

## FIGHTING WIND EROSION

*one aspect of the combat  
against desertification*



# Les dossiers thématiques du CSFD Issue 3

## Managing Editor

### Richard Escadafal

President of CSFD

Research Director at CESBIO (Centre for the Study of the Biosphere from Space, Toulouse, France) for IRD (*Institut de recherche pour le développement*, France)

## Authors

### Monique Mainguet

Member of the *Institut universitaire de France* and Director of the *Laboratoire de géographie zonale pour le développement* (LGZD), Researcher associated with the *Groupe d'étude sur les géomatériaux et environnements naturels et anthropiques* (GEGENA<sup>2</sup>), University of Reims Champagne-Ardenne, France  
monique.mainguet@univ-reims.fr

### Frédéric Dumay

Research Engineer at GEGENA<sup>2</sup>

University of Reims Champagne-Ardenne, France  
frederic.dumay@univ-reims.fr

## Scientific editing and iconography

### Isabelle Amsellem

Agropolis Productions

info@agropolis-productions.fr

## Design and production

### Olivier Piau

Agropolis Productions

info@agropolis-productions.fr

## Photography credits



**Danièle Cavanna and Christelle**

**Mary** (INDIGO picture library of the *Institut de recherche pour le*

*développement*) as well as the authors of the pictures shown in this report.

## Translation

### David Manley

Editing, production and distribution of *Les dossiers thématiques du CSFD* are fully supported by this Committee through the backing of relevant French Ministries as well as the French Development Agency. *Les dossiers thématiques du CSFD* may be freely downloaded from the Committee website:  
[www.csf-desertification.org](http://www.csf-desertification.org)

Printed with solvent-free inks on certified chlorine-free bleached paper derived from sustainably managed forests.

**Printed by:** Les Petites Affiches (Montpellier, France)

**Copyright registration on publication**

**ISSN:** 1772-6964 • 1,500 copies

© CSFD / Agropolis International, May 2011

**For reference:** Mainguet M. & Dumay F., 2011. Fighting wind erosion. one aspect of the combat against desertification. *Les dossiers thématiques du CSFD*. N°3. May 2011. CSFD/Agropolis International, Montpellier, France. 44 pp.

## French Scientific Committee on Desertification

The creation in 1997 of the French Scientific Committee on Desertification (CSFD) has met two concerns of the Ministries in charge of the United Nations Convention to Combat Desertification. First, CSFD materializes the will to involve the French scientific community versed in desertification, land degradation, and development of arid, semi-arid and sub-humid areas, in generating knowledge as well as guiding and advising policymakers and stakeholders associated in this combat. Its other aim is to strengthen the position of this French community within the international context. In order to meet such expectations, CSFD is meant to be a driving force regarding analysis and assessment, prediction and monitoring, information and promotion. Within French delegations, CSFD also takes part in the various statutory meetings of organs of the United Nations Convention to Combat Desertification: Conference of the Parties (CoP), Committee on Science and Technology (CST), Committee for the Review of the Implementation of the Convention. It also participates in meetings of European and international scope. It contributes to advocacy activities concerning dryland development, in connection with civil society and media. It cooperates with DesertNet International (DNI).

CSFD includes a score of members and a President, who are appointed *intuitu personae* by the Ministry for Higher Education and Research, and come from various specialties of the main relevant institutions and universities. CSFD is managed and hosted by the Agropolis International Association that gathers, in the French town of Montpellier and Languedoc-Roussillon region, a large scientific community specialised in agriculture, food and environment of tropical and Mediterranean countries. The Committee acts as an independent advisory organ without decisionmaking powers or legal status.

Its operating budget is financed by subsidies from the French Ministries of Foreign and European Affairs and of Ecology, Energy, Sustainable Development and the Sea in charge of Green Technologies and Climate Change Negotiations as well as the French Development Agency. CSFD members participate voluntarily to its activities, as a contribution from the Ministry for Higher Education and Research.

## More about CSFD:

[www.csf-desertification.org](http://www.csf-desertification.org)

## Également disponible en version française originale

Mainguet M. et Dumay F., 2006.  
Combattre l'érosion éolienne : un volet de la lutte contre la désertification.  
*Les dossiers thématiques du CSFD*. N°3.  
Avril 2006. CSFD/Agropolis International,  
Montpellier, France. 44 pp.





# Foreword

**M**ankind is now confronted with an issue of worldwide concern, i.e. desertification, which is both a natural phenomenon and a process induced by human activities. Our planet and natural ecosystems have never been so degraded by our presence. Long considered as a local problem, desertification is now a global issue that affects us all, including scientists, decisionmakers, citizens from both the South and North. Within this setting, it is urgent to boost the awareness of civil society to convince it to get involved. People must first be given the elements necessary to better understand the desertification phenomenon and the concerns. Everyone should have access to relevant scientific knowledge in a readily understandable language and format.

Within this scope, the French Scientific Committee on Desertification has decided to launch a new series entitled *Les dossiers thématiques du CSFD*, which is designed to provide sound scientific information on desertification, its implications and stakes. This series is intended for policymakers and advisers from the North and South, in addition to the general public and scientific journalists involved in development and the environment. It also aims at providing teachers, trainers and trainees with additional information on various associated fields. Lastly, it endeavours to help disseminate knowledge on the combat against desertification, land degradation, and poverty to stakeholders such as representatives of professional, nongovernmental, and international solidarity organisations.

These reports are devoted to different themes such as global public good, remote sensing, wind erosion, agroecology, pastoralism, etc, in order to take stock of current knowledge on these various subjects. The goal is also to set out ideological and new concept debates, including controversial issues; to expound widely used methodologies and results derived from a number of projects; and lastly to supply operational and intellectual references, addresses and useful websites.

These reports are to be broadly circulated, especially within the countries most affected by desertification, by e-mail (upon request), through our website, and in print. Your feedback and suggestions will be much appreciated! Editing, production and distribution of *Les dossiers thématiques du CSFD* are fully supported by this Committee thanks to the backing of relevant French Ministries and the French Development Agency. The opinions expressed in these reports are endorsed by the Committee.

**Richard Escadafal**

President of CSFD

Research Director at CESBIO (Centre for the Study of the Biosphere from Space, Toulouse, France) for IRD  
(Institut de recherche pour le développement, France)



# Preamble

**D**esertification and land degradation give rise to several phenomena (or processes) whose severity can vary depending on the region and prevailing conditions: soil fertility loss, reduction in plant and tree cover, loss of soil water retention capacity, runoff, water and wind erosion. The impacts include increased environmental fragility, reductions in crop yields and thus in inhabitants' income, increased food insecurity and increased overall vulnerability of societies to climatic risks and economic crises, thus promoting outmigration.

This *Dossier thématique du CSFD* is of considerable interest as it is focused on one of the most flagrant signs of desertification—wind erosion. As pointed out by the authors at the outset, winds and dust storms are currently worsening, thus fostering wind erosion. This situation is especially worrisome in Mauritania and along the Niger Loop.

The *Dossier* highlights wind-driven mechanisms, factors that trigger erosion and land degradation, as well as monitoring strategies. It also provides a crucial update on what is currently known about techniques for combating sand invasion and this form of erosion. The need for an integrated approach is also stressed. Many examples are presented which demonstrate both the advantages and shortcomings of different control methods, while also providing the cost ranges for carrying out control operations.

This readiness to provide decisionmakers and other stakeholders with access to this pool of expertise should be applauded. Our network of francophone researchers specialized on erosion and sustainable water and soil management (EGCES Network), supported by the *Agence universitaire de la francophonie*, is in full agreement with the conclusions of this *Dossier* and praises the initiative. This Network, which developed out of a former network that was very active at ORSTOM, i.e. now the *Institut de recherche pour le développement* (IRD), would like to play an active role, while working alongside communities of francophone researchers, developers and teachers in developed and developing countries to boost awareness on the serious global problem of soil erosion. The EGCES Network also welcomes researchers from various scientific fields who could fuel the soil erosion debate: methods (spatial biophysical indicators), socioeconomic aspects, conventional and modern erosion control strategies, water and water quality management, land rehabilitation and biodiversity.

The EGCES Network is close to the activities of CSFD in semiarid regions where vegetation cover degradation gives rise to most problems concerning land erosion (since the wind is highly active), dam silting and access to good quality water supplies. It is essential to overcome these problems in order to be able to fulfil the basic needs of a growing population. These issues were stressed during the Network's scientific seminars that were held within the framework of the last International Soil Conservation Organization (ISCO) Conference, in May 2006, Marrakech, Morocco.

**Éric Roose**

President of the EGCES Network

**Georges De Noni**

Scientific Secretary of the EGCES Network

## Frédéric Dumay (1970-2011)

Frédéric Dumay passed away on 18 February 2011, he was 41 years old. He has been a very fine, excellent, intelligent, devoted and efficient collaborator for the last 20 years. His university studies and professional functions were based at the University of Reims Champagne-Ardenne from 1989 until his passing.

■ After beginning his university studies in Geography, Frédéric immediately took a passionate interest in tropical dryland environments. In 1992, he became a Technical Collaborator for the French *Laboratoire de géographie zonale pour le développement* (LGZD).

■ In his MSc thesis in 1993, he analysed the negative environmental impacts of the war in Kuwait.

■ In 1993, he successfully passed the French national competitive design engineering examination and became one of the pillars of LGZD.

■ In 1993, wind erosion phenomena in Mauritania was the topic of his postgraduate *diplôme d'études approfondies* PhD qualification thesis. In 2007, he became a Research Engineer at GEGENA<sup>2</sup>.

Frédéric was highly proficient in his field work, underpinned by his preliminary satellite image analysis skills.

His research was carried out in Africa (Morocco, Mauritania, Senegal, Niger, northern Cameroon) and Asia (Israel, China). From 14 to 27 May 2010, he launched a collaboration with Hunan University in Changsha (China). Frédéric was always ready to invest time and energy in helping others.

Vincent Barbin,

Professor of Geoscience, Director of GEGENA<sup>2</sup>

Monique Manguet,

Professor associated with GEGENA<sup>2</sup>

© F. Dumay and M. Mainguet



© F. Dumay



© F. Dumay



# Table of Contents

Wind erosion—a complex environmental degradation mechanism	4
Wind erosion onset thresholds and land degradation triggering factors highlighted by remote sensing	6
Wind erosion mechanisms at the Man-Nature interface	16
Wind erosion control techniques	24
Hope for the future of wind erosion control	40
List of acronyms and abbreviations	41
For further information...	42
Glossary	44



# Wind erosion a complex environmental degradation mechanism

**W**ind erosion is one of the most serious environmental degradation mechanisms, inducing soil textural and mineral depletion, as well as the mobilization of high volumes of sand and dust. The first imperceptible stages are insidious, and nonspecialists will only notice the process once it has reached a severe hard to control stage. This phenomenon is illustrated by the sand encroachment history of ancient Mauritanian caravan trading city of Chinguetti (designated as a UNESCO World Heritage Site in 1996), which was partially buried under sand but has now been exhumed through a rescue project. However, in 2005, there was still 5 m of sand in some alleyways within the city.

In dry ecosystems (southern Algeria, Mauritania, etc.), wind erosion, boosted by the sudden change in the pace of degradation over the last four decades, is such that it now cannot be assessed using the conventional three-stage model (causes, mechanisms and consequences) developed in the late 1970s. For instance, the 800% increase in dust-bearing winds, and thus in wind erosion in Nouakchott (Mauritania) between 1960 and 1995, clearly illustrates that the process is accelerating. It is now impossible to separate these three stages and determine the chronological pattern because of the many feedbacks and insidious links between stages. These three stages must therefore be analysed together to ensure their contextual relevance. Note that each case is different and that a solution that works in one situation cannot be directly applied elsewhere without adjustment to the local prevailing conditions—the ‘green barrier model’ developed in Algeria in the mid-1970s is striking evidence of this failure!

To combat wind erosion more effectively, decision-makers should be aware of the space-time concept so as to be in the right mindset to detect erosion triggering thresholds and to monitor new changing boundaries of areas threatened by wind erosion.

The functional units delineated under the global wind action system (GWAS, concept discussed hereafter), ranging from the sand source area to the deposition area, must be taken into account. It is essential to set up wind erosion control initiatives and make strategic choices of intervention areas on this functional unit scale (continental scale).

Thresholds for the onset of environmental degradation induced by wind along with other key wind erosion triggering factors (natural and human) could be clearly perceived using [remote sensing tools](#)<sup>\*</sup> (satellite images and aerial photographs). Once clarified, the complex interlaced wind erosion mechanisms should be placed in the GWAS context. The physical and biological wind erosion control and resource preservation measures that have been proposed highlight that this initiative is part of the desertification combat and that it cannot be successful without the involvement of the international community.

---

<sup>\*</sup> Terms defined in the glossary (page 44) are highlighted in blue and underlined in the text.





▲ Arrival of a sandstorm in the area of *Mare d'Oursi*, Oundalan, Burkina Faso. Note that behind the huts the red color of the sandstorm is due to the origin of the winnowed particles (surface bedrock or red sand). The higher particles are derived from a different origin resulting from deflation of an aeolian sandsheet. This highlights the long trajectory that a sandstorm may have. The sand deposited on the surface is thus of different origins.

F. Sodter © IRD

Wind erosion—a complex environmental degradation mechanism



# Wind erosion onset thresholds and land degradation triggering factors highlighted by remote sensing



**I**t is now recognized that anthropogenic factors (socioeconomic, population pressure, such as excessive tapping of natural resources, deforestation, overgrazing, excessive irrigation and, consequently, salinization, etc.) are major land degradation triggering factors in dryland areas. The impacts of these factors are worsened when they overlap recurrent drought periods or severe rainstorms.

People, including farmers, cattle breeders, town dwellers and policymakers—through their activities and developments—play a key role in wind erosion onset. This process may also be accelerated by severe climatic events (drought, flooding, peaks in water and wind erosion).

In dryland environments (which in Africa, according to our observations, reaches isohyet 600 mm/year in the southern Sahel), aeolian mechanisms are the main factors that determine the vulnerability of farmland and urban areas located in sandy environments (e.g. in Nouakchott, rainfall 100 mm/year), sometimes leading to desertification.

This phenomenon is under way in the groundnut growing area in Senegal. The extent of degradation noted in the northern part of this area around the end of the first decade of the 21<sup>st</sup> century was similar to that observed at the latitude of Nouakchott, Mauritania, in the early 1970s (Fall, 2001). It would thus be essential to analyse satellite images and aerial photographs, before and after ground checks, to quickly determine the wind erosion onset threshold in order to develop and implement preventive control initiatives.

All concerned countries should have several permanent teams working on this issue.

## DETECTION OF THE FIRST SIGNS OF WIND EROSION

The wind erosion onset threshold is the point at which the balance\* between natural resources and human pressure, aggravated by severe climatic conditions, is upset. It is essential to determine this threshold so as to be able to rapidly (on temporal and spatial scales) identify premonitory signs of environmental degradation before the degradation stage and ultimate desertification stage. Improvements are needed with respect to detecting these thresholds and the different degrees of preliminary degradation in order to be able to rapidly boost awareness on wind erosion onset.

Precursory signs detected by [remote sensing](#) include [overdeepening](#) of the surface layer ([blowouts](#)), increases in the density of small aeolian sand deposits or [nebkas](#) (sand arrow leewards of a bush or stone), the emergence of irregular mobile sand deposits, reactivation of the crests of sand dunes, changes in [soil reflectance](#). Monitoring tools are available that should be tailored to different monitoring scales and supplemented by field surveys and quantified data. These signs must also be clearly and quickly interpreted so as to enable rapid and effective interventions.

\* In dryland ecosystems, this refers to a steady state in soils and in the naturally open vegetation cover.





▲ Oblique aerial view of the centre of the city of Nouakchott, Mauritania, 1996. This photograph shows that there is very little vegetation in the town, and progressive sand and dust invasion, which has been steadily increasing since 1996 under the effect of harmattan sandstorms.

Y. Boulvert ©IRD

## SATELLITE IMAGES AND THE GWAS CONCEPT

Satellite images are key tools for environmental investigations. They provide users with access to in-depth detailed and repetitive information. The observations may be combined to obtain a multiscale view, ranging from the synoptic scale with METEOSAT and NOAA images, to the regional scale with LANDSAT and SPOT images.

Based on these satellite images, the global (or regional) wind action system (GWAS [or RWAS]) concept was developed and the limits were determined (Mainguet, 1984). A GWAS (or RWAS) is a series of particle-laden wind currents marked out by open interlinked **ergs** (sand seas) that form **erg chains** like those linking the Sahara and the Sahel (Mainguet and Dumay, 1995). Geostationary satellites (having a stationary orbit, i.e. METEOSAT for Africa or circumpolar regions, NOAA for Eurasia) generally covering an entire GWAS.

The smallest scale images (METEOSTAT, NOAA) are used to identify different wind system units: source area, transit areas and deposition areas. Scales may overlap within these units depending on the presence of megaobstacles (mountains and plains, Mainguet, 1976) and the roughness of the local landscape (relief, vegetation, buildings). Defined subunits may, for instance, be an erosion area within a deposition unit or, conversely, a deposition area within a unit in which erosion prevails, as detected on large-scale satellite images (SPOT or LANDSAT satellites).

When assessing a regional system, an image mosaic can be constructed, e.g. the regional wind action system in the Aral Basin in Central Asia (Mainguet, Dumay and Létolle, 2002). Aerial photographic coverage is essential when highly detailed observations are required for infrastructure protection (buildings, roads, irrigation canals, etc.).

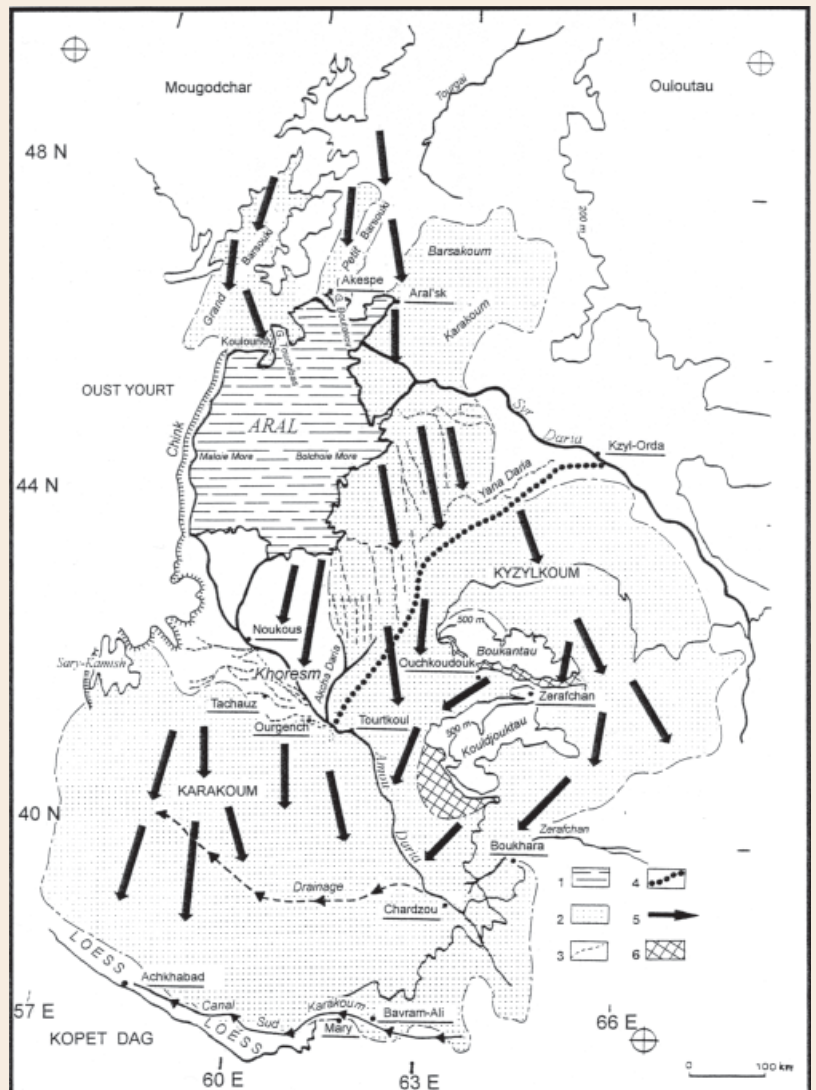
## > FOCUS | Regional wind action system (RWAS) on the eastern side of the Aral Basin

Aral Basin (1.8 million km<sup>2</sup>) accounts for 4% of the global temperate dryland area. This RWAS, which is studied in the field and on Cosmos, NOAA and SPOT satellite images, begins at the southern outlet of the Tourgai Corridor at the interface of the Siberian Plain and Aral Basin. At its centre, there is a deflation area where satellite images reveal a dense paleohydrographic network, Sir Daria and Amou Daria Basins, the only permanent allogenic streams and, in the south, the temporary Tedjen and Mourgab streams. It ends at the northern foot of Kopet Dag (3 349 m) with a 375 km by 40 km loess strip.

The wind releases its load of sand at the outlet of the Tourgai Venturi, which has led to the formation of four **ergs** north of Aral Lake: Grand Barsouki, Small Barsouki, Barsakoum and Karakoum, which should not be mistaken for the Grand Karakoum erg. At their southern edge, shifting **barchan dunes** are invading the villages of Kulandy and Akespe (46°5 N, 60°3 E). Grand Barsouki (46° à 48°N, 58°5 à 60°E) is 250 km long by 25-50 km wide. At the point of contact with Aral Lake, near Koulandy (59°3 N and 46°1 E), it is the only erg west of the lake within the RWAS. In its downwind part, it comes up against Tchink Escarpment. Small Barsouki is 110 km long by 30 km wide, starting at 47°N and 61°E. These two ergs blanket the early Quaternary paleovalleys. Their dunes form part of the shores of the Gulfs of Boutakov and Touchibas. The sand derives from glaciofluvial deposits extending from the Mougodjar hills in the southern Ural region to the Tourgai Corridor plains (Irgiz, etc.).

A 1957 geological map (at 7 500 000 scale) indicates that the material is of tertiary paleogenic fluvial origin and the result of wind erosion. The RWAS extends along the eastern side of Aral Basin. **Deflation** in the Kazakh steppe south of the Siberian plate is the source of sand for the NNW-SSE **longitudinal dunes** in the northern Karakoum erg. Sir Daria interrupts the continuity of the ergs and supplies sand for the Kyzylkoum erg that begins just south of it. The general NNW-SSE orientation of the dunes continues south of Sir Daria and then shifts 44°N to become NNE-SSW as the dunes encompass Aral Basin, which in turn serves as an obstacle to the wind.

Sand deposits thus do not accumulate to a great extent in the sheltered lake basin but rather on the first reverse slopes. The inflexion can be seen on satellite images up to 150 km east of the lake, at the northern edge of the Amou Daria paleodelta where the wind direction measured in the field is NNE-SSW 10°. Between Sir Daria delta and the southeastern Aral Basin (former Akpekti Archipelago), the Kyzylkoum erg sand particle size decreases to become silt in the Sir Daria delta region.



▲ This RWAS clearly highlights the regional aspect of aeolian currents that determine the surface features in sandy regions covering an area of 1 500 km from north to south.

1. Aral • 2. Sand sheets and ergs • 3. Paleo-wadis • 4. Western boundary of riverine paleochannels not blocked by aeolian material • 5. Major wind directions in the regional wind action system (RWAS) in Aral Basin • 6. Sheltered areas on the leeward side of obstacles • 7. Erg boundary

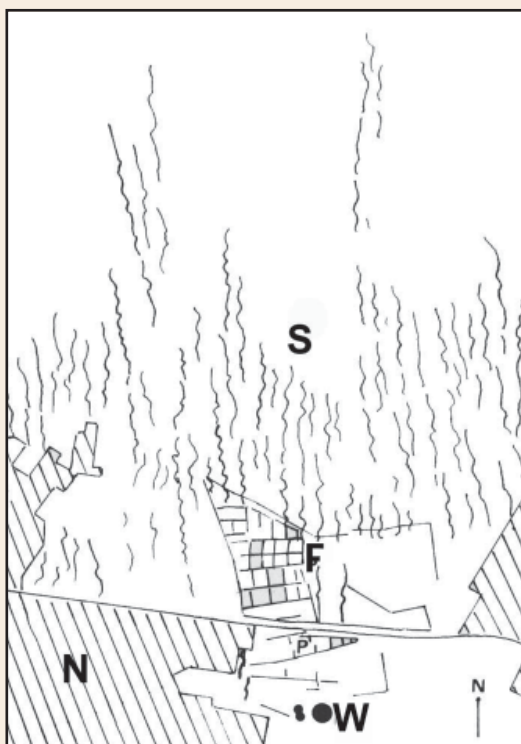
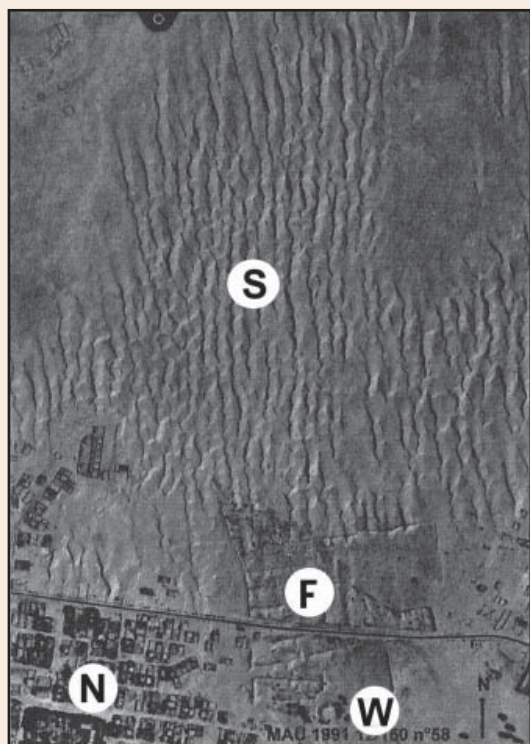
Zana Daria paleostreams crossed the Kyzylkoum erg until the late Bronze Age, whereas the Amou and Sir Daria deltas converged. The western part consists of longitudinal dunes that cross the network of paleovalleys visible on satellite images.

Less clearcut dunes are found on the older eastern part. Kyzylkoum sandseas extend to the right banks of Syr Daria river and, simultaneously, to the left banks. The wind streams cross the river carrying the sand that has emerged during the dry season. This could explain why alluvial material blends fine carbonate-rich (20-30%) aeolian material from Kyzylkoum sandsea with alluvial silts. In this sector, the wind currents form a divergence which is responsible for the formation of Grand Karakoum sandsea, which is followed downwind by the Kyzylkoum sandsea. The Karakoum sandsea is formed north of the loess strips in the southern part of the RWAS.

From Mainguet M., Dumay F. and Létolle R., 2002.



## > EXAMPLE | Using aerial photographs to monitor sand dunes in Mauritania



On an aerial photograph taken in 1991, there is a clear increase in the number of seif dunes and in the extent of sand invasion in the vicinity of the water tower northwest of Nouakchott.

▲ N. Nouakchott • W. Water tower • S. Seif dunes • F. Fence

1. Aerial photograph IGN MAU 1991 12/150 n°58 © IGN 1998  
2. Interpretation sketch drawn by LGZD.

### AERIAL PHOTOGRAPHS AND CLOSE MONITORING OF SAND DUNE TYPES AND THEIR SURFACE STATUS

When used alongside satellite images, aerial photographs provide more detailed information, especially on types of individual sand dunes and on their surface status. They are essential tools for erosion control studies in urban areas (Nouakchott in Mauritania, Draa Oasis, or the Kénitra-Larache motorway in Morocco).

In wind erosion control, they are excellent indicators for detecting premonitory signs of degradation: **blowouts** (aeolian overdeepening) of the landscape surface, formation or extension of **nebkas**, increased **sand powdering** or **sand veils**, and neogenesis of small aeolian dunes that are not visible on satellite images. Finally, accurate detailed maps can be drawn up from aerial photographs and used to combat sand encroachment and monitor individual aeolian dunes.

### ESSENTIAL GROUND CHECKS

The combined analysis of satellite images and aerial photographs is an essential support for field surveys. Preliminary overall knowledge of sectors investigated in the field enhances the *in situ* understanding of sand encroachment and wind erosion areas and their dynamics. In the field, geographers' expertise—an essential tool—and ability to consider landscapes in terms of **morphodynamic units**, enable them to pinpoint and sample key wind dynamics sectors. Assessments of aeolian dune types (**barchan dunes**, **seif dunes**, **longitudinal dunes**, etc.) inform geographers on the nature of the local **aeolian sediment budget**: is the area in a particle loss (erosion, with a negative sediment budget) or accumulation period (deposition, with a positive sediment budget)? All collected soil samples are then sent to the laboratory for particle size (concerning the size of sand grains), morphoscopic (concerning the shape and surface status of particles and transport processes) and mineralogical analyses, which determine the geographical (and associated transport mechanisms) and geological origins of particles, thus enabling confirmation of the findings and hypotheses put forward.



▲ Children carrying fuelwood collected at dawn on the dyke of the Sologo barrier lake (Côte d'Ivoire).

C. Lévêque © IRD

## HUMAN ACTIVITIES—THE MAIN WIND EROSION TRIGGERING FACTOR

Contrary to the desertification definition put forward in Agenda 21 where climatic variations are placed ahead of human factors, we rank humans (or societies) as the main initiators of aeolian degradation mechanisms, and then they represent causes, mechanisms and consequences once the process has been set in motion.

Cornet (2002) stresses that *“land degradation occurs when humans modify the balances or natural dynamics [...]. Human activities are generally voluntary, sometimes due to ignorance and often determined by an increase in needs in a setting of insufficient technological development and an absence of resource access regulations.”* We would also add resource use without accounting for climatic variations.

During unusually rainy periods (1950-1960), Sahelians (the people most affected by wind erosion in the world) expanded their cropping area at the expense of the Saharo-Sahelian region because of the growing population and declining soil fertility. This situation became catastrophic during subsequent dry periods, especially since they spanned two decades (1970-1990).

Rainfall conditions improved in the 1990s, but the resilience potential of these ecosystems (natural improvement) seemed to be negatively impacted by human pressure and population growth.

## Population pressure—a wind erosion inducer

During the 1990s, the driest regions on Earth—most of which are located in Africa—had a population growth rate of over 3%/year (Evers, 1996). In many dry countries, over 50% of the population is under 25 years-old, i.e. the runaway population growth phenomenon is not under control. In agricultural areas of many countries, this population pressure, which is common in countries during development periods, is still synonymous with labour and thus prosperity. Population growth, however, aggravates environmental degradation via the constant high pressure placed on environmental resources.

Population concentrations have harmful environmental impacts regardless of the type of ecosystem. Dry ecosystems have a lower resilience than temperate ecosystems, with more sustained environmental degradation, especially since they are hampered by droughts and the environment is not protected by vegetation cover. Population concentrations lead to overgrazing and excessive consumption of timber and fuelwood. For fuelwood, nomadic people generally use wood that they collect during their movements, so their pressure on the environment is dispersed along carefully chosen routes that they follow in response to seasonal variations, contrary to settling, which leads to overgrazing and depletion of edible species. This results in the expansion of wood collection and grazing areas, thus creating centrifugally degraded patches that eventually merge (i.e. become linked and therefore broader). These patches represent desertification phases, forcing people to migrate towards cities, as already noted in Niger in 1976 (Mainguet, 1976). Field work carried out in Mauritania in October and November 2009, just after the rainy season, revealed rings of degradation around villages along the Nouakchott–Kiffa road.



## > FOCUS | Variations in the meaning of 'desertification'

Desertification takes its meaning from the Latin etymology:

- 'desert' has a dual Latin origin: from the adjective *desertus* (meaning 'unmanned') and from the substantive *desertum* (abandoned area).
- 'fication', meaning 'making or causing', comes from *fieri*, the passive form of the active verb *facere* (meaning 'to make' or 'to do')

In 1971, in J. Gilbert's *Dictionnaire des mots nouveaux* (Hachette-Tchou, p. 158), the term 'desertification' means: "...the almost complete withdrawal of all human activity in a region that has been gradually abandoned by its inhabitants."

In 1977, the United Nations Conference on Desertification proposed: "*Desertification is the diminution or destruction of the biological potential of the land, and can lead ultimately to desert-like conditions. It is an aspect of the widespread deterioration of ecosystems, and has diminished or destroyed the biological potential, i.e. plant and animal production [...] at a time when increased productivity is needed to support growing populations in quest of development.*"

In the ecological concept of a balance between humans and the natural environment, humans are responsible for desertification: the ultimate stage of environmental degradation has reached an irreversible point, but the notion of irreversibility warrants discussion. In December 1989, the UN General Assembly, asked the UN Environment Programme (UNEP) to reevaluate the term for subsequent submission to the UN Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992. UNEP then proposed the following definition to UNCED in June 1992: "*Desertification is land degradation in arid, semiarid and dry subhumid ecosystems resulting mainly from the impact of adverse human activities.*" By this definition, land degradation encompasses declining crop yields, vegetation cover deterioration, exacerbation of physical mechanisms at the soil surface, qualitative and quantitative decreases in water resources, soil degradation, and air pollution.

The UNDP definition was amended by UNCED as follows in July 1992: "*Desertification is land degradation in arid, semiarid and dry subhumid areas resulting from various factors, including climatic variations and human activities.*" According to this definition, the responsibility of humans is watered down and degrees of degradation severity are not taken into account, especially the ultimate irreversible degree, which should be considered since this is the essence of the meaning of the word 'desertification'. In practice, degradation is irreversible when the soil no longer contains seeds, or when (according to Dregne, 1984) the soil is so degraded that it has lost its water retention capacity, so any seeds it does harbour would be unable to germinate.

If desertification is synonymous with land degradation, then it is currently the most dramatic environmental problem on Earth. If the irreversibility concept is included in the current technical and economic context—since it is the endpoint of a series of processes leading to definitively barren environment—then it is almost nonexistent and, according to Dregne (1984), only 0.2% of the globe would be affected.

We proposed (Mainguet, 1991) the following definition based on three decades of observations in dryland parts of Africa and Asia: "*Desertification, as revealed by drought, is due to human activities when the carrying capacity of the land is surpassed. It proceeds by natural mechanisms that are exacerbated or induced by humans. They lead to plant and soil degradation and—on a human timescale—to a decrease or irreversible destruction of the biological potential of the land or its capacity to support people living on it.*" Within a few decades, human activities achieve what natural evolution takes a few millennia to achieve on a geological scale. This definition stresses human causes, with climatic parameters like drought simply revealing the process. It was proposed (UNEP, 1991) that the term 'desertification' be replaced by 'land degradation' or 'environmental degradation' to avoid inconsistencies.

Environmental degradation associated with human activities occurs in all ecozones, but it is especially in the driest areas that humans most contribute to turning environments into desert-like wastelands. This is why the term 'desertification' should be limited to arid, semiarid and dry subhumid areas.

### Economic pressure—another wind erosion inducer

Population growth in a limited area systematically increases the economic pressure and competition for resources. In dry countries, this pattern is reflected by the trend towards settling on new land at the expense of fragile and marginal areas (e.g. *Nouvelles Terres* in Eastern Senegal). Clearing, tilling and cropping these lands increases their vulnerability to wind erosion.

Competition between farmers and nomadic people worsens this situation and often leads to armed conflicts. There is also high pressure for access to water resources and wells, which are increasingly deep and require very heavy investment.

Economic pressure then forces many farmers and cattle breeders to find other subsistence solutions, often leading to migration to capital cities or settlement along main roads.

## > FOCUS | Uncontrolled building (gazra in Hassania) on longitudinal dunes on the outskirts of Nouakchott (Mauritania)

In 1991, a difference was noted between temporary inhabitations **(1)** built on dunes **(2)**, which is surmounted by seif dunes **(3)**, and organized neighbourhood areas **(4)** built in the depression and which were relatively well protected. The newly built inhabitations destabilised the dune and increased the risk of sand scouring and encroachment, while also creating rough surfaces and enhanced vorticity. In 1991, new observations highlighted that seif dunes were derived from sand barchanic domes arising in the urban environment.

Source: LGZD research



▲ Aerial photograph IGN mission MAU 1991 12/150.  
Photograph n°55 © IGN 1998

### Migration and settling—causes and consequences of wind erosion

For farmers—especially their sons—the option of moving to the capital to work is often a preliminary step towards a more complicated migration further abroad. Outmigration and settlement are sometimes promoted by policymakers and are also the result of riskier regional development policies. In Mauritania, for instance, the *Route de l'Espoir* (Nouakchott-Néma trans-Mauritanian highway crossing the country from west to east), which was built to open up the eastern part of the country and promote political unification, has become a settlement belt for nomads seeking to improve their food security situation.

This settlement of a new fringe population group has placed greater pressure on the economy and led to further departures towards the capital. Here again, the flow of migrants towards the capital is self-maintained. Uncontrolled installations (*gazra* or *kebba* in Hassania) in interdunal corridors between NNE-SSW longitudinal dunes create new rough areas in the landscape which naturally trap the mobile sand blown through these corridors and initiate sand deposition and encroachment mechanisms.

Moreover, population concentrations, which are generally in the vicinity of a well or medical dispensary along this road, degrade the soil structure (trampling,

especially by sharp hooves of goats, which are otherwise very useful) and of the sparse surrounding vegetation cover. These surfaces are then vulnerable to erosion as the wind lifts and carries away the loose sand.

Dairy cattle are being reared in the longitudinal dune system south of Nouakchott, extending between the capital and Rosso, to supply milk to markets in the city. This production, developed by nomad settlers, is very environmentally damaging since these former cattle breeders have maintained their transhumant herding habits but on much smaller transhumance rangelands. The grazing areas are highly degraded. Without any rehabilitation initiatives, the active dunes will eventually extend to the latitude of Rosso where, however, annual rainfall levels are as high as 280 mm. A field trip in November 2009 confirmed that the grassy and shrubby plant cover on longitudinal and transverse dunes located south of Nouakchott did not recover and that wind erosion is ongoing, as shown by the giant blowouts/deflation basins. The population boom is responsible for land and resource degradation, thus forcing people to migrate again. The waves of successive settlements and migrations are also responsible for unsustainable natural resource use, especially when they involve small population concentrations. When these populations flee to urban centres, especially to capital cities, they are generally crippled by poverty and structural breakdown.





▲ Southeastern part of the fixed Erg Aouker on the Toghba-Tamchekket road, Mauritania, December 2001. Violent rains during the July–September rainy season induce concentrated runoff, which etches wide rills (here 2 m. deep) in compacted and ferruginous (turning red) paleosols from fixed transverse dunes. Sand particles loosened by water erosion can be more readily mobilized by wind erosion (deflation).

© F. Dumay and M. Mainguet

### Urbanization and impoverishment—starting points of wind erosion

Since the late 1960s, developing countries have been affected by runaway urbanization and many countries are impeded by oversized cities, which has given rise to serious problems of economic rebalancing and clearcut population distribution disparities.

Metropolitan Nouakchott (800 000 inhabitants) pools 30% of the population of the Republic of Mauritania, which has led to problems of delinquency and an increase in numbers of beggars and homeless people. This urban boom also has impacts on the countryside—there is increased pressure on farmers to practice commercial farming to supply the expanding urban markets, to the detriment of conventional, more environmentally friendly, subsistence farming.

The profit lure has prompted farmers to produce more, while ruining those who are unable to do so. Moreover, these profit seekers are sterilizing their lands. This trend is boosting the flow of migrants to the cities. Shelters are required for these people and the quest for materials to build these shelters is a further source of environmental degradation—the offshore barrier sandbar east of Nouakchott, which has been largely reactivated, has been so overexploited that it is no longer completely effective in protecting the city during very strong tides, i.e. sea water penetrates at certain points and floods low-lying urban neighbourhoods. All the anthropogenic pressures described earlier affect ecosystems that have been fragilised by severe climatic conditions. The resulting ecological catastrophes accentuate imbalances between the anthropogenic pressure, available resources and social disparities.

### ENVIRONMENTAL VULNERABILITY FACTORS INHERENT TO DRY ECOSYSTEMS

The first environmental vulnerability factor, which should normally be a source of natural wealth, is the soil. The high diversity of soils in dryland ecosystems is a key resource, but their thinness and vulnerability favour wind erosion, especially with respect to sandy soils. This vulnerability is heightened by water erosion in clayey soils, i.e. paleosols of ancient genesis. Blowouts and gullies are very common in Sahelian landscapes.

#### Vulnerability of soils to wind erosion

The vulnerability of dryland ecosystem soils is associated with the very long time required for their genesis because of the absence of chemical weathering of rocks. Edaphic drought promotes the formation of single grain structures (i.e. that may be easily powdered). These soils are initially degraded by aeolian winnowing of sand particles and silts. **Deflation** (wind-induced drifting) gathers the particles, while winnowing sorts them and a new generation of mobile dunes is created via their deposition. These organic matter depleted soils can soon become barren through overexploitation and aeolian winnowing, or when they can no longer be cultivated, except under irrigation, due to the prevailing climatic conditions. Irrigation often causes excessive soil salinization, especially when sprinkling is ill-timed and the washing and drainage conditions are poor. When there is a balance between crop planting and soil conservation, it often falters as a result of seasonal degradation under specific climatic variations, e.g. rainfall delays, droughts or, conversely, ill-timed excessive rainfalls.

## > FOCUS | Impact of soil conditions: erosivity and erodibility

The wind velocity at the soil surface varies according to the roughness of the topography. It starts declining at an altitude tenfold above the height of the vegetation cover, natural and anthropogenic roughness. The wind is slowed down by a frictional effect in contact with the sandy surface or mobile particles. The lower air layer has zero velocity on a thickness of around  $1/30^{\text{th}}$  of the particle diameter.

The effects of a wind system at the soil surface vary depending on the rain and wind **erosivity** and the soil **erodibility**.

Its erosion capacity decreases when the values of some variables increase  $\uparrow$  and when those of other variables decrease  $\downarrow$ :

- **EROSIVITY** (capacity of rain and wind to induce sufficient erosion to remove the top soil layer, Mainguet and Dumay, 2005).

### Wind parameters:

- Velocity ( $\uparrow$ )
- Frequency ( $\uparrow$ )
- Duration ( $\uparrow$ )
- Area ( $\uparrow$ )
- Shear ( $\uparrow$ )
- Turbulence ( $\uparrow$ )

- **ERODIBILITY** (dependent on the soil properties)

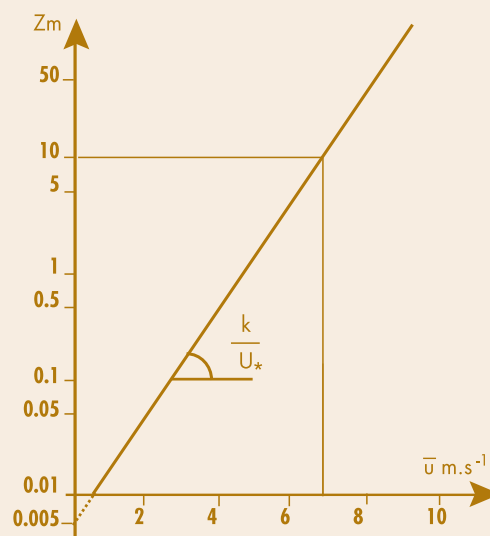
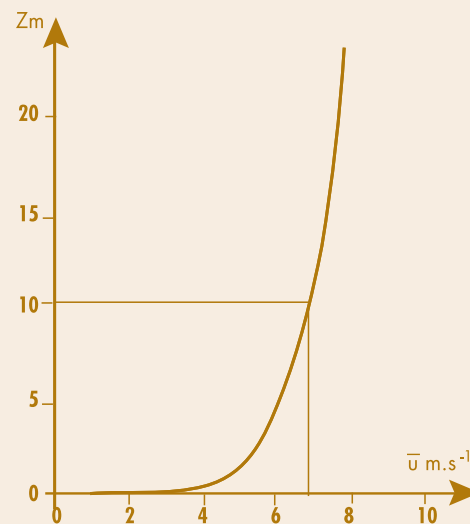
### Sedimentological parameters:

- Grain size ( $\uparrow$  /  $\downarrow$ )
- Height ( $\downarrow$ )
- Orientation ( $\downarrow$ )
- Abradability ( $\uparrow$ , capacity to be eroded and carried away)
- Transportability ( $\downarrow$ , wind transport potential)
- Organic matter ( $\downarrow$ )

### Surface parameters:

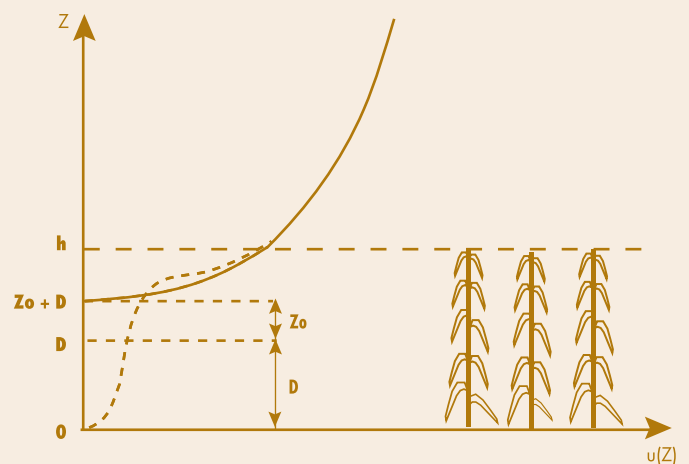
- Vegetation: Residue ( $\downarrow$ ), Height ( $\downarrow$ ), Orientation ( $\downarrow$ ), Density ( $\downarrow$ ), Smoothness ( $\downarrow$ ), Extent of cover ( $\downarrow$ )
- Soil moisture ( $\downarrow$ )
- Soil roughness ( $\downarrow$ )
- Surface length ( $\downarrow$ )
- Surface slope ( $\uparrow$  /  $\downarrow$ )

When the soil is covered with dense vegetation of height  $h$ , everything takes place as though the ground level had been raised to a height of  $D < h$ , i.e. the so-called displacement height. When a windbreak is installed, its height minus  $D$  should be taken into account rather than its total height.



▲ Wind velocity profiles close to the ground represented in Cartesian coordinates (a) and semi-logarithmic coordinates (b).

Zm: height in metres;  $U \cdot s^{-1}$ : wind velocity;  $U^*$ : breaking power of the soil; Zo: roughness parameter at zero wind velocity; k: Von Karman constant [= 0.35]



▲ Effect of high vegetation on the velocity profile.

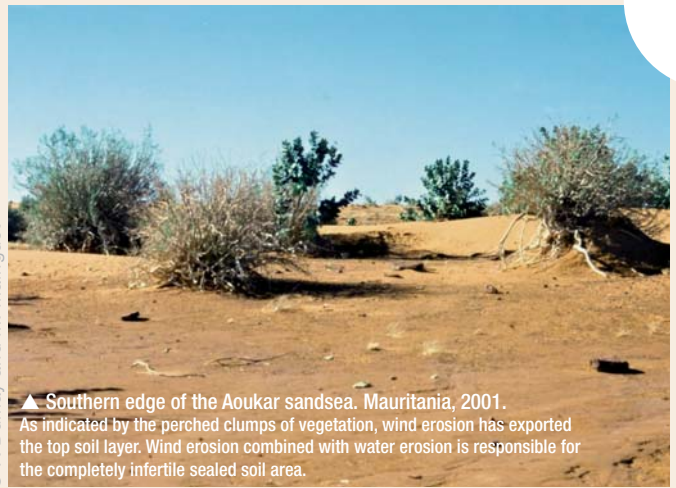


## > FOCUS | Soil drought—the result of wind erosion

In the 1950s, natural vegetation cover, especially grasses, fixed all sandy areas in semiarid African regions, which benefited from over 150 mm/year of rainfall. Since then, overgrazing has exposed these sandy surfaces to wind mechanisms during the dry season, as well as loss of the A horizon.

Wind export of the A horizon led to outcropping of the B horizon, which in turn was subjected to so-called ‘sealing’, i.e. polishing via sand grain saltation (successive skipping-like grain transport process), thus sealing the soil surface and making it impermeable to rainwater infiltration. This situation makes the soil vulnerable to water erosion: [splash](#), with [compaction](#) phenomena, then leading to [crusting](#) or [runoff](#) with the formation of [rills](#). This compacted soil behaves like a rock upon which wind erosion can lead to the development of [corrasion](#) streaks and blowout-type aeolian depressions.

© F. Dumay and M. Mainguet



▲ Southern edge of the Aoukar sandsea. Mauritania, 2001.  
As indicated by the perched clumps of vegetation, wind erosion has exported the top soil layer. Wind erosion combined with water erosion is responsible for the completely infertile sealed soil area.

All of these phenomena are what is called soil drought (occurring within the soil):

- the vegetation is hampered by both moisture and oxygen deficits
- during germination, seeds are unable to penetrate the hardened upper soil layer, so they dry out and are exported by the wind.

### Role of climate crises in aggravating wind erosion

Climatic variability is acute in dry tropical ecosystems—mean monthly or annual rainfall levels do not reflect the chaotic rainfall distributions, despite the fact that a dry phase seems to be taking shape in the last few decades. Although a deficit mean rainfall pattern may be recorded, devastating rainstorms could have occurred over the same period.

#### *Recurrent droughts increase the vulnerability to wind erosion*

Four major droughts have occurred in the Sahel since the beginning of the 20th century (1900-1903, 1911-1920, 1939-1944, 1968-1985), representing a cumulated total of almost 35 years of deficit rainfall conditions. Hence, it is not surprising that public authorities put forward the drought criterion inherent to the ecosystem as the main cause of desertification in recent decades. However, dust storms are closely correlated with drought periods, suggesting that these droughts are responsible for exportation of part of the fine soil fraction, which is the main soil fertility and structure constituent. Note also that the last droughts in the 1980s captured the attention of donors and policymakers because of their high media coverage. It is recognized that drought is not unusual in so-called dry ecosystems, and thus should be taken into account in local food supply management. The aim is to avoid having to rely on massive food aid imports, which may trigger substantial outmigration of people seeking easy to acquire food resources in capital cities.

It should therefore not be claimed that droughts are the only causes of desertification since they are common events in arid and semiarid ecosystems. Sustainably cultivated land will recover from droughts upon the return of normal rainfall conditions, whereas poor cultivation practices increase soil degradation.

#### *Excess rainfall participates in destructuring the soil*

Contrasting climatic events in the Sahel are ‘exceptional’. Drought periods can be interlaced with devastating rainy climatic events—devastating for both crops and dwellings made of banco (a dried mixture of clay and chopped straw) with flat roofs that become waterlogged and collapse (e.g. at the 9<sup>th</sup> century Tichit Oasis in Mauritania, in a hyperarid region, where many houses collapsed during violent rainstorms in 1999). A very short-lasting violent rainstorm can thus be as fatal as a long drought period! On fragile soils that have been laid bare by drought and excessive cultivation, heavy rains can destroy the soil cohesion, inducing wide loose cracks that can turn into deep gullies, with downslope deposition of small alluvial cones of loosened material. This soil fraction that was previously compacted can thus be mobilized by the wind upon the return of dry periods. Conversely, but just as damaging for agriculture, heavy rainfall combined with aeolian winnowing can lead the formation of a [surface sealing](#).

It also seems that during years of excess rain local farmers tend to give up their parsimonious resource management in order to benefit maximally from this ‘climatic godsend’, but the return to normal is just more difficult!

# Wind erosion mechanisms at the Man-Nature interface

**W**ind actions that take place at the soil-atmosphere interface in a dynamic terrestrial framework are structured in large dynamic units on synoptic or continental scales—these so-called global wind action systems (GWAS) cover the entire Sahara and Sahel region. Human activities also interact in regional wind action systems (RWAS). El-Baz (1988) used the expression regional wind action system to describe regional wind circulation phenomena that sweep through Egypt from north to south.

These synoptic wind units are influenced by mountain obstacles, soil conditions, vegetation and sometimes climatic events. Wind dynamics are not limited to sand encroachment, even though this is the most obvious and immediately disturbing associated phenomenon. Wind dynamics should be considered within the GWAS framework and assessed with respect to all aspects, e.g. erosion, transport and accumulation, so as to gain insight into the dynamics of this process overall and enhance management of the negative effects.

## GLOBAL WIND ACTION SYSTEMS—NATURAL UNITS AND LIVING ENVIRONMENTS

A global wind action system consists of a patchwork of small interrelated units that are grouped in three main units that differ with respect to the [sediment budget](#) and they are delineated in the environment on the basis of the dunes or wind forms that prevail. These three subunits, which succeed each other according to the wind direction, are: a particle export area with a negative sediment budget, a particle transit area, and a particle accumulation area with a positive sediment budget.

Even smaller local entities may be nested in each of these subunits. Depending on the extent of area involved, human activities can have a range of harmful impacts requiring different management strategies. These three subunits cannot be dissociated when assessing global wind dynamics. Due to its vastness, satellite imagery is required to obtain an overview of the general system.



▲ N'Beika, Mauritania. Seif dunes with a star dune trend.

The GWAS theory was formulated in 1972 (Mainguet, 1972) on the basis of an analysis of an aerial photograph mosaic of northern Chad that had been published by the French *Institut Géographique National* (IGN) along with an analysis of data collected in many field surveys. A single sand-bearing wind current was documented. It was found to be a discontinuous spatiotemporal system spanning several hundreds of kilometres linking Libya to Chad, then circumventing the Tibesti Mountains, and extending as far as Niger. These observations were confirmed and supplemented by METEOSAT imagery, which is a valuable tool for detecting links between Saharo-Sahelian [ergs](#).

### ▼ Sediment budget (SB) in sandy Saharo-Sahelian environments







J.J. Lemasson © IRD

### Aeolian particle source area

The source area is a [deflation](#) and winnowing surface where erosion processes and particle export predominate. The effects of the wind differ according to the substrate:

- scouring [corrasion](#) phenomena occur in bare rocky areas leading to the formation of [kaluts](#) and yardangs;
- the wind carries away the sandy matrix on stony alluvial deposits, leaving worn down [dreikanter](#) stones;
- wind winnowing occurs in sandy areas and the ground becomes fixed [desert pavement](#) at the terminal stage.

Paradoxically, erosion is also involved in building individual or adjoining aeolian dunes such as [parabolic dunes](#) through a [deflation](#) process in hilly sandy landscapes fixed by vegetation cover. The wind rushes through openings in the vegetation cover, etches out sandy hillocks and builds up dunes whose concave windward slopes consist of shifting sand, whereas vegetation can immobilize the sand on the slipface. These dunes threaten cropping and grazing areas via deflation and the migration of sand particles from these dunes.

[Longitudinal dunes](#) are also found in particle source areas. The axis of these erosion dunes is parallel to the prevailing wind. According to Jordan (1964), these are the most common dunes on Earth, and they even cover as much as 72% of all Saharan sandy areas. This confirms the hypothesis that the sand exportation is the main process under way in the Sahara Desert, probably since the Late Holocene.

On a geological timescale, this Saharan sand exportation process has increased the volume of sandsheets in the actual Sahelian millet-growing area (Mainguet, 1985). Longitudinal dunes can reach hundreds of kilometres long and 200-1 500 m wide, separated by 500-3 500 m wide [deflation](#) corridors. They are active dunes in arid and hyperarid areas and are only stabilized when the surface develops into [desert pavement](#) consisting of coarse sand particles (over 400 µm).

These dunes are normally fixed by vegetation cover in semiarid environments (annual precipitation: 150-600 mm/year). However, destructuring of the surface pavement and/or overgrazing may reactivate and turn them into mobile sand reservoirs. People traditionally settle in the interdune corridors.

## > FOCUS | Wind impacts according to the substrate in the source area

### • Desert pavement



▲ Desert pavement of coarse sand grains. Surface state of longitudinal dune in Akchar Erg (Mauritania, 2005).

### • Dreikanter

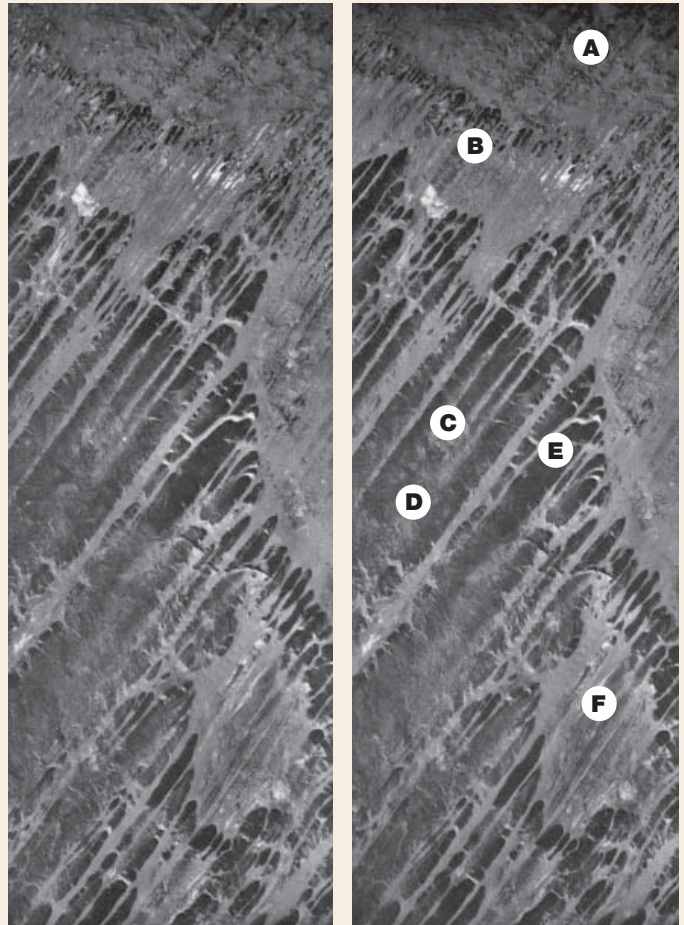


▲ A dreikanter is a wind-carved stone, generally with three sides, a flat base, two faces under the sharp crest, rounded edges and a matt surface. Dreikanter are found on the surface of deserts or in geological layers formed under arid climatic conditions with high saltating sand-laden winds.

### • Corrasion ridges

Longitudinal variations in the size and frequency of sandstone ridges, in association with layer changes, may be noted on these photographs. Four uniform areas succeed each other from NE to SW:

- A disorganized area **A**, where the ridges are not clearly formed.
- A clearcut thin-ridged area **B**, separated from sector **C** by an escarpment where the ridges start widening.
- The ridges in **C** are much broader. The best formed ridges are found right after the escarpment. The grooves become shallower as they get further away from the escarpment in the windward direction.



▲ Impact of layer changes on the size and frequency of corrasion ridges, Sol-Solé sector (18°30'N, 19°20'E), Bembéché, Chad (Aerial photographs AE 54-55, NE-34-XIV, n° 254-255; scale: 1/50 000).

- In the **D** area, two ridge systems overlap, sometimes with deeper grooves. The best preserved desert varnish is located right behind the escarpment, which is an area **E** where the ridges are likely best preserved.

The best ridges are found in gentle landscapes and areas with **barchan dunes** where corrasion is less marked. In **F**, a hydroaeolian basin with lacustrine deposits is carved in extensions of the sandstone grooves. With every topographical obstacle there is a change in dimension and frequency since the rock joints (fractured rocks) continue in the same direction with layer changes, but their frequency is altered.

Source: Mainguet, 1972





▲ Self dune reactivation in the Trarza sandsea on the eastern outskirts of Nouakchott (Mauritania, 2005). Reactivated self dunes composed of sand bleached by hydromorphy. They are obliquely oriented NNE 5° to 10° with respect to the direction of the prevailing wind (harmattan, NNE 30°) which is responsible for the paleoclimatic longitudinal dunes. These dunes elongate obliquely within the interdune corridors.

© F. Dumay and M. Mainguet

Presently, the reactivation of [longitudinal dunes](#) leads to sand release. This sand can be locally worked and give rise to a new generation of [seif dunes](#) that, in turn, extend obliquely and cross the interdune corridors where they are channelled and reworked into [barchan dunes](#) or mobile [sand veils](#).

Sand released from the dunes transits through the interdune corridors where it can be blocked by human structures. This increases the risk of sand invasion, which is originally due to an erosion phenomenon. This is the situation in Trarza [Erg](#), Mauritania, where inhabitants are obliged to abandon the interdune areas—that previously served also as pathways and grazing areas for herds and as roads for cars—which are gradually filled with locally reactivated sand. It also seems that this phenomenon is self-sustained by the population. People flee from the interdune depressions and from the sand transiting through them and massively settle on the longitudinal dunes. This leads to destruction of the structure of red soils that were formed under more humid paleoclimatic conditions, with compaction of the sand and subsequent release of even more material that could be carried away by the wind.

### Predominantly wind transit areas

At the soil-atmosphere interface, sand is transported by stages for long distances over very long periods (millenia) along hierarchically arranged flow channels, which is why it is tempting to talk about 'sand rivers'. These wind flows differ from water flows. Although effectively channelled by the topographical features, they have no banks and they blow over relatively gentle windward slopes. Along these transit areas, the surface roughness can increase to reach such a level that parts of the area become deposition areas. The reverse also holds true, with the most original example concerning Kaouar escarpment (Niger) in the middle of Ténéré Desert. The Ténéré sandsea stops upwind of

the relief exposed to harmattan winds, and turns into a sandstone escarpment. The Ténéré Sandsea reappears a few kilometres downwind of an [aeolian overdeepening](#) depression close to the foot of the escarpment.

In the transit area, along the same current, the wind can bear sand or not. The transporting wind and the material transported should be considered separately. In Saharan winds, material accumulated along the desert edges is not necessarily of such remote origin, i.e. it could have been picked up anywhere along the wind current. Sand migrates in the form of sand grains, saltation veils or dunes.

### > FOCUS | **Nebkas—indicators of wind erosion and short-range transport**



▲ *Nebka* and sand veils in the Moroccan Sahara (Morocco, 2006).

© F. Dumay / M. Mainguet

*Nebkas*, or sand arrows, are good indicators of deflation and short distance aeolian transport. They form on the leeward side of small obstacles such as stone blocks or isolated bushes that locally decrease the wind speed, thus leading to an accumulation of up to 50 cm high. Here the wind direction is from the right to the left of the photograph.

## Sand accumulation area

Sedimentation processes prevail in sand accumulation areas. Sand can accumulate at a GWAS terminal or locally every time the wind comes up against an obstacle. For instance, a sand-laden wind that meets a reverse slope that is sufficiently steep to neutralize the vertical wind component (which it generated itself) will release its sand load onto a slope if it is gentle or, if it is steep to vertical, create an echo dune some distance from the obstacle. As the volume of an echo dune increases, it becomes a climbing dune leaning on the slope, and then surpasses the peak and may extend further to become a linear dune (or [seif dune](#)).

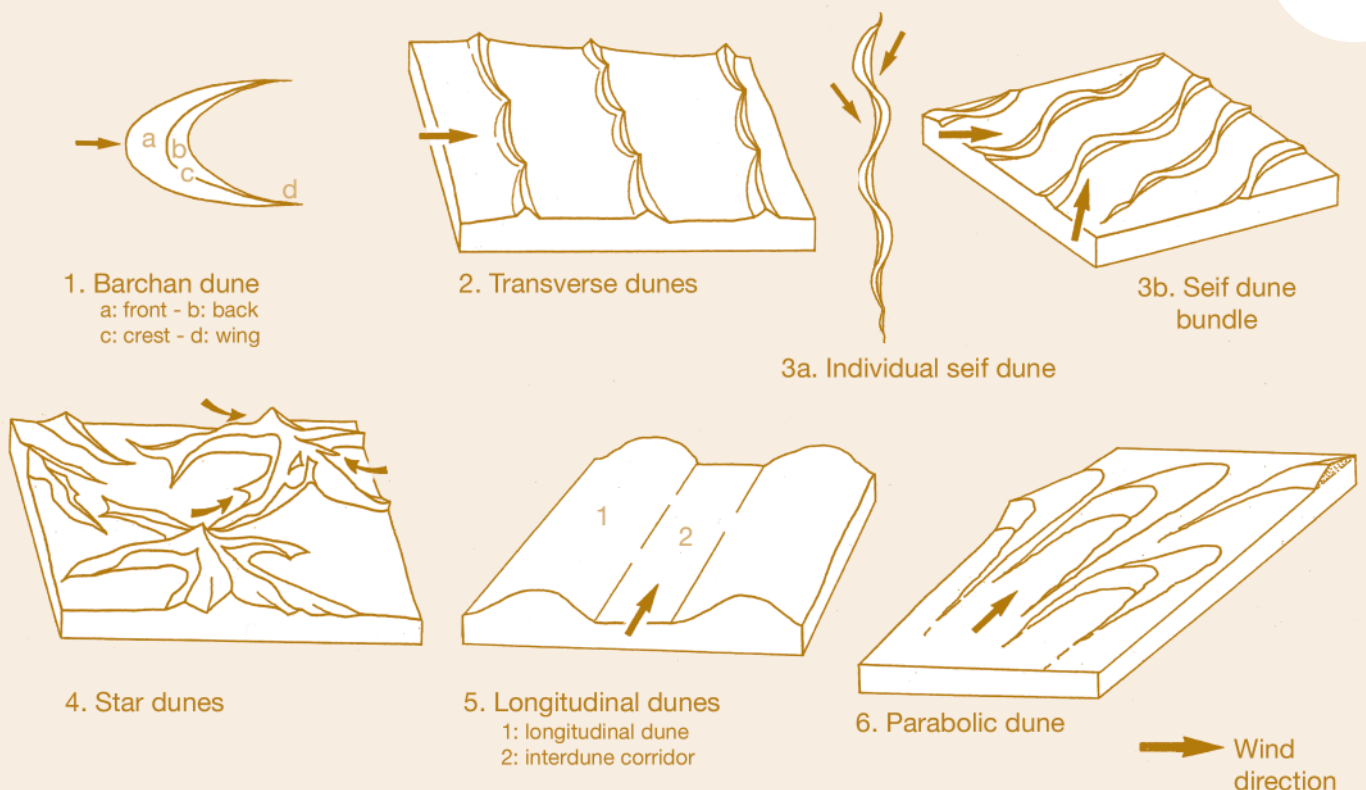
Sand encroachment concerns and strategies to control it are critical in such accumulation areas. Here again, the nature of the [sediment budget](#) can be determined on the basis of the types of dunes present. In accumulation areas, depending on the type of wind system, various dunes may be found, e.g. [barchans](#), seif dunes and [star dunes](#). They have several roles: sand reservoirs, transport (except star dunes, which are not mobile), and especially accumulation.

A monodirectional wind system is required for the formation of barchan dunes, which are aligned in the prevailing wind direction. These dunes move in the direction of the wind, which blows from the convex to the concave side of the dune according to the orientation of their symmetry axis. As barchan dunes are mobile, they threaten human infrastructures, sometimes engulfing roads, railway tracks or accumulating on the windward side of buildings and villages lying on

their path. When dune movements are slowed down by vegetation cover or rough ground, they can fuse together to form [barchan dune](#) chains and a system of transverse dunes that, in turn, form vast deposition sandseas, e.g. Aoukar Erg in Mauritania.

Seif dunes, or linear dunes, with an angular and sinuous profile, are obliquely oriented with respect to two prevailing winds. They can be several dozens of kilometres long, a few dozens of metres wide and 20-30 m high. They are formed as a result of these two combined winds, by: prolonging barchan dune wings; building up in areas where leeward winds meet behind an obstacle; or deriving from the reactivation of [longitudinal dunes](#). The sand that they are made of migrates by surpassing the dune peak and migrates also parallel parallel to the foot of the dune slope. The bottoms of the slopes of the seif dunes serve as sand transport routes, which is why they are always narrow and their dynamics favour elongation. Seif dunes on the outskirts of Nouakchott extended 450 m between 1984 and 1991. They 'slither' (i.e. by sideways undulation) in the direction of the winds that shape them. When they are located close enough to each other they can fuse as a result of seasonal wind changes, giving rise to complex braid-shaped dunes or seif clusters. This dune elongation trend is especially threatening for human infrastructures, e.g. every day during the dry season they block the *Route de l'Espoir* in Mauritania. Contrary to [barchan dunes](#) which just pass over infrastructures, seif dunes do not move but instead continue lengthening, thus often blocking roads and channels running perpendicularly with respect to their elongation direction.

### > FOCUS | Different types of aeolian dunes





## > FOCUS | **Ripplemarks—deflation and winnowing indicators**

These are ripplemarks consisting of coarse particles larger than those which can be carried by the wind. Ripplemarks are residual and highlight the presence of deflation and winnowing. A common error is to consider that ripplemarks are sand deposit indicators. Instead, they are the result of deflation and of exportation of finer particles.

► **Ripplemarks in the Northern part of the second dune bundle in Akchar Erg, Mauritania 2005.**  
In the background, three *rebouds*: accumulation of silt in a small bush, which grows in height as the trapped sand rises.

© F. Dumay and M. Mainguet



**Star dunes**, which are the highest accumulation dunes on Earth (up to 400 m high), are pyramidal dunes with three to four arms 500-3 000 m long, shaped by a multidirectional wind system. A concentration of many star dunes can lead to complex areas called star dune fields, where dunes are aligned transversally with respect to the prevailing wind or aligned parallel to the prevailing wind, e.g. the upwind part of Grand Erg of Bilma in Niger. Star dune fields could result from the complex extension of different dunes (barchans) when the wind system becomes multidirectional. The extension of an upwind transverse arm leads to the formation of star dune chains, as noted by McKee (1979) at Hassi Messaoud in the Grand Erg Oriental (Algeria). Nielson and Koçurek (1986) observed that small star dunes formed in winter turned into barchan dunes in summer when the wind shifted back to being monodirectional, which Pye and Tsoar (1990) suggested could mean that star dunes must be above a threshold minimum size to persist.

These are *bona fide* sand reservoirs: the ‘mother dune’ in Morocco, i.e. *N’Teguedei* in the Draa Valley, serves as a sand supply for a chain of star dunes that are invading the ancient Tinfou Oasis. These dunes are major constraints to human activities, i.e. seasonal shifts in their divergent arms obstruct all communication routes (Mainguet and Chemin, 1979).

### **WIND PARTICLE TRANSPORT PROCESSES—EFFECTS ON HUMAN POPULATIONS, AGRICULTURE AND INFRASTRUCTURES**

Particles are winnowed (sorted by particle size) when taken up by the wind (deflation). Once set in motion, these particles are responsible for **corrasion**: wearing down of rocks or foliage by mechanical abrasion. For sand particles to be taken up and set in motion by the wind, the wind velocity must be greater than the friction velocity, which is generally estimated to be 4 m/s for a substrate consisting of particles of a suitable size for wind transport (transport capacity). Windborne sands have modes (the most common size in a sample) ranging from 125 to 250  $\mu\text{m}$ .

Windborne transport concerns particles from the size of dust to 2 mm diameter, with displacement ranging from a few metres to several thousands of kilometres for dust. The negative impacts on human populations and the environment differ according to the particle size. Particle uptake, erosion and transport are spatiotemporally discontinuous processes.

### **Windborne suspended particle transport**

Suspension (or turbulent diffusion) is a means of transport for fine particles ranging from 1 to 100  $\mu\text{m}$  in size, including organic and mineral particles such as clay, loam, silt, fine sand as well as organic and chemical products. These materials can be carried from one continent to another at altitudes of 3000-4000 m. Particles smaller than 20  $\mu\text{m}$  (e.g. volcanic dust) can remain in suspension for several months and circumvent the Earth several times.

Windborne dust has a role in soil genesis (origin and formation of soil) and in the fertilization of areas located very far from the source area. For instance, in Barbados (West Indies), the annual volume of accumulated dust increased from 8 to 42 g/m<sup>2</sup> between 1967 and 1973, while dust-laden winds increased in the Saharo-Sahelian region during the same period. In 1998, in China, a 6-day dust storm carried loess from the Urumchi region to the town of Guilin, located over 2 000 km away (H. Guang, pers. comm., 2001). Inoue and Naruse (1987) showed that the wind particle diameter has been decreasing in the windward direction from eastern China to Japan. It is thus essential to pay close attention to the effects of windborne dust on soil genesis in the Japanese archipelago and Korea, where arable land is invaluable and in very short supply!

The Gobi desert, in China, is the main source area of dust/sandstorms over Beijing. It was thought that desertification in this area could explain these storms. However, further observations revealed other causes, especially new land cultivation: clearing, tilling and cropping these lands increase their vulnerability to wind erosion. The wind thus has access to a high percentage of loose exportable particles when bare soils are exposed.

## ■ Transcontinental scale of windborne suspended particle transport and impacts on the climate, plants and monuments

Suspended particles are involved in the hydrological cycle, especially during cloud formation, fog and rainfall. They affect the climate by absorbing or diffusing solar radiation. When they settle on plant leaves, these particles can hamper photosynthesis by blocking stomata, and, when they are salt particles, they may also be pollutants.

## ■ Harmful effects of suspended particles on human health

The toxicity of suspended particles mainly concerns particles of less than 10 µm diameter, as larger particles are filtered out within the nose or upper respiratory tract. Suspended dust is known to have a role in some functional respiratory disorders, in triggering asthma attacks and in the rise in the number of deaths due to cardiovascular or respiratory diseases, especially in sensitive subjects. Dust also induces eye infections.

In Africa, fine particles are constantly being exported in suspension by the wind to South America, Greenland and Europe. They are also being redistributed in more nearby regions, such as in the tropical forest in the Gulf of Guinea, thus fertilizing the soils therein. Since the severe droughts in the Sahel (1973-1986), a sharp increase in the number of dust storm days (i.e. days when visibility is less than 1 000 m) has been noted. The number of days of sand dust storms affecting Nouakchott increased tremendously from 415 days between 1960 and 1972 to 3 362 days between 1972 to 1995. These dust storms upset air and terrestrial transportation.

These dust storms disturb air and terrestrial transportation due to poor visibility. They also have an impact on human health, especially on respiratory and cardiovascular systems.

### Wind transport via saltation

The term saltation was first used in reference to waterborne particle displacement. As the wind is a fluid like water, the term saltation is now naturally applied to the movement of particles in air and designates the successive bouncing displacement of sand grains. Saltation affects particles in the 100-600 µm size range. Once the movement is initiated by the wind, saltation is partially self-sustained by the impact due to the collision of falling sand grains with the sandy substrate, thus propelling other sand particles that, in turn, fall a few centimetres to a few metres further on, again propelling more sand particles, etc.



▲ Initiation of a local sandstorm in the Chtam region (Morocco, 01/04/2005).

Windborne sand displacement generally occurs at heights of under 50 cm, but sand-laden winds can blow as high as 2 m over very rough substrates (e.g. pebble [regs](#)). Saltation is a displacement process that is very traumatizing for vegetation due to the abrasive effects of continuous sand grain bombardment of plant leaves and stems.

On a microscopic scale, saltating sand induces lesions on the waxy epidermal layer of plant leaves, thus increasing water evaporation from the plant. Injured leaves wither faster than healthy leaves. Wind can also stall flowering by desiccating flower buds. Pollination is also affected by violent winds that desiccate and disperse the pollen, while also sometimes damaging fruit by saltation—fruits can be scarred when wind velocities are over 6-7 m/s, and velocities of 10-12 m/s can cause fruit fall. Turbulent winds of over 12 m/s can cause lodging of cereal crops, with yields thus being reduced by as much as 40%.

Moreover, seeds or short adult plants may be buried under sand deposits, or otherwise uprooted. Grasses are susceptible to 6 m/s winds, whereas woody plants can be damaged when wind speeds reach 12 m/s. Experiments carried out by Armbrust and Paulsen (1973) showed that winds also have an impact on chemical processes in plants.



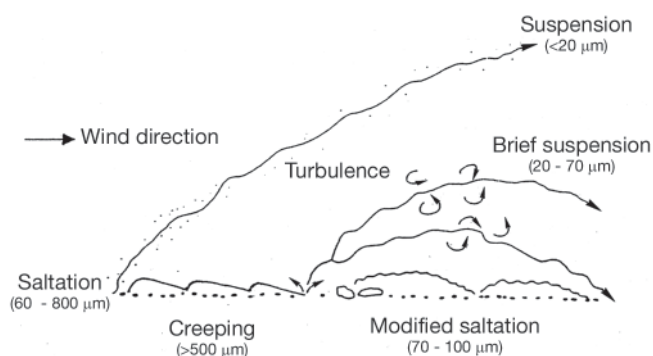


© F. Dumay

### Wind transport by creeping and rolling

These are means of transport for coarse sand particles (over  $630\ \mu\text{m}$  diameter) that cannot be uplifted and carried by the wind. The wind is still able to shift blocks and pebbles laterally.

During windborne displacement, particles are sorted by decreasing size according to the wind direction. This sorting occurs during transport and has a substantial role in soil redistribution, i.e. impoverishment via erosion or enrichment through the contribution of fines and organic particles. This has impacts on the spatial redistribution of human populations who abandon land that has become barren as a result of windborne particle exportation and subsequently colonize new lands. Many marginal areas have thus been newly cultivated in the northern Sahel, where erosion and soil exportation processes are already under way.



▲ The different wind transport processes and the size of the particles (in  $\mu\text{m}$ ) processes (from Pye and Tsoar, 1990).

## > FOCUS | Influence of the topography on wind transport

Applications of Bernoulli (Swiss physicist, 1700–1782) of Boyle's law (whereby, for fluids in motion, the product of the pressure and velocity is constant) gave rise to the Venturi Principle. In practice, this means that in a wind current the pressure drops as the velocity increases. Converging windstreams thus behave as if they were flowing through a bottleneck, with an increase in velocity and a drop in pressure. Conversely, when the same windstreams diverge, the pressure increases as the velocity declines.

Note that this model applies to any relief obstacle (hill, mountain, dune, road embankment, building, etc.) and to obstacles in hollows, e.g. depressions. It may seem strange that, in a wind line, the reverse slope of a depression can serve as a wind accelerator. The gradient of a slope upwind from an obstacle has a considerable effect on windborne sand transport patterns:

- For steep windward slopes, the wind velocity accelerates as the wind approaches the obstacle because the windstreams are compressed and the pressure is thus markedly reduced. At the foot of the obstacle, windstreams have enough room to remain separate, so the pressure increases as the velocity declines. In this case, particles are deposited at the boundary of the turbulence zone generated by the obstacle, and where the wind velocity has dropped to almost zero. Vertical impervious obstacles (wall or fence) oriented perpendicularly with respect to the wind have the greatest effect on the wind.
- A wind-permeable obstacle (e.g. a windbreak) of 50% porosity will reduce the wind velocity without deflecting the windstreams. Windward and leeward sand sedimentation depends on the porosity and shape of the obstacle. For a porosity of over 50%, the sedimentary deposit profile is long and low, whereas it is short and high when the porosity is below 50%. The dynamics associated with the shape and height of orographic obstacles was investigated by Rémini (2002).

# Wind erosion control techniques

**I**n analyses conducted prior to selecting a sand encroachment control strategy, a distinction must be made between individual particle displacement and dune movements. It is also important to differentiate windstreams and sand flows. Wind streams are governed by synoptic and regional meteorological conditions, while local and regional conditions mainly regulate sand flows—this includes sand uptake, transport and deposition, according to physical load substitution mechanisms\*, which in turn are regulated by the landscape, vegetation cover and human infrastructures.

In control initiatives against the impacts of wind, generally involving sand depletion or encroachment, the sediment budget and dune type should be taken into account, while also distinguishing between:

- sand mobility in source areas with a negative sediment budget, where mobile particles should be blocked;
- sand mobility in transit areas where the windstreams should be deviated to avoid burying human infrastructures in sand, and
- sand mobility in deposit areas with a positive sediment budget (Mainguet, 1995), where excessive sand accumulation and dune genesis are problematic for human settlements.

Wind erosion control is a two-step process:

- In the first step, the site to be protected is classified as belonging to a global wind action system (GWAS) or a regional wind action system (RWAS), while taking the topography and the dune type or mobile sand conditions into account. The area to stabilize or protect is estimated at the end of this phase.
- The second step is operational (FAO, 1988) and aimed at reducing the wind velocity at ground level, e.g. by increasing the surface roughness, while improving the soil moisture conditions so as to promote densification of the vegetation cover (Diatta, 1994).

\* The wind recovers energy after it releases its sand load and it can then take up another load downwind.



▲ Moudjéria region, Mauritania, 1999. Roads are rapidly covered with tongues of sand in sandstorm conditions. The car gives an indication of the scale of the sand tongues.

M. Dukhan ©IRD

## SAND ENCROACHMENT CONTROL TECHNIQUES ARE OF LOCAL INTEREST

The protection methods implemented and established standards vary depending on the level of experience of each country, the features of the treated area, the type and availability of local natural or artificial materials, as well as on the political-economic strategy adopted on the basis of the target objectives. The techniques are effective on a local scale, but cannot be generally implemented at all threatened sites—this is a key point in sand encroachment control.

In all cases, however, technical choices are made on the basis of the criteria used for evaluating infrastructure and community protection results, either to promote sand accumulation upwind from structures, or to disperse accumulated sand.



Assessments of the efficiency of sand encroachment control techniques are also generally done on a case-by-case basis and focused directly on the success rate of specific operations. Field results and levels of protection of infrastructures, including communities (Mainguet and Chemin, 1982 in the Kaouar oasis and palm groves in Niger; Bisson, 1983 and Gravier, 1993, at Moudjéria in Mauritania), are (in addition to the cost) the main efficiency assessment criteria.

The control efficiency with respect to infrastructures and installations is also a key factor in deciding on what techniques to develop. All methods should take into account:

- access of farmers and cattle breeders to their fields and rangelands;
- effective distribution of agricultural products;
- traditional organization of villages;
- financial cost of control techniques and especially of their maintenance.

## TOWARDS AN INTEGRATED WIND EROSION CONTROL STRATEGY

For effective control in the vicinity of installations, protection programmes have to account for risks associated with wind mechanisms that are set in motion as a result of human activities and development projects:

- for villages and suburban areas;
- for public infrastructures and equipment: airports (Salama *et al.*, 1991), roads (Aïci, 1980; Lémone oud Elhacen, 2000), channels;
- for oases (Selassi, 1983), crop fields (Chepil, 1959) irrigation systems, in order to preserve agricultural land and increase its value via the development of the natural environment, by creating a suitable microclimate and setting to preserve wildlife and plants. In southern and eastern Morocco, *séguis* (clay irrigation canals) and *khettaras* (drainage galleries to carry well water to crop fields) are often blocked by shifting sands, so protective vegetation barriers are required.

Specific local ecological and human resources must be utilized and promoted to ensure the success of control programmes by reducing costs and coming up with sustainable solutions for local communities (Eren, 1985).

A project was set up in 1978 at Zagora (Morocco) to control sand mobility through a technical cooperation programme involving collaboration between the

Moroccan government, FAO and GTZ. This type of integrated approach is based on the assumption that all sectorial strategies will underlie interactions with policymakers of associated sectors, e.g. in a rural environment, with coordination between sectors concerning water points in rangelands, pasture improvement and more general measures on agroforestry and herding.

All of these methods designed to control the negative impacts of the wind are based on a dual strategy, i.e. mechanical and biological control, to reduce sand uptake and transport and control the organization and distribution of sand during its deposition and accumulation, and especially to stabilize it on the spot.

## MECHANICAL SAND ENCROACHMENT CONTROL

Mechanical fixation is usually essential for sustainable short- and medium-term stabilization of mobile sand and dunes. This technique immobilizes sand long enough for vegetation to take root.

This control technique should be recommended when areas to protect have saline soils and rainfall levels of less than 60 mm/year. This encompasses all techniques designed for stabilization of moving sand masses and for sand deposition prevention. There are three overall categories: fencing, mulching and the aerodynamic method. The aims are:

- to immobilize sand in small-sized source areas (e.g. coastal dunes in Somalia and Morocco);
- to immobilize dunes, i.e. stabilize sand on the windward side, which is necessary for [barchan dunes](#) via various fixation processes. In China, Liu Shu (1986) showed that barchan dunes were destroyed by sowing grasses in the interdune corridors.

### > EXAMPLE | Improvement project in Niger

In Niger, afforestation of the *Dallos* Bosso and Maouri (wide dry valleys running north to south in tributaries of the Niger River) with *Acacia albida* in order to improve millet yields also prevented [deflation](#) of fine river sand from these *dallos*. This fine sand has an excellent moisture-holding capacity and is suitable for millet cropping.



© F. Dumay

▲ Sand deposited by the harmattan wind blocked on the northern side of the *Route de l'Espoir*, Mauritania, November 2009.

This sand block was achieved through the installation of mechanical barriers of dried *Leptadenia pyrotechnica* and biological fixation with *Prosopis juliflora*. This blocking is clearly insufficient because the *Leptadenia pyrotechnica* barrier is almost completely buried, along with the *Prosopis juliflora* cover, with only the canopy showing above the sand. Other plants also grew naturally, such as *Calotropis procera* in the centre of the photograph and a few grass clumps.

## Erecting fences perpendicular to the prevailing wind

Fencing provides a linear obstacle to the power of the prevailing wind, thus decreasing its velocity, reducing its load capacity, while blocking sand and forcing sand deposition in the vicinity of the fence. This leads to the formation of an artificial 'blocking dune' if the fencing is oriented perpendicularly with respect to the prevailing wind, or a 'tapered blocking dune' when it is oriented 120-140° with respect to the wind direction (FAO, 1988).

Once the sand has accumulated to the top of the fence, it is no longer trapped and is carried away. A new fence then has to be installed over the initial one (conventional method already used to stall sand invasion in Algerian oases in the early 20<sup>th</sup> century).

Hamidov (1974) pointed out that cement sheets could be raised and used several times and that their service life is fivefold greater than that of vegetation fencing. When the artificial dune created by these raised fences has a balanced profile, a new fence should be installed upwind from the initial one. According to Watson (1990), sand accumulation in height stops when the dune slipface becomes too steep and unstable, leading to an avalanche phenomenon.

The efficiency of a fence depends on its wind permeability, i.e. it has to reduce the wind velocity without generating vortex. It depends on the fence orientation with respect to the prevailing wind, and on its profile and layout (linear strips, crosses, checker boards, circles) on the surrounding types of sand deposits, on preliminary surface treatments of surfaces to be protected, and especially on the location of the site in the GWAS and RWAS.

It also depends on the positioning of the fence, its porosity, which in turn depends on its density, with the optimal porosity being 40-50%. Under systems with violent multidirectional winds with vortex formation, the fencing should be supplemented by setting up checkerboards throughout the area between two successive fences. Kaul (1985) proposed to plant quickset hedges as a first step in a global dune area reforestation programme.

As saltation accounts for 95% of the sand transported 30 cm above the soil surface (UNSO, 1991), fencing does not need to be installed much higher than this level. All sand blocking systems should be continuously maintained and gaps have to be repaired immediately since they promote wind acceleration.



> EXAMPLE | **A long asbestos cement fence northwest of the *Lycée de Boudnib* to protect this secondary school (Morocco, March 2005)**

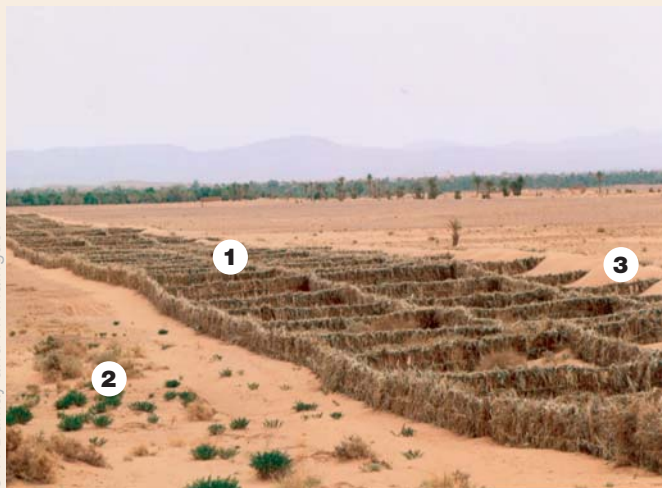
This fence is, unfortunately, not oriented perpendicularly with respect to the prevailing wind (*Sahéli*), nor is it maintained. In the background, accumulated sand has reached the top and is blown over the fence, while in the foreground there are gaps in the fence that increase the wind velocity, and thus actively participate in [deflation](#) of sandy material that in turn is transported towards the village by saltation. Rather than providing protection, this fence is actually more of a handicap since it is creating a reservoir of sand, which has already been partially mobilized by the wind just a few metres from the outskirts of the village!

© F. Dumay and M. Mainguet



> EXAMPLE | **Setting up a sand encroachment control system to protect a palm grove (southwest of Ait Ben Omar palm grove, Morocco)**

© F. Dumay and M. Mainguet



This is a grid of braided palm leaves extending a few hundreds of metres and oriented NW-SE 330°, perpendicular to the *Sahéli* wind. It consists of three grid squares of palms **(1)** and, on the leeward side of the grid, 6-9 rows of tamarisks are planted in a staggered pattern in small depressions **(2)**. This grid was set up in 2002. After 3 years, the grid squares located upwind were filled with sand **(3)**: this mechanical protection strip is thus efficiently fulfilling its blocking role upwind of the palm grove. The tamarisk plants are not doing well because of insufficient watering. This overall system is interesting because it is functional in the medium term rather than just the short term. It provides protection against sand invasion for one generation, and for several generations if the biological fixation is effective.

If the system includes several rows of plant material, the area between the two fences can be 20-25-fold greater than their height without loss of efficiency. The material supply conditions and costs are crucial with respect to fencing choices.

More checkerboards have been built than isolated or series of fences to facilitate sand trapping and immobilization. The grid dimensions are determined on the basis of the speed of the wind to be neutralized, the slope grade, dune shape and grid height, which varies according to the type of plant material used, e.g. palm stipes or leaves, esparto grass (*Stipa tenacissima*) in Morocco, reeds in Tunisia, rachis of dum palms or *Leptadenia pyrotechnica* in Mauritania.

As an example, the mean dimensions of grids used on pre-Saharan dunes in Morocco are 10 x 15 m at peaks, 3 x 3 m on slopes and 4 x 4 m in depressions (FAO, 1988). Plants are transplanted or sown within the grid mesh to enhance biological sand stabilization. In the Shapotou dune area, Chinese scientists have found that a low grid (20-30 cm) is the a sufficient solution for immobilizing sand prior to the formation of a [biological soil crust](#) which in turn stabilizes and protects the soil from erosion.



▲ Stabilization of sand dunes northeast of Ait Ben Omar palm grove (Morocco, March 2005). The stabilization technique used here combines mechanical fixation of an aeolian dune using a grid of braided palm leaves and natural fixation with shrub species.

© F. Dumay and M. Mainguet

## > EXAMPLE | A sand dune stabilization programme in the vicinity of Tinrheras (Morocco, 2005)



© F. Dumay and M. Mainguet

▲ Vicinity of Tinrheras.

This programme was implemented by the Moroccan Water and Forestry Service in the 1980s. A grid of braided palm leaves and *Andropogon gayanus* was set up prior to sowing plants (mainly tamarisks) to ensure biological fixation. A thin fragile biological soil crust developed on these dunes. However, the program was not successful as the trees were in poor condition.

### Fencing made with local plant material

The material supply conditions and costs are crucial with respect to fencing choices. Grids made with plant materials are relatively expensive and may quickly rot or burn. Braided palm leaf fences are used in oases and in the Sahelian region depending on available local resources and traditional uses. The advantage is that they can last for 3-4 years, or longer if they are carefully maintained to ensure that they do not fall or become dislodged, or that gaps do not open. Moreover, they should be regularly raised by installing a new fence over the previous one until the profile of the formed artificial dune becomes balanced.

It was noted in Egypt that fences, when installed upwind of crop fields, also reduce evapotranspiration, thus boosting crop yields by 30-100%. The average number of palm leaves per linear metre ranges from 10 to 40 depending on their size and degree of dessication, according to the results of experiments carried out in Tunisia and Morocco (FAO, 1988). In Mauritania, *Leptadenia pyrotechnica* is used for fencing along the *Route de l'Espoir*. It is carefully harvested to avoid upsetting its natural renewal.

The following plant material can be used:

- branches of tamarisk (*Tamarix* spp.), *Retama raetam* or *Leptadenia pyrotechnica*, etc.;
- crop residue (e.g. millet stems).

Branches should be carefully collected in order to avoid degrading the surrounding natural vegetation.



### Fencing made with synthetic material

Fencing can be made of synthetic sunresistant netting with a 6 x 6 mm mesh or plastic nets. In the Algerian *steppe* region, 4 x 4 mm mesh plastic netting was used prior to biological stabilization. Golinski and Lindbeck (1979) proposed plastic netting to stabilize coastal dunes. Bilbro and Stout (1999) assessed the effects of plastic tube fencing that had been successfully tested in the Tashkent region in Uzbekistan (Mainguet, 1991). Netting has to be held down with 1.5-m long wooden pickets, which are driven 30 cm into the ground, and metal wire to attach the netting to the pickets (FAO, 1988). In Mauritania, 20 km east of the capital, on the *Route de l'Espoir*, synthetic nets are less efficient than *Leptadenia pyrotechnica* fencing, and they are also more expensive, unsightly, and disturb water circulation in the soil.

Asbestos cement sheets (FAO, 1988) are fragile, expensive and should be avoided because they contain asbestos. They have only been used experimentally to make up for palm leaf shortages. They are just used in transit areas when the aim is to reduce sand deposition on threatening dunes. The success rates are low, i.e. under 15% concerning experiments in palm groves in Draa Valley, Morocco. The inefficiency seems to be especially associated with the fact that no or few preliminary studies have been carried out on local or regional wind dynamics within the framework of an RWAS, and with the poor choice of location and orientation of these sheets. For instance, in Kyzyl Koum Desert, north of Boukhara (Uzbekistan), sheets are installed parallel to the roads instead of perpendicularly with respect to the sand-bearing wind.

The impermeability of these sheets also creates turbulence unless they are perforated for permeability. This type of fencing is raised by lifting the sheets partially until they are again around 1 m above ground.

### > EXAMPLE | Fencing made of synthetic material (Mauritania)



© F. Dumay and M. Mainguet

▲ Mauritania 2001, PK 22, *Route de l'Espoir*.

The method used here is based on the erroneous idea that a 'sand blocking dune' parallel to an infrastructure to be protected (located 20 m from the *Route de l'Espoir*) could keep sand from covering the road. This technique was a major failure—during the year of its installation, sand reservoirs built up near the road, and then sand blown from the reservoirs covered it in many places.

▼ At the top of the artificial sand dune in the background, fencing made with braided palm leaves, regularly enhanced until a dune with a balanced profile is obtained (Tunisia, December 1993). A vegetation barrier was planted leeward of this dune. It is somewhat unfortunate that mesquite and eucalyptus were selected for this barrier.



## Wind erosion reduced using the mulching technique

Mulching is used to block sand in source or transit areas. The technique involves covering sand with natural or artificial materials to form a protective layer. This layer is relatively dense and as uniform as possible to hamper sand uptake from the soil surface by the wind, curb saltation and preserve moisture by increasing the soil cohesion, thus promoting restoration of the vegetation cover.

### Plant and mineral mulch

Mulching with dry woody products or crop residue such as millet, sorghum or wheat stubble, protects the soil and improves its structure via organic matter input. Plant residue is the best material for mulch when locally available and inexpensive, but it is essential that this will not deprive livestock of fodder.

Michels *et al.* (1998), in the Sahel in western Niger, estimated that 2 t/ha of millet stubble would be efficient but unavailable under local conditions. In the same experimental areas, Buerkert *et al.* (1996) noted a 36-67% drop in sediment transport in the first 10 cm air layer above the ground surface after spreading 2 t/ha of millet straw. Bastow *et al.* (1978) described three types of mulch based on rye residue, stubble and lime that were incorporated in the sand. In experiments carried out in the Rajasthan Desert in India, cultivated sandy soils were efficiently fixed by cutting cereal stems at a height of 30-40 cm, thus leaving 1.5-2.2 t/ha of plant residue on the ground (CAZRI, 1984).

In Morocco, in the Essaouira region, 25 t of red juniper branches were found to be necessary to cover 1 ha of sandy soil, which means that a high quantity of available material would be necessary (which is not the case). In Niger, mulching is limited because there is very little available biomass, and agricultural residue, such as millet straw, which is used for other domestic purposes (hut walls, garden fences, etc.).

A thin protective layer is only effective under light wind conditions. Strong winds can increase particle transport by creating turbulence around the mulch straw. The quantity of mulch required varies according to the sand texture (FAO, 1988). Application procedures differ depending on the texture of the mulching material, e.g. a mulch layer that is too thin should be compacted, buried or mixed with a binding agent to formulate loam mortar with straw.

Mulching materials that are too coarse can create a rough surface and thus facilitate sand uptake by the wind. The soil should thus be scarified along with mulching to increase its efficiency. Cotton crop yields can be increased by 66-79% when the cotton crop residue has been left on the ground to protect the roots, or when sorghum and millet is intercropped with cotton.



▲ A Moor cattle breeder grazing his camel herd in a tree and shrub rangeland. Thanks to the nocturnal dew that falls, the hungry livestock have some green vegetation to graze, which grows on a partly reactivated sand sheet surmounted by pre-barchanic and pre-seif dunes (southern Mauritania).

A layer of clay can also serve as mulch. This technique was used to stabilize coastal dunes in Somalia, but this initiative was a partial failure because it triggered severe water erosion on the dune slopes. In Tunisia, a soil layer of around 2 cm was applied and stabilized by watering.

This method has also been applied on the embankments of Saharan roads in Morocco. It has the advantage of reducing evaporation from the soil, thus improving moisture retention in sandy soils and increasing its availability for vegetation. Zakirov (1980) described an application of a 20 cm clay layer on sandy slopes along the trans-Caspian and Turksib railway lines (Turkmenistan-Siberia).

Rainfall cannot be over 300 mm/year for a clay layer to be efficient, otherwise intense water erosion will soon be triggered, as noted in Somalia. In Afghanistan, clay is collected and spread on the sand with bulldozers.





M. Dukhan © IRD

Rainfall and water spraying can also immobilize sand by promoting cohesion between sand grains, thus increasing resistance to wind erosion. The lack of water supplies in dry ecosystems is a limiting factor of this method. In Egypt, this technique was successfully applied from 1950 until the Essad El Ali dam was completed (FAO, 1988), which resulted in depleting previously available water supplies.

#### *Synthetic and chemical mulch*

Synthetic products such as polymeric structuring agents are used in Algeria and Egypt. This can involve plastic films attached to the soil, which hamper evaporation and avoid surface [crusting](#), or acrylic roving made of an assembly of plastic filaments (50 kg/ha), or textile fibres laid out in a parallel pattern (50-60 kg/ha). In Algeria, old flattened tires are used at a rate of 1 600 tires/ha, but this is an unsuitable strategy because it is unsightly.

Non-phytotoxic chemical amendments (substances that are not harmful to plants at dosages of 100-150 kg/ha/year), such as Unosol 096, Helsel 801, Agroxif 614, Shell Sandfix, Hydromal, Agrosel, Polyacrilamide or Petroset SP, are sprayed to stabilize mobile sand and foster vegetation regrowth. This technique of stabilizing sand with chemical products is still in the testing phase. It is applied especially to coastal dunes (Egypt, Libya, Algeria) because water is required to dilute the substances.

The prohibitive cost is a drawback of this technique, since it requires latex or synthetic vinyl resin emulsions produced from acetylene. Papanyas and Makhsudov (1984) applied two preparations (K9 and SSB) on sandy soils in Uzbekistan to assess their soil fixation efficacy: they were found to reduce evaporation and promote [crust](#) formation, thus enhancing wind erosion resistance.

Petroleum products and mineral oils were used in Libya, Iran, Algeria and Saudi Arabia in the 1960s. These products were spread in a continuous coating or in strips alternated with strips of vegetation in Ferghana Valley in Uzbekistan, or sprayed to stabilize the sand, especially in the vicinity of human infrastructures.

These coatings hamper evaporation from the soil but they are unsightly, so their use is not recommended. There are three general product types:

- Asphalt and bitumen that are sprayed to obtain a thin layer (Algeria, Tunisia, Morocco, Iran and Egypt), which must be constantly monitored so that damage caused by movements of machinery or people can be quickly patched. These emulsions are applied at a rate of 1 t/ha.
- Heavy or lubricating oils, conversely, penetrate deep into the soil to provide more sustainable sand fixation. Over the last decade, these oils have been tested in Algeria, with applications in parallel or V-shaped strips at a rate of 2-9 t/ha (FAO, 1988).
- Crude oils generally only provide a short-term solution because the 0.5 cm protective layer does not soak into the sand. However, 3 years of stabilization is enough for vegetation to colonize the area, so this technique actually does offer a medium-term solution (FAO, 1988).

Chemical binders were very commonly used in ex-USSR. Gas pipelines in the town of Ourguentch (Uzbekistan) are protected by this technique. Some products, such as nerosine, which are considered toxic, are still used at a rate of 300 t/ha to protect the gas pipelines and even intra-urban roads (Podgornov, 1973). The results of these applications are nevertheless controversial since sand very quickly covers the thin film formed by these products.

## Aerodynamic sand excavation methods

By these techniques, sand is evacuated through the force and velocity of the wind. Installations should not hamper sand circulation. Public awareness is thus essential, while implementing procedures for evacuating sand via wind energy developed on the basis of long-standing practices.

This type of sand clearance is based on the aerodynamic effect of modifications of the wind velocity and direction, on accelerations or turbulences that enable the wind to remove accumulated sand through an increase in its load capacity.

### Use of the wind force for sand removal

Sand can be evacuated by increasing the wind velocity, by:

- systematically orienting streets parallel to the prevailing wind direction (Mainguet, 1991) while, if possible, raising and orienting doors and windows away from the prevailing wind;
- successively setting up fences around plots and gardens to create a load substitution phenomenon and to remove sand from croplands, as at Fachi in Niger (FAO, 1988);
- conventionally installing 20-50 cm diameter rocks on the top of each [barchan dune](#) to create turbulence, as in oases in Merzouga region (southern Morocco), and in Mauritania north of the *Société nationale industrielle et minière* (SNIM) Zouhérate-Nouadhibou railway line, where cones of coarse material have been built on the [barchan dune](#) peaks upwind of the railway. For large dunes, the wind velocity is increased by laying palm stipes on stone alignments (FAO, 1988).

## > EXAMPLE | Controlling sand encroachment on a railway line in Mauritania

The railway line **(1)** is perpendicular to the N-S prevailing wind that regularly generates [barchan dunes](#) crossing the tracks, often causing derailments. In this area, SNIM uses an aerodynamic method to disperse dunes upwind of the railway line. By this technique, cones are constructed **(2)** (with railroad embankment material) and installed on the barchan dune tops. The turbulence created by these 1-m high cones of coarse materials helps to break down the dunes. The sand is then dispersed across the track in the form of a saltating [sand veil](#).



▲ Controlling sand encroachment on the Nouadhibou-Zouérate railway line, northern border of Mauritania (2001).



### Obstacle shaping and the Venturi technique

The aerodynamic method also involves shaping obstacles hit by the wind. This generates a compression phenomenon whereby the wind velocity is not decelerated in contact with the counter slope of obstacles—this avoids sand deposition. A mean width of 25 m is now often shaped on each side of roadways in North Africa, and of channels and pipelines in the Daouanas region in Mali.

The wind velocity is accelerated by convergence and slowed down by divergence. Based on this principle, and as tested in southern Morocco, the Venturi technique involves building a solid tilted and trapezoid-shaped structure in the immediate vicinity of infrastructures to accelerate the wind velocity right around the roadway or railway tracks, as was done at Shapotou, China.

### Forced particle deposition upwind of human infrastructures

Creating artificial dunes upwind of infrastructures to be protected (plantations, roads, villages) is recommended to hamper sand invasion. Asbestos cement or plastic fencing should thus be installed perpendicular to and upwind of the prevailing wind, at least 200 m from the structure to protect, rather than right against it, as is still often done in Mauritania along the first 30 km of the *Route de l'Espoir*, east of the capital. However, this method is inefficient if the sand source is too abundant. For this specific road, one solution could be to develop a wooded strip upwind, i.e. north of the road.

### Biological sand encroachment control techniques

The development of permanent vegetation cover is the only sustainable technique for overcoming the negative effects of the wind. This must follow mechanical

techniques for stabilizing mobile sand and dunes—these are expensive, unaesthetic and the effects are only temporary. Grass strips have been successfully planted along roads in ex-USSR, with an exponential decline in wind erosion as the vegetation cover increases. Local ecological conditions must be taken into sufficient account to ensure the success of biological techniques. Their implementation is based on the assumption that moisture is present in the soil at a reachable depth for plants, or otherwise plants must be watered until their root systems have grown deep enough to tap the groundwater.

### Role of vegetation in wind erosion control in sandy areas

Dunes in hot tropical deserts are formed mainly with quartz sands which are almost sterile for plants that could stabilize moving dunes or for crops growing on fixed dunes. Symbiosis between nitrogen-fixing microorganisms (supplied in irrigation water) and plants should be promoted in order to increase the sand fertility and the organic matter content of soils.

The quantity of soil nitrogen present determines the density of the vegetation cover. Moreover, the soil structure has to be suitable for vegetation to grow properly. Arnagueldiev (1979) pointed out that, in Central Asia, destruction of the sandsheet by preliminary construction work made it impossible to grow any plants for the next 4 years.

Biological techniques include all techniques designed to increase vegetation cover with grasses, shrubs, bushes or trees that could serve to immobilize the sandy substrate. In Mexico, for instance, *Prosopis juliflora* plants and cover of different annual species were planted for this purpose.

► An *Acacia raddiana* tree growing in the interdunal depression. This *Acacia* is the an ideal tree species in arid and semiarid ecosystems. *Panicum turgidum*, a grass species, is growing under this tree. The other tree on the right is *Balanites aegyptiaca*. The interdunal area is surmounted by a star dune in the background. The same landscape can be divided into areas with different degrees of land degradation. The star dune in the background indicates a very severe degree of degradation, on the contrary the area at the foot of the star dune has three levels of vegetation cover (grass, bush and tree levels). This is a good demonstration that a landscape cannot be classified only with satellite tools.

Wind erosion control techniques





▲ A sand dune generated by the wind via particle trapping. The clump of vegetation responsible for the trapping keeps growing higher than the sand as it accumulates. Mauritania.

O. Barrière © IRD

In Burkina Faso, with under 350 mm/year of rainfall, grass cover is regenerated in bare areas using a shallow ploughing technique to facilitate plant germination and growth and by imposing 2-3 years of exclosure. The exclosure period necessary can be as long as 10-12 years if there is only 100-120 mm/year of rainfall, as in southern Tunisia.

In Senegal, *Casuarinas* spp. trees imported from Australia are massively planted on nitrogen-depleted soils to form a green barrier from Dakar to Saint-Louis and stall the progression of mobile sands. In Niger, *Acacia albida*, *A. senegal* and *A. adansonia* are planted to enrich the soils. The nitrogen deficiency of soils does not affect the growth of plants with hairy roots that secrete a mucilage containing sodium which curbs the effects of nitrogen-consuming bacteria in the rhizosphere.

In Somalia, dune fixation initiatives supported by the World Bank are based on choices of fast-growing plant species such as *Prosopis*. However, *Prosopis juliflora* is a tree that only grows properly in lowland areas with substantial groundwater resources, so it is not a good dune stabilizer because it is often uprooted on dunes or buried under shifting sands. Moreover, this tree can endanger local vegetation and considerably deplete the soils. In ex-USSR, strips of *Haloxylum* vegetation were also planted on railway embankments.

Psammophilic species (sand-loving species such as the grass *Aristida pungens* in the Sahel) often have unique morphological and physiological characteristics, especially grasses whose roots grow up to 15 m horizontally. The type of vegetation depends on the

particle-size range of the sand. For instance, in the Near East:

- on coarse and relatively immobile sand: *Aristida coerulescens*, *Salsola vermiculata*, etc.;
- on very coarse sand affected by **deflation**: *Astragalus gyzensis*, etc.;
- on mobile dunes: *Retama raetam*, *Haloxylon schmittianum*, *Euphorbia paralias* or *Calligonum comosum*.

Plant species are chosen for biological rehabilitation on the basis of their resistance to environmental factors (climate, soil, human activities), their reproduction mode, wood or fodder yields, etc. In some conditions, *Eucalyptus* (Morocco), *Prosopis juliflora* and *Tamarix* spp. are chosen for their fast growth, although *Acacia raddiana*, which is a slow-growing species, is more ecologically adapted for growth under semiarid Sahelian conditions.

The vegetation cover can also be rehabilitated by seed sowing, but this operation sometimes has to be repeated up to three times. In oases, it is of considerable interest to develop a multilayered vegetation cover with different plant species in order to control deflation—this can reduce insolation, and thus evaporation and soil drying, and hamper soil uptake by the wind.

In central China, 1 300 ha of bare dunes were transformed by farmers into a research station to assess the results of sowing different plant species. After 2-3 years, *Salix psammophila*, *Hedysarum scoparium*, *Hedysarum laeve* and *Artemisia sphaerocephala* generated a 25-37% vegetation cover under mean rainfall conditions of 150 mm/year.



In North Africa, rainfall of over 200-300 mm/year during winter and spring, in conjunction with enclosure, can be sufficient for vegetation rehabilitation. *Saccharum aegyptiacum*, *Tamarix articulata*, *Ammophila arenaria* and *Artemisia* spp. are adapted plant species that effectively stabilize sandsheets. This technique can be applied on a large scale but it will only be efficient if the soil has been stabilized previously and there is sufficient moisture in the soil surface layer (FAO, 1988).

These biological techniques depend on the ecological conditions in which they are used. They can thus be applied with or without additional irrigation or watering, by natural regeneration, planting or sowing, using seedbeds or not, with suitable protection from mobile sand, after plant selection, while avoiding 'aliens' (non-native plants) and preferring native plants, especially woody species. In Mauritania, Meunier proposed to systematically introduce *Prosopis juliflora* (a non-native tree), but this initiative was catastrophic, especially in the opinion of local inhabitants who called it the 'devil's tree' because it hampered the growth of other plants—in palm groves, it was detrimental to palm trees. It dried up wells when grown in their vicinity.

#### Windbreak and vegetation barriers

Guyot *et al.* (1986) described that, “on plains, where woody plant stands of various heights and densities occupied the landscape to different extents, agricultural operations led to the elimination of these stands, resulting in completely cleared open fields. On vast areas, this generally caused an increase in wind velocity, which in turn led to a reduction in soil fertility and crop yields. Developers proposed to build windbreaks to offset the negative impacts of the wind on agricultural production and herding. This is considered to be one of the most efficient conservation measures to counteract the risks associated with the absence of trees on bare areas (...). Despite the recognized usefulness of windbreaks, very few overall initiatives have been implemented to promote their widespread use for rural development protection (...).”

Windbreaks are partial covers consisting of one or several rows of trees and/or bushes. These barriers reduce the wind velocity and turbulence in their vicinity, both upwind and downwind. Their effectiveness varies, depending on:

- the profile of the vegetation strip;
- the permeability of this vegetation strip;
- the watering and/or drainage potential;
- the area to be protected;
- and available funding.

The efficiency of vegetation in hampering particle movement and in reducing the wind velocity at the soil surface varies with the density of the canopy, which serves as a sand trap. This efficiency also depends on the plant morphological features (shape of the canopy, trunk lengths), which affect sand flow. In transit areas, small **nebkas** are formed in the vicinity of isolated bushes.

#### > FOCUS | Velocity ratio and efficiency of windbreaks

“Maximum wind braking is achieved with spacing (between two windbreaks) equivalent to fivefold the windbreak height (*H*). According to experimental findings, the optimum spacing for agriculture ranges from 15 to 25 *H*.” The effect of a windbreak can be evaluated by the “ratio between the mean wind velocity reduced by the windbreak and that of the undisturbed wind at the considered height and distance.” To determine this ratio, the terms ‘velocity ratio’, ‘relative velocity’, ‘relative wind velocity’ and ‘efficiency’ are used, all in reference to the reduction in wind velocity at a given velocity and height. The Chinese Lanzhou team defines the windbreak efficiency by the following equation:

$$K = (Q_0 / Q_1) \times 100\%$$

Where  $Q_0$  is the quantity of blocked sand,  $Q_1$  is the maximum quantity of potentially transportable sand, while **K** also depends on the porosity, the windbreak orientation and height, as well as on the transported load (Ling Yuquan, 1994).

Wind tunnel experiments were carried out at the International Centre for Eremology at Ghent University (Belgium) to determine the optimal windbreak configuration. The effects of five windbreaks on reducing the wind velocity in a single circuit line and in two combinations of several lines were assessed. **Deflation** and sand deposit areas were specified on the basis of wind velocity measurements and compared with experimental sand transport data.

Sand deposition began at wind velocities of less than 3 m/s. Windbreaks with uniform porosity over their entire height provided the longest protected area because they generated sand deposits at distances equivalent to fivefold the windbreak height (**H**) upwind of the barrier and **22 H** downwind of it. Windbreaks with a dense lower part were more efficient in reducing the wind velocity than those with a dense upper part.

Several techniques were tested in single circuit lines or quadrants because the optimum windbreak configuration has yet to be clearly determined. Research has shown that windbreaks have no effect after a distance equivalent to 15- to 25-fold the windbreak height according to the velocity ratio.

Gupta *et al.* (1984) noted that some plant species used in windbreaks, such as *Cassia siamea* (tree), are more effective in reducing wind erosion and soil loss than *Andropogon gayanus* or *Oxytenanthera* (perennial grasses). They recommend alternating the row heights. Under a monodirectional wind regime, vegetation barriers should be oriented at a right angle to the prevailing wind direction. Under bidirectional wind systems, they should be perpendicular to the two winds and thus, in the case of linear dunes (seif dunes), oriented obliquely with respect to the dunes.

The results of many experiments revealed that successions of windbreaks have a very substantial positive impact on crop yields despite the shade they cast and root competition. They have a marked impact in countries where the growing season is short and dry. Good results have been obtained in arid and semiarid regions where crop yield increases of 80-200% have often been recorded. According to Guyot *et al.* (1986), 10 m high windbreaks spaced 150-250 m apart caused a crop yield reduction within the area 5-10 m from the windbreak, and beyond this area yields increased by as much as threefold. The authors conclude that, “up to a distance of around 100 m—midway between windbreaks spaced 150-250 m apart—trees have a ‘remote role’ on the fertility of the field. Competition between windbreak plants and crops (...) resulted in a decrease in yield as compared to the control areas, within a 0.5-1 H\* strip.”

\* where H is the windbreak height (Ed.)

Farmers are generally unaware of the extent of protection windbreaks provide, despite their confirmed positive impacts on crop production. They often only notice their drawbacks: wasted land, complicated mechanized cultivation, reduced crop yields due to shading and root competition, habitats created for *kélé kélé* or millet-eating birds in Africa. Moreover, they claim that trees and bushes are ‘parasite dormitories’.

Garczinski (2000) stated that, “no technical-scientific overdoses ruin agriculture, environment and health more than cutting down trees, bushes and shrubs in fields from the Equator to the polar circle—errors of brutes and agronomists.”

#### *Afforestation and wooded bands: their role in controlling wind erosion within the framework of environmental rehabilitation*

Afforestation by planting shrub- or tree-based vegetation cover after perennial grasses have been sown is the most efficient method for stabilizing sand and dunes in the long term, but the plant species used must be very carefully selected.

For the fixation of linear dunes (seif), planting should be done in the interdune corridors and on the lower half of the two dune slopes (Mainguet, 1991) and not, as it is too often the case, on the entire dune.

The abrasive effects of windborne sand grains hitting the surface of leaves and young shoots, along with the stripping of roots by [deflation](#) and the burial of plants under the sand are major problems for afforestation. For some species, it is thus preferable to transplant 80-100 cm high nursery plants that already have roots that are 20-40 cm long.

▼ Protection of the railway line of the *Société Nationale d'Industrie Minière* (SNIM) between Nouadhibou and Zouérate in Mauritania, December 2001. Mesquite plantlets are placed inside metal drums to be sheltered from wind abrasion. This green barrier is aimed at protecting the SNIM Nouadhibou-Zouérate railway line in an area especially susceptible to the deposition of windborne material.

© F. Dumay and M. Mainguet





## > FOCUS | The 'green barrier model' unsuited to the conditions prevailing in Algeria

In the early 1970s, a simplistic view of desertification in Algeria was based on the hypothesis that the desert advances northwards like a steamroller. The entire strategy of setting up a 'green barrier' was thus formulated on a false assumption. The green barrier project was launched in 1972 to control the desert advance process under the slogan: '*Algeria advances as the desert retreats*'. Algeria decided to establish a NE-SW wooded band of around 40 km wide on the high plains. This green barrier was part of a large-scale agrarian reform project geared towards employing the abundant inactive youth population.

All projections for success put forward at the onset of the project faltered, because: there were no effects on sand invasion since the tree planting objectives for the area initially set out were not fulfilled; overgrazing increased due to the rise in livestock herds; and technical errors increased during the planting operations, leading to heavy losses. Moreover, generally just one species was planted (Aleppo pine), so the plantations were susceptible to parasite infestations. Following this failure, the idea of creating a nationwide barrier was dropped in favour of small-scale integrated projects.

The green barrier concept first appeared in the 1950s in USSR and China, particularly with the experimental 'Green Wall', which was planted around the Gobi Desert to protect China from mobile sands. This vegetation barrier technique was also used in Mastung Valley, Baluchistan (Pakistan).

Wooded belts were initially designed for urban applications. The first projects were implemented in the early 20th century, around London and Jerusalem (Cohen, 1994). The aim was to confine uncontrolled urban development and decorate cities with some greenery. These green areas were nevertheless quite limited in size.

Large-scale desertification control projects are more recent. In China, initiatives were undertaken in the early 1960s, during the Cultural Revolution, with the aim of controlling sand encroachment in the Taklamakan Desert.

The 'Green Barrier' project in Algeria, based on the Chinese model, was carried out in the 1970s to offset the potential arrival of Saharan sand. It turned out, however, that the mobile sand was the result of erosion promoted by overgrazing, fires and land clearing (UNESCO, 1988). The project was initially planned to encompass an area 1 500 km long and 20-40 km wide within the framework of an agrosilvopastoral development programme. There were several phases. In 1968, work began at a very large-scale afforestation project site—a forerunner to the Green Barrier—around Wilaya de Djelfa, on Moudjebara plain.

The Mergueb natural reserve north of Bou-Saada was afforested during the same period. In 1972, President

Houari Boumediene launched the Green Barrier at Saïda. Development of the steppe rangelands was to be the third phase of the agrarian revolution, with afforestation carried out in the fourth phase.

The first Green Barrier afforestation initiatives started efficiently in 1974. The aim was to occupy the overabundant youth population and to meet the challenge of an enormous afforestation project aimed at increasing the forest area twofold within 10 years—this area was barely 3 million ha in size after independence. In the early 1980s, this Green Barrier had evolved from a monospecific afforestation to an integrated development design. Roadsides between the towns of Ain-Ousséra and Djelfa, and between Djelfa and Bou-Saada, were planted by soldiers as part of their national military service. As of 1992, after the army withdrew from participating in civil activities, the forestry service took over supervision of the Green Barrier project, but these activities are currently limited to continental dune fixation operations.

The first green belt planted on the northern outskirts of Nouakchott (Mauritania), which began in 1975 upon the initiative of the Lutheran World Federation, was designed to protect the city from mobile sand dunes. This belt, which covered a 325 ha area and consisted of *Prosopis juliflora*, with 2 500 plants/ha, was not very effective. FAO assessed the situation in the late 1980s and, in 1991, initiated the Environmental Protection and Village Afforestation project, funded by the Lutheran World Federation. At the beginning of the 21<sup>st</sup> century, the project was back on the agenda in the form of a green barrier northeast of the city.

▼ Summary of the different wind erosion control techniques and the results of their applications in Tunisia, Morocco, Mauritania and Niger

Location		Methods	Results/Drawbacks
TUNISIA	Governorate of Médenine	<ul style="list-style-type: none"><li>• Afforestation and enclosure</li><li>• Creation of 500 km of fencing and grids (corrugated iron and asbestos cement sheets on artificial sandy bunds: <i>tabia</i>)</li><li>• 2nd phase: biological fixation with <i>Eucalyptus</i>, <i>Calligonum</i>, <i>Ratama</i>, <i>Tamarix</i>, etc.</li></ul>	<ul style="list-style-type: none"><li>• Rangeland rehabilitation</li><li>• Attempts to replace corrugated iron sheets with less expensive braided palm leaves</li></ul>
	Governorate of southern Tunisia	<ul style="list-style-type: none"><li>• Mechanical fixation: artificial dunes and grids with asbestos cement sheets, reed stems and palm stipes</li></ul>	<ul style="list-style-type: none"><li>• 6 942 km of <i>tabias</i> erected.</li><li>• The technique using perforated sheets was abandoned because considered inefficient. In the most exposed areas, the sheets have to be raised 4 to 5 times a year, requiring substantial manpower.</li></ul>
		<ul style="list-style-type: none"><li>• Biological fixation, nursery development</li></ul>	<ul style="list-style-type: none"><li>• Need to transport plants long distances, leading to major plant losses.</li><li>• Priority to native species</li><li>• Afforested area: 11 ha</li></ul>
		<ul style="list-style-type: none"><li>• Enclosure and plantation watering</li></ul>	<ul style="list-style-type: none"><li>• Lack of water and poor water quality</li></ul>
<b>Conclusion:</b> Improvements necessary in the supervision of nursery work and planting methods; greater insight into the plant species best adapted to dune environments required; irrigation techniques should be improved; awareness of local inhabitants should be boosted in order to encourage them to help out.			
MOROCCO	in a continental environment	<ul style="list-style-type: none"><li>• Local interventions</li><li>• Mechanical control with fencing made of vegetation or asbestos cement sheets and plastic mesh. Grids and bidirectional wind system</li><li>• Biological control</li></ul>	<ul style="list-style-type: none"><li>• Less expensive, but unsatisfactory results</li><li>• Need to maintain this fencing</li><li>• Implies a &gt;2% fines content with irrigation</li></ul>
	in a coastal environment	<ul style="list-style-type: none"><li>• Installation of an artificial dune perpendicular to the prevailing wind</li><li>• Soil cover with local branches</li><li>• Biological fixation by planting or sowing</li></ul>	<ul style="list-style-type: none"><li>• Wind directions poorly estimated</li><li>• Local shrubs cut</li><li>• High grazing pressure and lack of dune maintenance</li></ul>
<b>Conclusion:</b> Initiatives considered too point-to-point and focused on emergency situations, without any overall protection plan; problem of management of enclosure areas; local inhabitants should be more involved.			
MAURITANIA		<ul style="list-style-type: none"><li>• Droughts of the 1970s-1980s gave rise to sand encroachment control programmes:<ul style="list-style-type: none"><li>▣ Mechanical protection of the <i>Route de l'Espoir</i> with nets and <i>Leptadenia pyrotechnica</i> branches</li><li>▣ On the outskirts of Nouakchott: afforestation of a few sites with <i>Prosopis juliflora</i></li></ul></li></ul>	<ul style="list-style-type: none"><li>• Inefficient because the technique is not tailored for the dunes to treat</li><li>• Species not recommended because it eliminates local vegetation: depletion of bushy and grassy vegetation within a 70 km radius around Nouakchott</li></ul>
<b>Conclusion:</b> Lack of work on a global scale (scant use of satellite imagery); an effective enclosure policy required around the capital; this country lacks a legal framework, especially a grazing code and land-use laws.			
NIGER	Zinder and Diffa Regions	<ul style="list-style-type: none"><li>• Study of a dune model</li><li>• Mechanical fixation: creation of artificial dunes with installation of fences made with local vegetation</li><li>• Biological fixation</li><li>• Mulching</li></ul>	<ul style="list-style-type: none"><li>• 300 km of fencing and screens</li><li>• 1 274 000 plants on a 912 ha dune area</li><li>• 197 ha with enclosure</li><li>• Good participation of local inhabitants, with 426 532 work days</li><li>• Unfortunately, only shrub species used</li></ul>
<b>Conclusion:</b> Good participatory approach, end of rural migration; 1 000 ha of dunes were stabilized.			





© F. Dumay

▲ Grid of braided palm leaves, Boria palm grove (Morocco, 2005).  
The project was partially successful because the sand trapping was quite efficient but, since there was no biological rehabilitation, the project results were not sustainable.

## A few wind erosion control costs

In Morocco, according to Khardi (soil science and water conservation engineer, oral communication, 2005), mechanical fixation using 80 cm palm stipes for the grid costs 13-14 dirhams\* a linear metre.

3 200 linear m of fencing is required to stabilize 1 ha. Biological fixation on the leeward side of this fencing costs 8 000 to 10 000 dirhams, excluding the irrigation and maintenance expenditures. In many Moroccan palm groves, palm growers sell individual palm leaves (0.65-1 dirham), which provides them with supplementary income but the plants are considerably weakened.

Due to poverty, the lack of reliable information and differences in geographical areas (areas to treat, origin of sand encroachment, volume of sand to deal with, etc.), it is not possible to recommend cost-effective solutions. Cost criteria have to be combined with other criteria such as locally available material, water resources, manpower, etc.

\* 1 euro = 11.1349 Moroccan dirhams (exchange rate September 2010)

▼ Comparative costs (Euros) of different wind erosion control techniques on the basis of Moroccan, Algerian and Egyptian experiments  
km: kilometre; ha: hectare

Techniques		Cost in Euros		
		Morocco	Algeria	Egypt
Fencing	palm leaves	2 197/km	165/ha	424-970/km
	branches	2 377/km	311/ha	60/km
	sunflower residue			233-1 206/km
	asbestos cement		1 600/ha	
Grids	palm leaves ( <i>Phoenix dactylifera</i> )	6 351/ha		792/km
	esparto grass ( <i>Stipa tenacissima</i> )	5 043/ha		
	sunflower residue			265/km
	plastic screen		3335/ha	
Mulching	branches	444/ha		1 431/ha
	Retama retam	407/ha		
	rice straw			64-97/ha
	clay			127/ha
	used tires		267/ha	
	asphalt coating		603/ha	96-318/ha
	asphalt strips		166/ha	60-73/ha
	film		4 900/ha	
Vegetation hedges		566/ha		

# Hope for the future of wind erosion control

**I**n dryland regions, sandy landscapes are most affected by environmental changes. In the mid-20<sup>th</sup> century, a Sahelian steppe cover prevailed in sandy parts of the Sahelian area located between isohyets 150 mm and 600 mm south of the Sahara Desert. However, with recurrent droughts and the increase in human activities, a new generation of dunes developed (in northern Mali in the early 1970s) in areas where dunes had formerly been stabilized by paleoclimatic soil genesis.

It is the timescale of phenomena that has changed in recent decades with respect to the genesis of this new generation of dunes. It took millenia for large-scale [longitudinal dunes](#) to form, whereas it just took two decades for them to be altered, usually into [seif dunes](#), and sometimes into [barchan dunes](#). Control strategies therefore must be developed to deal with this change of pace from a geological to a human historical scale (25 years).

Fundamental research has established that wind erosion control cannot be focused simply on dealing with local problems. Based on the discovery that wind dynamics units can reach continental scale, e.g. the Sahara Desert and Sahel, control programmes should be applied on regional or synoptic scales. Indeed, all wind erosion control initiatives should deal with spatial forms and units along with their links and feedbacks while also proposing solutions on a medium time scale of one or two generations.

Wind erosion control has two components:

- an assessment component: this has progressed with the use of modern research tools ([remote sensing](#), sedimentology), but there are still some shortcomings with respect to assessing overlapping scales, i.e. synoptic to local, and to understanding different types of dunes;
- a management component: there has been marked progress, but there are still problems concerning the excessive cost of operations and, even more so, the psychological and financial requirements for maintenance.

Effective remedies are hard to find, but it is especially important to recommend solutions involving local materials. For instance, palm tree stipes may be used to immobilize dunes in palm groves in the northern Sahara, and *Leptadenia pyrotechnica* branches can be used in the southern Sahara. These are better options than asbestos cement sheets or plastic mesh, which are more expensive, aesthetically unsatisfactory, and they may hamper normal groundwater circulation when buried in the sand. Medium-term solutions should also be recommended for biological dune consolidation, and again with local rather than imported vegetation.

▼ Ja Ragdou, Niger. A highly degraded area with visible signs of the former steppic shrub cover with three vegetation levels (grass, bushes and trees), some *Acacia* trees are still visible.





▼ Daily tea breaks are important times for relaxing and exchanging information in campsites. In Waggar, Niger. Behind the sitting people, there is a shelter made with thorny plant material from which a goatskin container, called a *gerba*, is hanging.

## List of acronyms and abbreviations

<b>C3ED</b>	Centre of Economics and Ethics for Environment and Development, <i>Centre d'économie et d'éthique pour l'environnement et le développement</i>
<b>CSFD</b>	French Scientific Committee on Desertification, <i>Comité Scientifique Français de la Désertification</i>
<b>EGCES</b>	<i>Réseau francophone sur l'érosion et la gestion conservatoire des eaux et des sols</i> , France
<b>FAO</b>	Food and Agriculture Organization of the United Nations
<b>GTZ</b>	German Agency for Technical Cooperation, <i>Gesellschaft für Technische Zusammenarbeit</i>
<b>GWAS</b>	Global wind action system
<b>IGN</b>	French Geographic Institute, <i>Institut Géographique National</i>
<b>IRD</b>	<i>Institut de recherche pour le développement</i> , France
<b>ISCO</b>	International Soil Conservation Organization
<b>LGZD</b>	<i>Laboratoire de géographie zonale pour le développement</i> , France
<b>RWAS</b>	Regional wind action system
<b>SNIM</b>	<i>Société nationale industrielle et minière</i> , Mauritania
<b>UMR</b>	Joint research unit, <i>Unité mixte de recherche</i>
<b>UNEP</b>	United Nations Environment Programme
<b>UNESCO</b>	United Nations Educational, Scientific and Cultural Organization
<b>UVSQ</b>	University of Versailles Saint-Quentin-en-Yvelines, <i>Université de Versailles Saint-Quentin-en-Yvelines</i> , France



# For further information...

## BIBLIOGRAPHY

Aïci M., 1980. *Étude pédobiologique des bandes routières reboisées de la région de Djelfa*. Mémoire d'ingénieur, INA, Alger. 64 pp.

Armbrust D.V. & Paulsen G.M., 1973. Effect of wind and sandblast injury on nitrate accumulation and on nitrate reductase activity in soyabean seedlings. *Communications in Soil Science and Plant Analysis*. 4(3): 197-204.

Arnagueldiev A., 1979. *Péski centralnoy tchasti Karakoumov i méri borbi s ney*. Achkhabad: Ilim, Turkmenistan. 121 pp.

Bastow J., Peck W., Astill C. & Roebuck D., 1978. Wind erosion three methods of lessening the damage caused by the big blow. *British Sugar Beet Review*. 46: 14-17.

Bilbro J.D. & Stout J.E., 1999. Wind velocity patterns as modified by plastic pipe wind barriers. *Journal of soil and water conservation*. 54 (3): 551-556.

Bisson J., 1983. De la mobilité des terroirs à la stabilisation de l'espace utile : l'exemple du Gourara (Sahara algérien). In: Larbi Talha. Coll. *Annuaire de l'Afrique du Nord*, CNRS Editions, Paris. 22: 389-399.

Buerkert B. et al., 1996. (Eds.). *Wind erosion in West Africa: The problem and its control*. Proc. Int. Symp., Stuttgart, Germany. Margraf Verlag, Weikersheim, Germany.

CAZRI, 1984. *Research Highlights 1959-1984*. Central Arid Zone Research Institute, Jodhpur, India.

Chepil W.S., 1959. Wind erodibility of farm fields. *Journal of Soil and Water Conservation*. 14: 214-219.

Cohen S.E., 1994. Greenbelts in London and Jerusalem. *Pl. the Am. Georg. soc. of N.Y. Geographical review*. Jan. 1994: 74-89.

Cornet A., 2002. La désertification à la croisée de l'environnement et du développement. In: MAE. *Johannesburg, Sommet Mondial du Développement Durable. Quels enjeux ? Quelle contribution des scientifiques ?* Paris: 93-134.

De Noni G., Viennot M., Asseline J., Trujillo G., 2001. *Terres d'altitude, terres de risques. La lutte contre l'érosion des sols dans les Andes*. Collection Latitude 23, Édition de l'IRD, Paris. 219 pp.

Diatta M., 1994. *Mises en défens et techniques agroforestières au Sine Saloum (Sénégal). Effet sur la conservation de l'eau, du sol et sur la production primaire*. Doctorate Thesis, Unpublished, Université de Strasbourg, France. 202 pp.

Dregne H.F., 1984. Combatting desertification: evaluation of progress. *Environm. Conserv.* 11(2): 115-12.

El-Baz F., 1988. Origin and evolution of the Desert. *Interdisciplinary Science Reviews, J.W. Arrowsmith Ltd.* 3(4): 331-347.

Eren T., 1985. Agro-forestry in arid and semi-arid zones. In: FAO. *Sand dune stabilization, shelterbelts and afforestation in dry zones*. FAO Conservation Guide 10, Rome: 169-174.



▲ Sand encroachment in a concession and its barrier wall as a result of massive invasion by fine sand borne by the harmattan wind, *Dar es Salam* quarter, north of Nouakchott along the Nouakchott-Atar road, November 2009. Four points should be noted: the echo dune on the windward side of the small mud brick hut; the dislodged and overturned publicity panel; the windward and leeward sand encroachment over the 2.5 m high barrier wall; and the concession was abandoned because of sand encroachment. All buildings and structures on the outskirts of Nouakchott are affected in this way.

Evers Y.D., 1996. *The social dimension of Desertification. Annotated bibliography and Literature Review*. UNEP, UNRISD, IIED. 154 pp.

Fall O., 2001. *L'érosion éolienne dans le bassin arachidier du Sénégal: causes, mécanismes et solutions*. Doctorate Thesis, Laboratoire de Géographie Zonale pour le Développement, Université de Reims, France. 355 pp. Unpublished.

FAO, 1988. *Manuel de fixation des dunes*. Cahiers Conservation n°18, Rome. 68 pp.

Garczinsky F., 2000. *Nouvelle 5 bis*. 14 pp. Cemagref, Grenoble, France. Unpublished.

Golinski K.D. & Lindbeck K.E., 1979. Woven plastic for coastal dune-forming fences. *Journal of Soil Conservation Service of New South Wales*. 35: 26-29.

Gravier M., 1993. Moudjeria, un village mauritanien face à la désertification. *Science et changements planétaires, Sécheresse*. 4(1): 31-36.

Gupta J.P., Rao G.G.S., Rmakrishna Y.S. & Rao B.V.R., 1984. Role of shelterbelts in arid zone. *Indian farming*. 34(7): 29-30.

Guyot G., Delecolle R. & Ben Salem B., 1986. Brise-vent. *Cahier FAO Conservation* 15. Rome.

Hamidov H., 1974. *Priménénie cémentno pestchanikh smésy s dobavkami dla prédotvrachénia défl acii podvijnikh péskov*. Pressde l'Institut Polytechnique, Tachkent. 27 pp.

Inoue K. & Naruse T., 1987. Physical, chemical, and mineralogical characteristics of modern aeolian dust in Japan and rate of dust deposition. *Soil Science and Plant Nutrition*. 3: 327-345.

Jordan W.M., 1964. Prevalence of sand-dune type in the Sahara desert. *Geol. Soc. Amer., Spec. Pap.* 82: 104-105.

Kaul R.N., 1985. Sand dune fixation and afforestation. Traditional procedures for dune fixation: the hedge system. In: FAO. *Sand dune stabilization, shelterbelts and afforestation in dry zones*. FAO Conservation Guide 10: 65-70.

Lemine Ould Elhacen M., 2000. *Infrastructures routières en milieux sableux : environnement bioclimatique et morphodynamique de la Route de l'Espoir (Mauritanie)*. Doctorate Thesis, Université de Reims Champagne-Ardenne, France. Unpublished. 228 pp.





© F. Dumay

Ling Y., 1994. The distributive heterogeneity of sand transporting quantity along horizontal direction. *Journal of experimental mechanics*. 9(4): 335-352.

Liu Shu, 1986. Osnovnye sposoby zakrepleniya podviznykh peskov v Kitae. (Principaux procédés de la fixation des sables mobiles en Chine). *Problemy osvoeniya pustyn'*. 3: 76-79.

Mainguet M., 1972. *Le Modelé des grès. Problèmes généraux*. Doctorate Thesis, Institut Géographique National. (In: Études de Photo-interprétation), France. 2 vol., 72 tables, 105 stereographs, 333 fig. phot. 637 pp.

Mainguet M., 1976. Étude géodynamique de l'effet d'obstacle topographique dans le transport éolien : Résultats obtenus à l'aide des images aériennes et satellites au Sahara. *Société Franç. de Photogram.* Bull. 61: 31-38.

Mainguet M., 1976. *Localisation d'une unité écologique expérimentale dans la région de Maradi (Niger). Reconnaissance morphodynamique des 100 000 ha du périmètre Tchadoua-Mayahi*. GERDAT, Paris, LGPZ, Reims, 52 pp. + pl I-V. 2 maps.

Mainguet M., 1984. A classification of dunes based on Aeolian dynamics and the sand budget. In: El-Baz F. (éd.). *Deserts and Arid Lands*. M. Nijhoff Publ., Holland: 30-58.

Mainguet M., 1985. Le Sahel, un laboratoire naturel pour l'étude du vent, mécanisme principal de la désertification. In: Barndorff-Nielsen O.E., Moller J.T., Rasmussen K.R. & Willetts B.B. (eds), *Proceedings of international workshop on the physics of blown sand*. Dept. Theoretical Statistics, Institute of Mathematics, Univ. Aarhus, Denmark, Mem. n°8: 545-561.

Mainguet M., 1991. *Desertification. Natural background and human mismanagement*. Springer, Series in physical environment, vol. 9, Springer-Verlag. 306 pp.

Mainguet M., 1995. *L'Homme et la Sécheresse*. Masson, Paris. 335 pp.

Mainguet M. & Chemin M.C., 1979. *Lutte contre l'ensablement des palmeraies et des oasis dans le Sud marocain. Rapport technique : étude préliminaire de l'avancement des sables. Apport de la photointerprétation, de la télédétection, et des critères géomorphologiques de terrain*. Rapport TCP/MOR/6702. FAO, Rome. 32 pp.

Mainguet M. & Chemin M.C., 1982. *Formulation d'un programme de lutte contre l'ensablement des palmeraies de Bilma, Niger*. FAO/UNSO. 106 pp.

Mainguet M. & Dumay F., 1995. Transaharan Wind Flows analysed on Meteosat 4 satellite imagery. Resources, urban, sand & wind, Desert Technology III, Lake Motosu, Japan. *Journal of Arid Land Studies*. 53: 89-94.

Mainguet M., Dumay F. et al., 2005. *Dictionnaire de Géographie*. Sous la direction de G. Wackermann. Éd. Ellipses, Paris.

Mainguet M., Dumay F. & Létolle R., 2002. Géologie. Le Système Régional d'Action Éolienne (SRAE) du Bassin de l'Aral (Kazakhstan, Ouzbékistan et Turkménistan). The Regional Aeolian Action System of the Aral Basin. *Compte-rendu à l'Académie des Sciences*. 334 (2002): 475-480.

MC Kee E.D., 1979. *A study of Global Sand Seas*. United States Government Printing Office, Washington, 429 pp.

Michels K., Lamers J.P.A. & Buekert A., 1998. Effects of wind-break species and mulching on wind erosion and millet yield in Sahel. *Exp. Agric.* 34: 449 - 464.

Nielson J. & Koçurek G., 1986. Surface processes, deposits and development of star dunes: Dumont dune field, California. *Bull. Geol. Soc. Am.* 99: 177-186.

Papanyas K.P. & Makhsudoc K.M., 1984. Chemical protection of sandy loam soils from wind erosion. *Problems of desert Development*. 4: 95-99.

Podgorn A.S., 1973. *Priménéníé nérosina dlya zakrépléníya i oblécéníya pískov na trassakh gazoprovodov*. Presse de l'Institut d'Agriculture d'Achkhabad, Turkmenistan. 23 pp.

Pye K & Tsoar H, 1990. *Aeolian sand and sand dunes*. Unwin Hyman, London. 396 pp.

Rémini B., 2002. *Méga-obstacles et dépressions, leurs influences sur la dynamique éolienne, les ergs et l'ensablement des espaces oasiens*. Doctorate Thesis, Laboratoire de Géographie Zonale pour le Développement, Université de Reims Champagne-Ardenne, France. 208 pp.

Roose E., 1994. Introduction à la gestion conservatoire de l'eau, de la biomasse et de la fertilité des sols (GCES). *Bulletin pédologique de la FAO*. 70. Rome, 420 pp.

Salama M., Deconink J.N., Lofty M.F. & Riser J., 1991. L'ensablement de Nouakchott - exemple de l'aéroport. *Science et changements planétaires, Sécheresse*. 2(2): 101-109.

Selassi M.L., 1983. *Lutte contre l'ensablement des palmeraies du Maroc, Rapport sur la consultation en météorologie*. PNUD, FAO, FO: DP/MOR/78/017, n°6. 49 pp.

UNEP, 1991. *Status of Desertification and implementation of the UN Plan of Action to Combat Desertification*. Nairobi, 94 pp.

UNESCO, 1988. *La lutte contre la désertification en Algérie. L'expérience du barrage vert en Algérie*. Séminaire organisé dans le cadre du projet pilote de lutte contre la désertification dans le Sud tunisien, 24-29 Nov. 1986, MAB/UNESCO, PNUE.

UNSO, 1991. *Sand encroachment control in Mauritania*. Tech. Publ. Series, n°5. Office to Combat Desertification and Drought, New York. 45 pp.

Watson A., 1990. The control of blowing sand and mobile desert dunes. In: Goudie A.S. (ed.). *Techniques for desert reclamation*. Wiley Publishers, UK: 35-85.

# Glossary

**Aeolian overdeepening:** this occurs when wind erosion wears away the sandy layer and then etches into the underlying bedrock.

**Aeolian sediment budget:** An aeolian sediment budget is considered to be positive when more sand particles are imported into a sector than are exported (aeolian accumulation) and negative when more particles are exported than imported.

**Barchan dune:** A moving crescent-shaped sand dune whose crests point downwind.

**Biological soil crust:** This is a mat of lichen and/or moss that covers and immobilizes shifting sands—the first stage in the biological fixation of shifting sands (dunes, sand sheets, etc.).

**Compaction:** Creation of a compact soil state (reduction in pore space and increase in soil density) by natural packing.

**Corrasion:** Erosion of the surfaces of solid rocks by the scouring action of abrasive windborne particles.

**Crusting:** Process whereby a soil crust is formed.

**Deflation:** Wind-induced drifting of loose debris and fine soil particles.

**Desert pavement:** A surface concentration of coarse packed materials remaining after the wind has swept away finer soil particles.

**Dreikanter:** Pyramid-shaped stone with three sides that have been worn down by the impact of desert sandstorms (term of German origin).

**Dusting or sand veil:** This is a thin layer, or veil, of sand formed by the deposition of sand dust.

**Erg:** A vast region in the Sahara Desert occupied by sand dunes (term of Arabic origin).

**Erodibility:** This is defined as the extent of resistance of a soil to erosion, which is associated with the susceptibility of soils or surface materials to be lifted and carried by runoff. This susceptibility is linked with the structural stability, while also depending on the physical state of the surface: packing, tillage, bealing.

**Kaluts:** A system of sand crests and corridors etched in solid rock by a particle-laden wind. This term comes from Iran, where kaluts have been hollowed out of Miocene molasse.

**Longitudinal dunes:** Extended sand dunes separated by deflation corridors, which are aligned in the direction of the dominant winds.

**Morphodynamic unit:** A landscape unit with constant topographical, structural (lithology, stratigraphy and tectonic) and dynamic features.

**Nebka:** A small aeolian sand deposit associated with the growth of a bush or shrub, often extended by a dune spit formed downwind under the shelter of the plant (term of Arabic origin).

**Parabolic dune:** An unsymmetrical horseshoe-shaped dune that is concave in the upwind direction. Its orientation with respect to the dune-building downwind flow is contrary to that of a barchan dune.

**Rain erosivity:** The capacity of rain to induce erosion phenomena.

**Reg:** A stony desert with a mosaic surface of gravel (ranging from coarse sand particles to blocks) left by aeolian winnowing (term of Arabic origin)

**Remote sensing:** A set of techniques deployed from aircraft, balloons or satellites for the purposes of monitoring the Earth (or other planets), or the atmosphere, using the properties of electromagnetic waves transmitted, reflected or diffracted by different observed bodies. This technique facilitates and enhances inventories of terrestrial resources, weather forecasting, etc.

**Rillwash:** A water erosion process in which small channels are formed via streamlet and rill flow. Contrary to sheetwash.

**Runoff:** Water flow that occurs when excess water from rain transits through catchments.

**Sand veil:** A thin layer of sand particles on the ground surface.

**Seif dune (or linear dune):** A sharp-crested two-sloped longitudinal dune (2-3 km long and 30-50 m wide) (term of Arabic origin).

**Soil capping:** Destruction of the soil structure due to rainfall, leading to the formation of a continuous solid layer or thin surface crust.

**Soil reflectance:** Ratio of the intensity of the reflected radiation to the incident radiation on the soil.

**Splash:** The splattering of individual soil particles caused by the destruction of aggregates or the soil structure.

**Star dune:** A dominant relatively pyramidal sand dune consisting of a star-shaped network of sinuous crests that circumscribe cauldron blowouts.



## Abstract

Wind erosion—alone or combined with other physical or socioeconomic causes—is a mechanism that may induce desertification, i.e. severe or irreversible degradation of water and soil resources. Now that this phenomenon is better understood, the model of the 1970s based on three distinct stages (causes, mechanisms, consequences) has been discarded, in view of the many feedbacks and insidious links generated by wind erosion. Timely detection of wind erosion onset thresholds with remote sensing tools (satellite images and aerial photographs), and spatial delimitation and positioning of the phenomena observed are essential to be able to efficiently combat the damaging effects of wind erosion. No field operations can be effective without prior knowledge of wind erosion mechanisms at the land-atmosphere interface.

At this interface, wind activities are organised in dynamic units on a continental scale, or so-called global wind action systems (GWAS) spanning the Saharan and Sahelian regions, or regional scale (sweeping southwards across Egypt), or so-called regional wind action system (RWAS), in which humans interact via their activities. A GWAS is divided into three (particle source, wind transport, deposition) areas, each of which may be found at several locations within the GWAS.

When striving to combat wind-induced threats, especially by controlling clay, silt and sand particle loss and, conversely, sand invasion, the sediment balance and types of prevailing dunes should be taken into account, while distinguishing between the:

- . mobility in source areas where mobile particles should be stabilised
- . mobility in transport areas where wind streams should be deflected so as to prevent human infrastructures from being filled with sand, and
- . mobility in deposition areas where sand invasion is at stake.

The first stage consists of defining the site to be protected in relation to the GWAS or RWAS (taking the topography and type of dune or mobile sand into due consideration), and assessing the surface to be stabilised or protected. The second operational stage aims at reducing the surface wind velocity through technical and biological strategies.

To ensure success, the specific features of local ecosystems and human communities must be taken into consideration and effectively tapped in wind erosion control programmes in order to minimise costs and come up with solutions that are viable for the communities involved.

**Keywords:** Wind dynamics, desertification, remote sensing, Global Wind Action System, rehabilitation, human activities

## Résumé

L'érosion éolienne est un mécanisme qui peut à lui seul ou en combinaison avec d'autres causes physiques ou socio-économiques aboutir à la désertification, c'est-à-dire à la dégradation sévère ou irréversible des ressources en eau et en sol. Avec une meilleure connaissance de ce phénomène, le modèle des années 1970 qui dissocie 3 phases (causes, mécanismes, conséquences) est obsolète compte-tenu des nombreuses rétroactions générées et des liens insidieux qu'elles entretiennent. Un combat efficace contre les méfaits de l'érosion éolienne exige de déceler dans le temps les seuils de déclenchement à l'aide des outils de télédétection (images satellites et photographies aériennes), de limiter et de localiser dans l'espace les phénomènes observés. Toute intervention sur le terrain ne peut-être efficace sans connaissance préalable des mécanismes de l'érosion éolienne à l'interface sol-atmosphère.

À l'interface sol-atmosphère, les actions éoliennes s'organisent en unités dynamiques d'échelle continentale appelées Système Global d'Action Éolienne (SGAE) -couvrant le Sahara et le Sahel- ou régionale (balayant l'Égypte du nord au sud), appelées Système Régional d'Action Éolienne (SRAE), dans lesquelles l'homme interagit par ses activités. Un SGAE se divise en trois aires (aires de départ de particules, de transport éolien, d'accumulation), chacune pouvant se retrouver en plusieurs points du SGAE.

La lutte contre la menace éolienne, qui s'exprime notamment contre l'appauvrissement en particules d'argile, de limons ou de sable et, à l'inverse, contre l'ensablement, doit prendre en compte le bilan sédimentaire, le type d'édifice dunaire et faire la différence entre : la mobilité dans les aires sources où les particules meubles doivent être bloquées ; la mobilité dans les aires de transport où le courant éolien doit être dévié pour éviter l'ensevelissement des infrastructures humaines et la mobilité dans les aires de dépôt où c'est l'excès d'ensablement qui est en cause.

La première étape replace le site à protéger dans le SGAE ou dans le SRAE, en tenant compte de la topographie et du type de dune ou de sable mobile et aboutit à estimer la superficie à stabiliser ou à protéger. La seconde étape est la phase opératoire visant à réduire la vitesse du vent à la surface du sol par des stratégies mécaniques et biologiques. La réussite des programmes de lutte suppose l'utilisation et la valorisation des spécificités écologiques et humaines locales pour minimiser les coûts et rendre les solutions viables pour les communautés.

**Mots clés :** Dynamique éolienne, désertification, télédétection, système global d'action éolienne, réhabilitation, activités anthropiques

## In the same series

### Available issues

#### **Is combating desertification an environmental global public good? Elements of an answer...**

(M. Requier-Desjardins & P. Caron, September 2005)  
*English & French versions*

#### **Remote sensing, a tool to monitor and assess desertification**

(G. Begni, R. Escadafal, D. Fontannaz & A.-T. Nguyen, December 2005)  
*English & French versions*

#### **Fighting wind erosion. one aspect of the combat against desertification**

(M. Mainguet & F. Dumay, May 2011)  
*English & French versions*

#### **Combating desertification through direct seeding mulch-based cropping systems (DMC)**

(M. Raunet & K. Naudin, April 2007)  
*English & French versions*

#### **Why we should invest in arid areas?**

(M. Requier-Desjardins, August 2007)  
*English & French versions*

#### **Science and civil society in the fight against desertification**

(M. Bied-Charretton & M. Requier-Desjardins, October 2007)  
*English & French versions*

#### **Restoring natural capital in arid and semiarid regions. Combining ecosystem health with human wellbeing**

(M. Lacombe & J. Aronson, June 2009)  
*English & French versions*

#### **A land degradation assessment and mapping method. A standard guideline proposal**

(P. Brabant, November 2010)  
*English & French versions*

### Forthcoming issues

#### **Synthèse des projets de recherche et développement du CSFD en Afrique**

#### **Biodiversité et désertification (A. Sarr)**

#### **Pastoralisme et désertification en zone subsaharienne (Ph. Lhoste et B. Toutain)**

#### **La révolution pastorale en Méditerranée et son impact sur la désertification (A. Bourbouze)**

#### **Biens, ressources naturelles et pauvreté dans les sociétés pastorales : quelles approches ? (A. Bourgeot)**

#### **Désertification et gestion des ressources en eau**

#### **L'information environnementale pour l'aide à la décision**

#### **Changement climatique et désertification**

#### **Arbres, arbustes et produits forestiers non ligneux**



**Ministère de l'Enseignement  
supérieur et de la Recherche**

1 rue Descartes  
75231 Paris CEDEX 05  
France  
Tel. +33 (0)1 55 55 90 90  
[www.enseignementsup-recherche.gouv.fr](http://www.enseignementsup-recherche.gouv.fr)



**Ministère des Affaires  
étrangères et européennes**

27, rue de la Convention  
CS 91533  
75732 Paris CEDEX 15  
France  
Tel. +33 (0)1 43 17 53 53  
[www.diplomatie.gouv.fr](http://www.diplomatie.gouv.fr)



**Ministère de l'Écologie, du  
Développement durable, des  
Transports et du Logement**

*en charge des Technologies vertes  
et des Négociations sur le climat*  
Grande Arche  
Tour Pascal A et B  
92055 La Défense CEDEX  
Tel. +33 (0)1 42 19 20 21  
[www.ecologie.gouv.fr](http://www.ecologie.gouv.fr)



**Agence Française  
de Développement**

5 rue Roland Barthes  
75598 Paris CEDEX 12  
France  
Tel. +33 (0)1 53 44 31 31  
[www.afd.fr](http://www.afd.fr)



**Secretariat of the United  
Nations Convention to Combat  
Desertification**

P.O. Box 260129  
Haus Carstanjen  
D-53153 Bonn  
Germany  
Tel. +49 228 815-2800  
[www.unccd.int](http://www.unccd.int)



**Agropolis International**

Avenue Agropolis  
F-34394 Montpellier CEDEX 5  
France  
Tel. +33 (0)4 67 04 75 75  
[www.agropolis.org](http://www.agropolis.org)

**HOW TO CONTACT US:**



**CSFD**

Comité Scientifique  
Français de la Désertification  
Agropolis International  
Avenue Agropolis  
F-34394 Montpellier CEDEX 5  
France  
Tel.: +33 (0)4 67 04 75 44  
Fax: +33 (0)4 67 04 75 99  
[csfd@agropolis.fr](mailto:csfd@agropolis.fr)  
[www.csf-desertification.org](http://www.csf-desertification.org)

**On cover**

1: Southern edge of the Aoukar  
sandsea. Mauritania, 2001.  
© F. Dumay and M. Mainguet

2: Initiation of a local sandstorm  
in the Chtam region (Morocco,  
01/04/2005).  
© F. Dumay

3: Grid of braided palm leaves,  
Boria palm grove (Morocco, 2005).  
© F. Dumay

Find us on

**facebook**

**twitter**  
[twitter.com/csf\\_d\\_fr](https://twitter.com/csf_d_fr)