the use of any soil-conservation technology must be made less risky for farmers. Future research must include the integration of technologies within a given farming system. Many farmers, as well as researchers and extension agencies, know how to increase yield, but do not know how to increase farmer income. The key question is not how farmers can make optimal use of the available resources, which has been the main objective in the past. The question now is how farmers can benefit from new technologies, since more risk is involved when implementing soil conservation technologies. Research should analyze the cost and benefit of the subsidy levels that are required to implement control measures leading to more agronomically and economically appropriate levels.

## Acknowledgments

Thanks are due to Drs P. Feil, K. Michels, and A. Buerkert for their skillful and supporting comments on earlier drafts.

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# Workshop Outcomes

The presentation of the preceding articles was followed by two days of brainstorming to identify major problems and priority areas. These sessions sought divergent views from the Group, engaged the Group in discussion, and arrived at a consensus view on research needs and development applications for each of the priority areas identified.

## Major Problems of Wind Erosion in West and Central Africa, and West Asia and North Africa

The participants identified the following as major problems (in no particular order) associated with wind erosion in West and Central Africa (WCA), and West Asia and North Africa (WANA).

### Land Degradation

- Decreasing soil fertility and loss of topsoil through nutrient and organic matter loss.
- Soil crusting.
- Reduced soil quality.
- Reduced moisture retention.
- Deflation and sand movement.
- Dune formation and movement.
- Different degrees of influence on and loss of biodiversity.

### Climate

- Impact on atmospheric circulation.
- Effect on tropical convection.
- Impact of increased dust pollution on regional climate.
- Drought and its effects.

### Environment

- Pollution.
- Decreasing quality of life.

### Farming Systems

- Increased pressure on arable land and rangeland for increased food and fodder production.
- Exploitation of marginal areas.
- Reduction of agricultural productivity.
- Reduction of grazing capacity and reduced fodder availability for livestock.
- Crop damage through burial, abrasion, and uprooting.
- Problems of crop establishment.
- Delayed crop development following sand blasting or burial of seedlings.
- Higher production costs.
- Limited information on soil and land use.
- Inadequate understanding of farming systems and indigenous practices of wind-erosion control.
- Conflicting farmer priorities for crop residue use (conservation vs domestic).

### Socioeconomic Conditions

- Insufficient awareness of farmer perceptions.
- Migration, including to urban centers.
- Inadequate investment/coordination.
- Development constraints in the areas affected by wind erosion.
- Lack of community participation.
- Loss of income.
- High cost of preventive actions and restorative programs
- Problem of food security in marginal areas.

### Policies and Institutions

- Insufficient numbers of trained personnel, including scientists, technicians, and extension staff.
- Lack of wind erosion hazard assessment.

- Policies not conducive to good stewardship of farmland.
- Inadequate policies for land tenure and property rights.
- Inadequate investment and coordination.
- Marginalization of resource users.
- Inadequate soil conservation and resource use.
- Lack of sustained funding from donors.
- Insufficient monitoring of the resource base.
- Lack of interdisciplinary and participatory research approaches.
- Inadequate attention to lessons learned from past experiences of wind-erosion control projects.
- Lack of sustainable management of conservation schemes.

### Off-site Consequences of Airborne Sediment and Related Chemicals

- Decreased visibility.
- Reduced air quality.
- Effects on human health.
- Poor water quality.
- Damaging effects on infrastructure (irrigation canals, railroads, etc.,) and human settlements.
- Household nuisance.
- Insufficient knowledge of potential contribution to soil fertility.

## Prioritization of Problems Based on Participant Evaluation (Percentage of Participants Recognizing the Problem as a Priority)

1. Loss of fertile topsoil and associated decline in productivity (64%).
2. Inadequate policies addressing land carrying capacity, land tenure, soil conservation policies, etc. (57%).
3. Lack of awareness of farmer perceptions and inadequate understanding of local knowledge (43%).

4. Impact of increased dust pollution on the regional climate (36%).
5. Lack of interdisciplinary and participatory research approaches (29%).
6. Increased crop damage (21%).
7. Lack of sustained funding from donors (21%).
8. Insufficient attention to lessons learned from past experiences of wind-erosion control projects (21%).
9. Loss of biodiversity (14%).
10. Poor quality of life (14%).

## Control Strategies

Following the prioritization of problems, participants discussed the following control strategies in close dialogue with farmers and with a participative mode to address each of the problems.

### Decreasing Soil Fertility and Loss of topsoil

- Encourage the collection of baseline data for soil-loss estimation, land-capability classification, and degradation-hazard surveys and promote dissemination of information on areas prone to wind-erosion damage for preventive action.
- Promote appropriate soil-fertility management techniques, including organic and inorganic amendments and available agrominerals to maintain adequate vegetative cover and enhance social investment in external inputs.
- Adopt appropriate soil-conservation measures including on-farm crop residue management, improved fallows, agroforestry, natural vegetation strips, mulches, and live fences.
- Integrate soil conservation measures with soil fertility management.

### Inadequate Policies Addressing Land Carrying Capacities, Land Tenure, Soil Conservation, etc.

- Assess the land carrying capacity of areas prone to wind erosion and promote policies to provide incentives to local populations to manage their resources in accordance with this capacity.
- Facilitate the participation of the civil society in policy making and promote policies to empower local people at all levels of resource management.

- Develop appropriate land-tenure policies to ensure ownership or long-term access rights to land users over the resources they use and enhance more efficient resource use.
- Encourage resource-use legislation at the national level and promote private and public investment in soil conservation.
- Promote incentives, including crop insurance schemes to encourage farmers to adopt appropriate conservation-effective wind-erosion control strategies.

## Lack of Awareness of Farmer Perceptions and Inadequate Understanding of Local Knowledge

- Conduct base-line surveys and document information on farmer perceptions of wind erosion as a problem, their indigenous control strategies, and their views on long-term wind-erosion control strategies.
- Encourage the establishment of farmer and herder associations to promote the exchange of knowledge and negotiation of control strategy choices.
- Promote dialogue between development partners.

## Impact of Increased Dust Pollution on Regional Climate

- Promote basic research on the relationships among regional changes in the atmospheric circulation, wind erosion, and dust and sand transport and deposition.
- Study the effect of increasing aridity and drought on wind activity, decreasing roughness, and increased export of sand particles.
- Promote forecasts of climatic events causing dust mobilization and wind erosion.
- Encourage regional cooperation in climatic data collection, exchange, and use, and develop regional modeling and climate prediction techniques.
- Standardize procedures to collect data on sand flux as a part of the meteorological data collection and promote such collection on a regular basis in areas prone to wind erosion.

## Lack of Participatory and Interdisciplinary Approaches

- Stimulate multi-institutional, interdisciplinary research approaches for devising wind-erosion control strategies involving researchers (meteorologists, agronomists, soil scientists, physiologists, economists etc.), extension agencies, farmers and their representatives, NGOs, etc.

- Encourage participation of resource users in designing research and extension agendas based on flexibility, partnership, and shared responsibility.

### Increased Crop Damage

- Understand the physical and physiological processes governing the damage to various crop and forage species caused by sand blasting to reduce the damage caused by wind erosion.
- Evaluate traditional and improved agronomic techniques such as ridging, mulching, strip cropping, wind breaks, and shelter belts to combat wind erosion.
- Promote the development and use of species and varieties more adapted and/or tolerant to the conditions of wind erosion.
- Develop simulation models for incorporation in decision-support systems for prevention and restoration of damage caused by wind erosion in a range of soil-crop-climatic conditions.

### Lack of Sustained Funding from Donors

- Emphasize: 1) the implications of wind-erosion damage to sustainable agriculture and food security by improving the quality and quantity of information, and its exchange; and 2) the need for long-term donor funding to devise appropriate solutions over a broad range.
- Promote awareness at the national level to include wind-erosion control amongst development priorities, and seek greater commitment from national governments.
- Promote campaigns to draw donor attention to extreme wind-erosion events and the need for research and development to minimize losses.
- Develop regional, multi-national cost-effective projects with definitive time- and result-orientation to attract funding and highlight the role of inter-governmental agencies in wind-erosion control projects.
- Encourage in-country donor coordination and more donor–civil society cooperation.

### Insufficient Attention to Lessons Learned from Past Experiences of Wind-erosion Control Projects

- Recognize that wind erosion is not just a local problem, but has regional and even global implications.

- Survey, document, and disseminate information on the non-adoption and/or discontinuation of recommended wind-erosion control strategies at the farm level.
- Collect information from national and inter-governmental agencies concerning past successes at the national and regional levels, and highlight the conditions/criteria conducive to ensure the success of future projects.
- Ensure the use of a participatory, bottom-up approach with adequate socioeconomic input in future projects.
- Incorporate appropriate assessment criteria and promote a networking approach involving multiple actors.

### Loss of Biodiversity

- As loss of biodiversity can be due to a number of factors, establish linkages between wind erosion and loss of genetic potential or biodiversity.
- Using a participatory approach and traditional knowledge, assess the loss of biodiversity due to wind erosion.
- Establish linkages with national biodiversity-assessment programs and monitor ecosystem behavior.
- Recommend utilization of adapted species for the restoration of grazing areas and reforestation projects, taking into account the impact on wind-erosion control.

### Poor Quality of Life

- Evaluate linkages between wind erosion and human health, in particular disease transmission by airborne dust, in affected areas in the drylands in collaboration with the medical community.
- Identify the on- and off-site effects of wind erosion to assess the short- and long-term impact of wind erosion on quality of life.
- Conduct case studies on the influence of wind erosion on air and water quality and on assessment of the cost of cleanup.
- Promote clean living environments in cities and villages.

## Conclusions

The Cairo Meeting concludes that:

- Wind erosion, an insidious process, is on the increase in the dryland areas of WCA and WANA, and more awareness is needed of the seriousness of the problem.
- As this is the first time that researchers from WCA and WANA have been brought together to share their experiences, major gaps in understanding of the problem were identified. The meeting helped identify major problems and strategies for wind-erosion control in these two regions.
- In view of Agenda 21 and, in particular, the Conventions on Climate Change, Biodiversity, and Desertification, wind erosion deserves greater attention from the research and development efforts of nations affected by it and from the international community.
- Wind erosion impacts people, soils, crops, animals, and climate, decreases crop yield and income, and affects food security and quality of life.
- Wind erosion is a process of land degradation and its control must start with the most effective use of local resources.
- Wind erosion requires a multi-scale approach that considers other natural and human factors.
- The current interaction between national governments on the one hand and donors and the civil society on the other is inadequate.

## Recommendations

To enhance global, regional, and national awareness of wind-erosion problems and develop appropriate control strategies, the Cairo meeting recommends that:

- Emphasis should be placed on participatory, inter-disciplinary, multi-institutional approaches to research and technology adoption.
- Design of wind erosion strategies should be approached on different spatial and temporal scales.
- International cooperation should be stimulated in wind-erosion programs and implementation of control measures.
- A multi-stakeholder, action-oriented research proposal should be developed to complement current eco-regional initiatives, address the priority issues identified in the international conventions and linked to existing networks

and national action programs of the United Nations Convention to Combat Desertification.

- To improve the quality of life, emphasis should be placed on the development of policies that encourage judicious and adequate land use and resource conservation.
- Priority should be given to developing methodologies of land-degradation assessment as it relates to wind erosion and associated risk evaluation.

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