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Research Priorities for the Study of Aeolian Activities and Sand Dune Reclamation

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Abstract : Rapidly increasing population in the dryland ecosystems and consequent shortages of agricultural land, climate-related threats to food security, especially in Africa, preference given to the strategy for food self-sufficiency and the compulsion of cultivating vulnerable aeolian areas like semi-fixed dunes, sand sheets and loess blankets increase the necessity of research on aeolian activities and sand dune reclamation. The detrimental effects of wind erosion on global environment are not yet well appreciated, because the processes are still not well understood and the initial symptoms are difficult to detect. The human impact on the wind action system is also not fully appreciated. This paper provides a brief history of aeolian research and then identifies the topics which require more studies and verification, like relationship among sand deposits, climate and vegetation cover, development of sand seas in relation to topography, dune orientation, dune building episodes and the concept of sediment balance. Finally, the paper discusses why wind erosion is so difficult to combat, and what knowledge-base is needed for the control measures.

Key words : Aeolian research, wind erosion, sand seas, sediment balance, bedforms, Global Wind Action System, control measures.

Aeolian sand covers 6% of the global land surface. About 97% of it is accumulated in the dry lands (defined as receiving an annual rainfall < 600 mm). On an average, about 20% of the world's arid zones are covered by aeolian sand (20% in North America, 20% in Sahara, >30% in Australia and >45% in Central Asia; (Pye and Tsoar, 1990). The semi-arid zones can be as rich and even richer in sand than the arid areas themselves, as has been found in the Sahara-Sahel region (Fig. 1).

In arid regions with active dunes and semi-arid regions with fixed and vegetated edifices, the sandy soils carry a denser vegetation than other terrains, because of their good capacity to retain available water, and are therefore attractive as grazing areas for nomads and as cultivated areas when precipitation is more than 300 mm/yr. With less capillarity these soils are less prone to salinization than the heavier silty, clayey soils.

Because of continuously increasing land degradation in the dry lands and because wind erosion is one of the most drastic physical processes of land degradation and desertification, research priority should be given to a better understanding of aeolian dynamics at different scales. This will help to combat wind erosion more efficiently and to find simple and cheaper sand dune reclamation methods.

Droughts and human activities make the aeolian deposits more vulnerable to wind erosion. Three types of areas are particularly sensitive. These are the loess areas like those of China, the desert margins where man interacts with the arable sandy land (Kaul, 1985) and the coastal dune fields.

In the dry land ecosystems, the rapid increase in population, and therefore the limita-

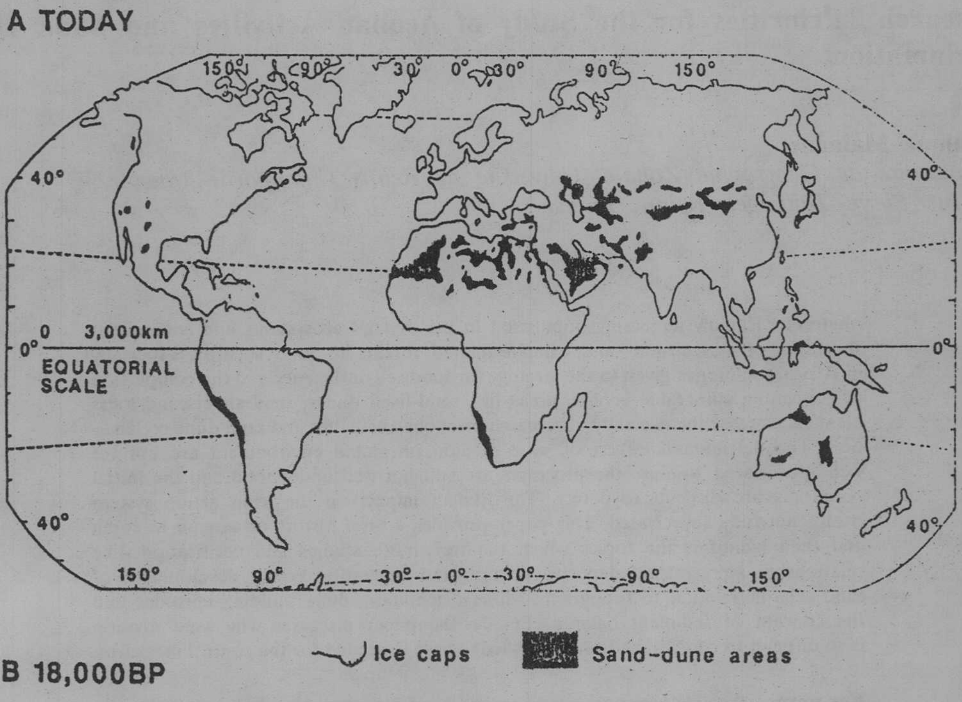

Fig. 1. Major sand seas today and during the last glacial maximum 18 000 yr. BP; (After Pye and Tsoar, 1990).

tion of agricultural space, climatic threats to food security, as in Africa, the preference given to the strategy for food self-sufficiency and the necessity for cultivation of vulnerable semi-fixed dunes, sand sheets and loess blankets (all being aeolian deposits), increase the necessity of research on aeolian activities and sand dune reclamation. The Thar desert is presently the most populated desert in the world.

The first part of this paper aims to show the birth and evolution of research on wind actions, while the second part will try to take stock of the numerous questions which remain to be solved in the areas of aeolian deposits, including sand dunes. Finally, an attempt will be made to summarize what should be done for better sand dune reclamation.

Birth of aeolian research and its evolution in the Twentieth Century

Research on aeolian processes began 150 years ago when Ehrenberg (1847) described the airborne dust transported from Africa to Europe. Blake (1855, in Pye and Tsoar, 1990) was one of the first few to recognize the abundance of aeolian and rocky wind-corroded landscapes in dry lands.

In the seventies and eighties of the last century studies were carried out on airborne dust, known as aerosol. The dust storms consist of small particles of clay, silt and fine sand. The aerosol size distribution indicates a maximum between 0.06 and 0.08 micrometer (D' Almedia and Schultz, 1983). After this period of discovery, there was almost no notable research on wind activities in the second part of the 19th century and the first three decades of the 20th century, except for Udden (1894) who understood the efficiency of wind action and began to study the aeolian particles during the transition from the 19th to the 20th century.

The Dust Bowl of the 1930's in the American Great Plains, which is the best known historical environmental aeolian disaster in dry lands, provided impetus to wind erosion research. Pioneering farmers began to plough the sandy grasslands of the Great Plains in the late 1870's for wheat cultivation, without regard to climatic and pedological compatibility of the region for wheat farming. Between 1914 and 1930 many new settlers ploughed ever larger areas of the grassland. This development occurred simultaneously with a tragic drought in 1931, "resulting in an unprecedented large scale wind erosion. By 1937 the US Soil Conservation Service estimated that 43% of the 6.5 million ha in the heart of the Dust Bowl had been seriously damaged by wind erosion" (Thomas and Middleton, 1994).

The Dust Bowl also resulted in migration of 3.5 million ecological refugees (Worster, 1979) and had a significant effect on science, putting man-induced wind erosion in the forefront with the research of Chepil (1941, 1945, 1951), Chepil and Milne (1941), Chepil and Woodruff (1963) and Woodruff and Siddoway (1965).

The work of Bagnold (1941) and Chepil on aeolian mechanisms for soil erosion revived the interest in aeolian studies. Simultaneously, French scientists and the Saharan camelers officers, became interested in wind activities in the Sahara and began to observe the dunes and the sand seas of that desert (Aufrere, 1931 and Chudeau, 1920).

After 10 years of research Meigs (1953, 1961) proposed to UNESCO his useful map of arid zones. This map became the base for all attempts of mapping desertification from the seventies. In the seventies, researches in the new oil provinces and the appearance of satellite imagery provided another impetus for geomorphological and sedimentological studies on sand seas and all other kinds of aeolian deposits. Earth Resources Satellite imagery became a good help for aeolian research. Mainguet (1972) described from Borku, north of the Republic of Chad, a huge system of *kaluts* which does not have its equivalent on the planet Earth, even in Iran. McCauley *et al.* (1977) described similar corrasion landscape from other parts of the world.

In 1979 McKee published his *Study of Global Sand Seas* in cooperation with the NASA. It was based on systematic use of Landsat images to analyse the dune types and their distribution in the desert sand seas.

Drought and soil loss by dust storms in the seventies were comparable to those in the thirties (Lockeretz, 1978). Purvis (1977) pointed out that "Perhaps the worst single dust storm event occurred after two years of drought, in the Portales Valley area of eastern New Mexico in late February, 1977. The dust falls were tracked on satellite imagery, obscuring 400,000 sq. km of ground surface of south central USA, and out over the Atlantic Ocean".

Small dust size particles of organic or mineral origin can be lifted far away from the source area by a vertical gust and transported over long distances without contact with the surface. This transport mode is traditionally called suspension. When the speed of rising air current is greater than the speed of the descending dust particle, the latter remains suspended even when the wind speed has decreased.

An extreme example of suspension is the occurrence of dust storms, called *simoon* in the Middle East and *haboob* in the Sudan, by which dust may be launched by turbulent eddies and transported up to altitudes of between 200 and 2,500 metres and at speeds up to 20 m s^{-1}

The most efficient way in which silt and clay-size particles are blown upwards is in a spiralling dust devil which may carry the dust up to a height of several kilometres. Dust devils are particularly common on sparsely vegetated surfaces where obstacles like trees and bushes, which slow down or break up the vortex, are absent. Around the margins of salt lakes and playas in Kenya we have seen strings of dust devils in areas of degraded savannah woodlands, despite the presence of trees. This is the result of a phenomenon known as *Salzprengung* by which the prevalence of airborne salts from the lake causes complete break down of the soil structure and even rock fragments. A fine powder is produced which is particularly susceptible to wind erosion. This phenomenon is also common in the Aral lake basin.

Dust storms were studied quantitatively in the eighties. All continents experience them. The more powerful have plumes 500-600 km wide and 2,500 km long (Pewe, 1981). Dust is carried thousands of kilometres by the wind: from the Sahara towards northern and central Europe and even towards Kazakhstan in the former USSR. Mineral dust is also transported from arid regions of North Africa into the tropical North Atlantic in summer months. The dust often moves 5-7 km up into the atmosphere and spreads over hundreds of kilometres, extending to the Caribbean Sea and the southeast United States. In the winter, large volume of dust is transported primarily to South America (Prospero *et al.*, 1981). The mass of Saharan dust transported annually over the North Atlantic Ocean is estimated to be 260 million tons.

The Chinese scientists have demonstrated that the abundant deposition of loess in China resulted from a long distance aeolian transport. The source areas of these particles are the Chinese deserts. "North to the Kunlun-Qilian-Qinling mountains line, Quaternary loess and loess-like deposits are widely distributed on plateaus, mountain slopes, intermontane basins and piedmont plains, comprising a total area of more than 600,000 sq. km. The deposits vary in thickness from a few metres to 100 to 200 m. The loess plateau is defined on its western margin by the Wushao Mountain (eastern tip of the Qilian mountains), on its eastern margin by the Taihang Mountains, and in the south and north by the Qinling Mountains and the Great Wall, respectively.

It has an area of about 300,000 sq. km. Within it, loess and loess-like deposits are extensively and thickly distributed. It is probably the most characteristic area in the world for loess landforms" (Zhao Sunqiao, 1986).

The Russian studies in Central Asia have shown that "dust storms in the dry areas of the former USSR may occur year-round. The greatest number of days with dust storms was observed in the Central Kara Kum (Cheshme : 113 days in 1948, Repetek : 106 days in 1939), in the Kopet-Dag piedmont areas (Molla-Kara : 146 days in 1939), as well as on the northern and southern shores of the Aral Sea (Muinak : 121 days in 1958, the Aral Sea : 92 days in 1952). The average figure for Central Asia in general is as large as 250 days a year. In the Kara Kum, the dust storms mostly occur in spring as a result of quick soil drying and the increased wind speed; in the Kyzyl Kum the peak in the recurrence of dust storms is in summer due to considerable wind speed; in the piedmont areas of the Kopet-Dag - in autumn, in the Kopet-Dag Mountains-in winter" (Romanov, 1974).

"Dust storms mostly last not more than three hours. In the west and utmost south-east of Turkmenia and in some regions of the Central Kara Kum the longest dust storms were recorded, lasting more than 24 hours in over 5% of cases. In May, 1950, in Nebit-Dag the dust storm was as long as 73 hours and in November, 1951, in Aidin-over 70 hours" (Orlovsky, 1982).

The interest for dust storm increased with the severe drought currently afflicting the Sudan-Sahelian zone to the south of the Sahara Desert from 1968 to 1985. The drought has been suggested to be instrumental in producing an increased input of soil-derived aerosols into the atmosphere from the region. During the very dry periods, 1972-74 and 1976-1984, the African Dust Plume increased the mean aerosol concentrations at Barbados, West Indies, by three times that of the pre-drought levels. A marked increase in the frequency of severe dust storms in northern Nigeria was also noted during 1972 and 1973. Data from selected meteorological stations show that dust storm activity in the east and west of the Sudano-Sahelian belt dramatically increased during the drought years, by a factor of 6 in Mauritania and up to a factor of 5 in Sudan (Middeleton, 1985).

The seventies and eighties witnessed a significant growth of interest for soil and nutrients loss in the soil. The clearing of land for agriculture is one cause for the loss of topsoil by deflation. All areas, seasonally or permanently vegetation-free or nearly vegetation-free in the arid and semi-arid regions, are the potential source areas for dust, silt and sand. In the semi-arid regions all devegetated dunes and sand sheets are also vulnerable. An example is the overgrazed vegetated red dune system of the Sahel which stretches from Senegal to Mali, Niger, Chad and Sudan and has become, as a result of desertification, a new source of sand and dust.

It is also to be recognised that desert dust can be, on the contrary, responsible for the origin and fertility of many soils. It may be deposited on the margins of deserts or further afield. For example, the soils of the tropical rain forests along the Gulf of Guinea and along the Nile Valley owe their fertility largely to wind deposition and not just to silt deposition by the Nile River. According to my observations from NOAA satellite imagery the Juba forest in Sudan receives dust from Kenya via the low corridor separating the Ethiopian Highlands in the north from the Kenya Highlands in the south. The evergreen forest in the Guinean zone of Africa receives probably a great part of its nutrients from the wind flows which are winnowing the Sahara-Sahel surface (Mainguet and Dumay, in press).

Knottnerus and Peerikamp (1972) observed a soil consisting of loose sand particles of 100-500 micrometres, highly susceptible to wind erosion, and demonstrated that reclaimed high moore soils are not susceptible if 15% of the organic matter is colloidal, nor are sandy soils containing 7% colloidal humus. Soils low in humus are not susceptible if the clay content exceeds 10%. In all, about 21% of 2-3 mm aggregates in soils is essential to prevent erosion. Wind erosion starts in susceptible soils at wind speeds exceeding 8 m sec^{-1} where the air humidity is 55% or lower.

Airborne dust sampled by Zobeck and Fryrear (1985) at 7 heights above the soil surface and analyzed for particle and aggregate size distributions and nutrient content has shown that the nutrient content of the dust was always greater than the parent soil and was, in general, equally well correlated to the sand, silt or clay content of the dust samples.

The influence of wind erosion on soil minerals, especially the total, water-soluble, exchangeable, and non-exchangeable potassium, was analysed by Petrova (1981) for calcareous Chernozem profiles differing in the content of wind erosion. It revealed that with the increasing erosion, all forms of potassium and the mobility of exchangeable potassium decrease. Wind erosion also depleted the humus and total nitrogen content of calcareous chernozems, as measured by Merva and Peterson (1983). In the humus of eroded soils the proportion of fulvic acids increased and among the humic acids the fraction linked to calcium predominated. Due to erosion the C/N ratio and the nitrification capacity of the soils decreased (Petrova, 1982). Total phosphorus analyses of the eroded material indicated that high levels of phosphorus are moved during wind erosion. Dust storms described by Vasil'yev *et al.* (1978) developed on Cis-Caucasian coarse clay loam chernozems containing more than 50% of aggregates 1 mm in diameter in their upper 5 cm, and at wind speeds of not less than 10 m sec^{-1} at 50 cm above the soil surface. The size of transported soil particles ranges from 1 mm at wind speeds of 9-12 m sec^{-1} to 2-3 mm at wind speeds of 15 m sec^{-1}. The transport of soil particles begins when their moisture content falls to 5-7%. Loss of the humus layer averages 1.0 to 2.3 cm yr^{-1}.

Atmospheric dust collected by Sidhu (1977) at Ludhiana, Punjab, was calcareous and mainly composed of silt-sized particle. Nevertheless, quartz was the major component. The mineralogy and physico-chemical properties were very similar to those of the Thar desert surface materials. During the premonsoon summer months when aeolian activity was maximum, the top 0.05 cm of 20 soils in Punjab, Himachal Pradesh and Haryana were high in carbonates and soluble salts, compared to the soil below 1.5 cm depth. The rate of accretion of aeolian carbonates decreased away from the Thar desert towards the Himalayas. This proves the transport of dust from the Thar desert towards the Himalayas with decreasing carbonate content.

Soil-derived aerosol was sampled at 3.5 m depth by Delany and Zenchelsky (1976) during the dust storm in spring, in the southern High Plains of Texas. This aerosol, together with a sample of the soil from which it was derived, was subdivided, using sonically agitated microsieves, and the percentage of organic content of each fraction was determined by a method involving autoclave oxidation and measurement of the CO_2 produced. The mass distribution of the aerosol exhibited the expected shift towards smaller sizes and the percentage of organic carbon increased in all size ranges, although particularly in the 10-100 micrometres size range. The content of organic C in the aerosol was twenty times greater than in the soil itself. Microscopic examination of the aerosol fractions showed the presence of typically elongated and low density vegetative residual material.

Wind-blown soil aerosol, generated during three dust storms in March, 1974, was collected by Delany and Zenchelsky (1976) at 1.5 m above the surface in High Plains, Texas, during periods of three different wind velocities. The mass distribution of TOC (Total Organic Carbon) in the aerosol decreased with increasing particle size at all the three wind velocities studied (7.3, 9.3 and 11.4 m sec^{-1}). The percentage of TOC in each size fraction decreased with increasing wind velocity. Moreover, the aerosol was enriched in TOC compared with the bulk parent soil, the amount of enrichment being greatest for the smallest particle size. The enrichment factor, integrated over all sizes, varied between 1 and 10, depending upon the wind velocity. These data are consistent with results obtained at 3.5 m, using a different sampling and sizing method. Microscopic examination of the aerosol revealed vegetative residue in all fractions, although its contribution to the TOC appeared to be small.

Millions of tons of topsoil can be removed by a single dust storm or by the repeated winnowing of fine material. This fine material contains the majority of soil nutrients and is able to retain soil moisture. Therefore, despite chemical fertilizers, soil productivity drops continuously in areas that experience regular dust storms (Fryrear, 1981). However, man does have the ability to use certain control measures against dust and sand erosion by wind.

As we noted earlier, after a period of good rainfall in the fifties, the Sahel entered a phase of severe drought in the late sixties. It continued till the middle of the eighties. With the drought, the overuse of the environment and the famine, wind erosion became an enemy of the farmers. UNEP, working on desertification, tried to assess the status, rate, risk, and to propose indicators defining the degrees of wind erosion. But, wind erosion was never well understood in its complexity and the attempt was more or less abandoned when in the eighties socio-economic factors were considered as the major triggering causes of desertification.

Despite intensive work on the physics of blown sand, wind velocity profile, genesis of aeolian landscape and soil conservation techniques in the last decade, the impressive research of Fryrear (1994) on a new wind erosion equation is showing that the numerous factors responsible for wind erosion are not adequately known for control measures.

According to Fryrear (1994), "The estimates of soil erosion will be influenced by the limits of the soils, crop, and rainfall data and the relationships of these variables and soil erosion losses. Calculation of soil erosion with RWEQ are centered around the equation:

$$Qx = Q_{inf}(1-e^{(-x2/s2)})$$

where,

Qx is quantity of soil being transported by the wind in a vertical plane 1 m wide and 2 m high (kg m^{-2}) at any field length "x"

Qinf is theoretical maximum transport capacity for this wind over this soil surface at this time

X is length of field where Qx is measured

s is length of field where wind has attained 63% of its maximum transport capacity.

This equation expresses soil movement as a function of field length that has a 'flat s' shape, the terms Qinf and s were determined using standard nonlinear statistical regression analysis techniques.

From the field validation sites data were available on wind force (WF) for erosion event, soil roughness (K'), vegetative term (V) including flat and standing residues and crop canopy, erodible fraction of soil (EF), and soil crust factor (SCF). These values were used to generate the equation :

$$Qinf = 8{,}295\ (W*K'*V*EF*SCF).$$

The same data and parameters were used to compute the relationships with S. From the statistical analysis the relationships were reduced to :

$$S = (5441{,}37 + ((11993985\ \ln(Qinf)))0.5/Qinf^{2}".$$

In the nineties, a team of mathematicians of the University of Aarhus (Denmark), Anderson *et al.* (1990), redefined the modes of aeolian particle transport: suspension, reptation, saltation and creep, introducing between suspension and saltation the notion of reptation, which is a mechanism of sand movement by small jumps without floating and shorter than in saltation.

Thus, at the end of the twentieth century many questions on wind erosion still remain unresolved. In the next section we shall try to identify the assertions concerning wind action which are not acceptable.

Many assertions concerning aeolian sand deposit need a relook

Among the factors which control major dune building episodes, some are confirmed, but others seem to be wrong or not at all verified. We shall propose those which are most doubtful.

Relationship between sand deposits, climate and vegetation cover

Dune building episodes are considered most likely to take place during dry periods. This statement should be discussed. The assertion that in arid lands peak dune formation corresponds to droughts should also be submitted to scientific criticism. The periods of increasing aridity and drought coincide, in fact, with increasing wind speeds, as proved by wind measurement in Niger during the drought of 1968-1975, and increasing wind activity. Export and not accumulation of particles is the result in the arid zones (Fig. 2). Therefore, the areas of dominant aeolian deposition do not systematically correspond to arid periods less prone to accumulation, but to the semi-arid ones.

Only one-fifth of the Sahara desert is now covered by sand. On the contrary, the deepest and most continuous sand cover is in the Sahel south of the Sahara. It appears as if the increased vegetation cover in the semi-arid zone south of the wind action system of Sahara can explain the increased roughness which leads to a decrease in the boundary layer winds. Increased density of the vegetation cover and the high accumulation of aeolian particles due to increased roughness at the soil surface are to be discussed.

Relationship between the regional changes in atmospheric pressure fields, aeolian erosion, aeolian transport and aeolian sand deposit are almost unknown and should be analysed through scientific measures, as also the view that the periods of persistent high wind frequency magnitude and aeolian deposits are simultaneous. Frank and Kocurek (1994) point out the "lack of significant data to quantify the effects of atmospheric conditions on airflow profiles, from which sand transport rates are calculated".

Development of sand seas in relation to topography

Why accumulation may result in a sand veneer or a sand sheet or the isolated dunes and the dunefields is still not adequately explained. Many uncertainties still exist around

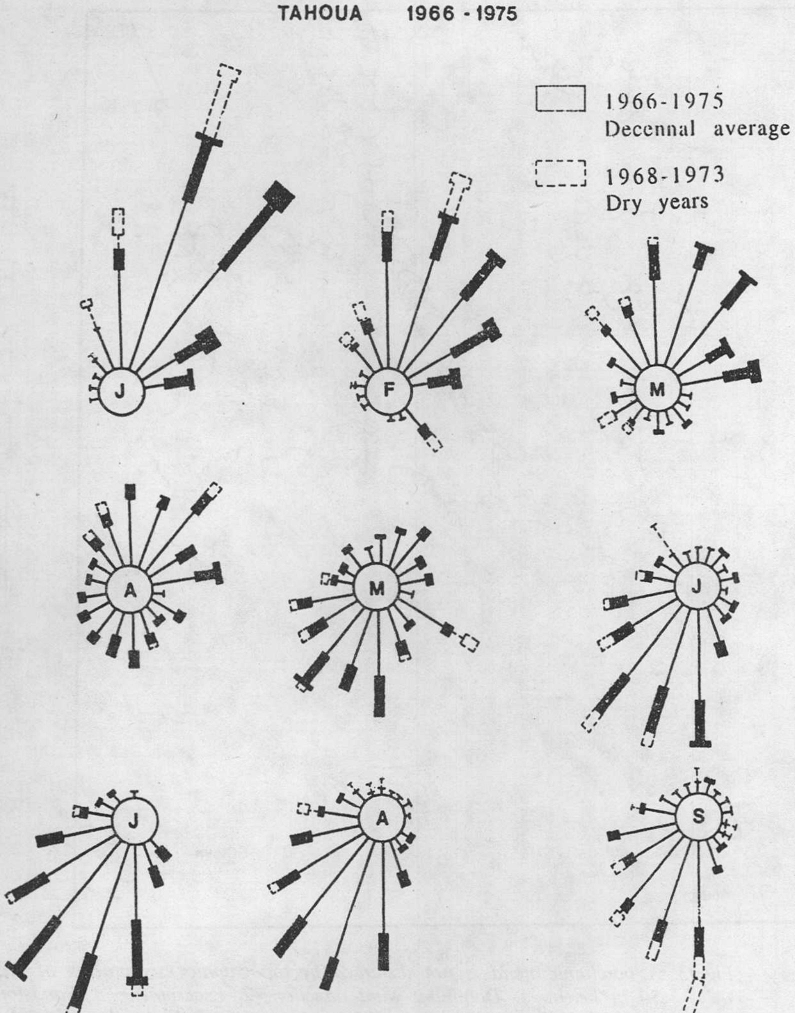

Fig. 2. Monthly wind at Tahoua, one of the synoptic weather stations of Niger. All the measures of wind in the twelve synoptic weather stations of Niger have shown an increase of wind activity during the drought between 1968 and 1975.

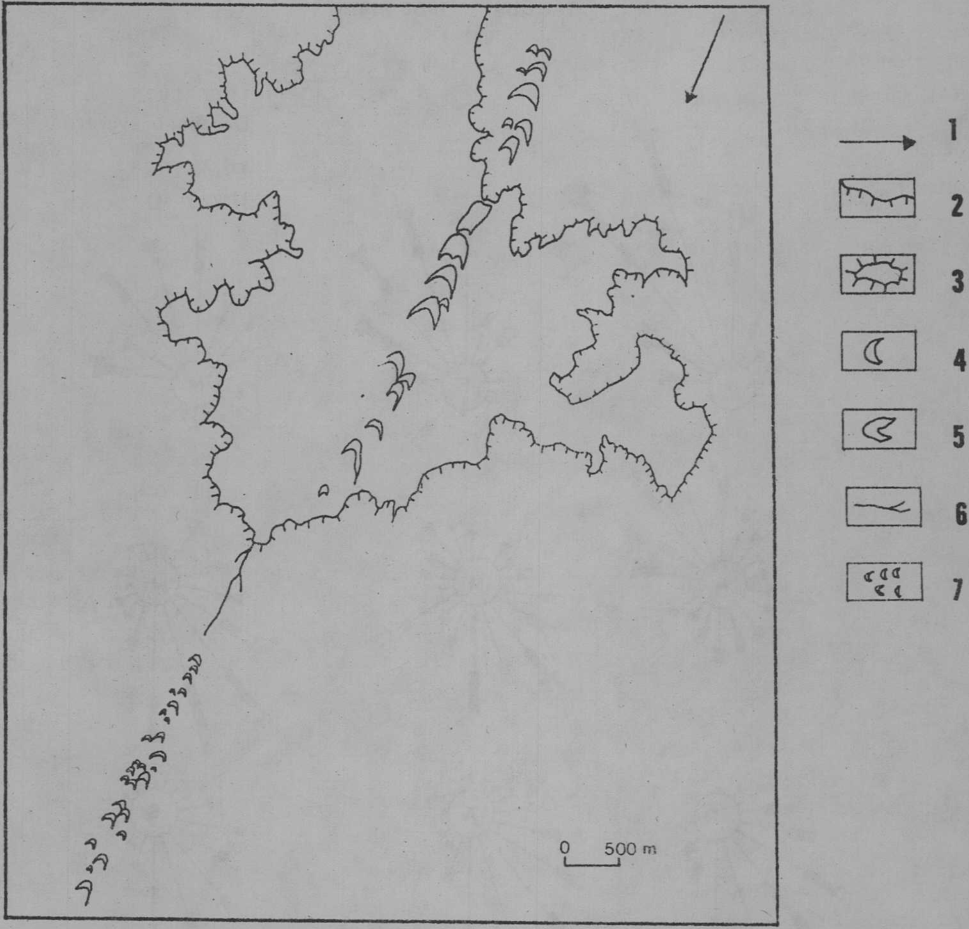

Fig. 3. A barchanic trend is not disturbed by topographic escarpments of even 50 m height. 1. Dominant wind direction; 2. Escarpment; 3. Sandstone plateau; 4. Barchan; 5. Degraded barchan; 6. Seif (linear dunes); and 7. Barchanic flow.

the mechanism of dune and dunefield initiation, on the rates of sediment transport over dunes, dunefields and sand seas, as well as on the influence of wind regime and topography. We have observed that when on a flat surface the dominant trend is to form the barchans, the natural and artificial obstacles tend to disturb the shape of these dunes, but as soon as the dunes cross the obstacle, barchans reappear (Fig. 3).

According to many authors, the location of the largest sand seas is preferably in basins (Wilson, 1973). This opinion is verified for the intermontane basins in Asia, especially Taklamakan which is the most convincing example, but is not verified for the Aral basin sand seas of Kara Kum and Kyzyl Kum, to the east and south of the Aral lake, which are on a gently climbing slope. So are the Grand Erg Occidental and the Grand Erg

Oriental in the north of Sahara. The sand seas in the Chad basin are at an altitude higher than the Bodele depression north-east of lake Chad, itself the second lowest point of the Chad basin.

Sediment balance and aeolian bedforms

The concept of sediment balance

Different dune building episodes were identified, referring to dune orientations. This identification is totally uncertain because the concept of sediment balance is not systematically taken into account.

An area which has a positive sediment balance (SB+) is a system receiving more sand than it can export. It represents a phase of sand accumulation. In general, the dunes are at right angle to the main wind direction. If the export of sand is higher than the import in the wind action system (WAS) then there is a negative sediment balance (SB-), and the dunes are mainly parallel to the main wind direction. Both can coexist in one sand sea as in the Grand Erg Oriental of south Tunisia (Mainguet and Jacqueminet, 1985).

The diagnosis of the sediment balance is obtained by the genetic analysis of the sandy edifices of the area. Transverse dunes and barchans are the indicators of SB+. Linear dunes (seifs), oblique to the dominant wind, are also an indicator of SB+. On the contrary, the erosion dunes, like the parabolic and longitudinal dunes, are indicators of SB-.

In the areas with a SB+, the risks of sand accumulation are severe as soon as the human activities (buildings, roads, railways) create obstacles or increase the roughness (agriculture, lines of communication). All new management practices must foresee a free circulation of the sand, avoiding blocking of the particles. To check sand accumulation in the existing human infrastructures two strategies are possible: to stimulate accumulation upwind, but at a considerable distance from the human settlements, or to induce dispersion of the deposits.

In the areas with SB-, export is dominant and the rule should be to avoid building human settlements on the leeward side. The SB- areas themselves should be protected from soil erosion through any kind of existing system.

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

Accumulation bedforms : The dunes developed by accumulation are crescentic (barchans) or linear (seif dunes), which are most difficult to control. When barchans are coalesced and aligned at right angle to the wind, they are called transverse chains or tranverse dunes. Linear dunes (also called seif) are another type of accumulation bedform.

Wind is also responsible for the wholesale movement of dunes. The most mobile dunes are the barchans, which can move in isolation, or in an organized manner like that of duck-flights or in sand-flows (Fig. 4). The best examples are from Mauritania.

Both barchans and seifs are the edifices where sand arrives at the upwind end and departs from the downwind end. The whole body of a barchan moves forward together and can invade all human settlements, while the seif evolves by elongation and can threaten human structures through that manner.

Other initial accumulations may occur : In (a) the lee of an obstacle as a falling dune, upwards of the obstacle as echo dune and climbing dune. The obstacle can be a rock outcrop or a stone or a plant giving

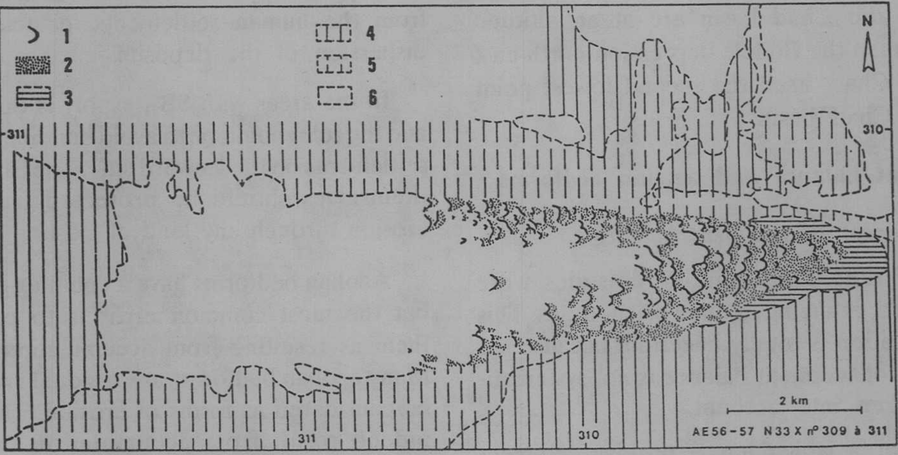

Fig. 4. *Barchans are organised like a duck flight, offering minimum resistance. 1. Barchan crest; 2. Dune; 3. Sand accumulation without organised dune; 4. Zibars (mega ripples); 5. Grooves with corrasion; and 6. Deflation area with sand.*

a coppice dune (nebka, rebdou); and in (b) an area of reduced wind speed where the roughness of the surface is increased by vegetation cover or relief.

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

The parabolic dunes, called by Watson (1990) as deflation dunes, are also erosion edifices. The most complex and typical are those formed in the Thar desert where "the compound parabolic dunes form the major component of the Thar dunefield" (Kar, 1993). This desert should now be considered as an area of sand export with a negative sediment balance.

Too often confounded with linear dunes (the *seif* dunes which are oblique to the main wind directions), the sand ridges are erosional aeolian bedforms. The most impressive ones are located in the central Sahara in the erg Check, Iguidi and the Tenere, where we described and measured them (Mainguet and Callot, 1978). The ridges are aligned parallel to each other and parallel to the main wind direction which justifies why these can be called 'longitudinal'.

The paucity of sand in the sand seas composed of longitudinal dunes, and the negative sand balance can be quantified by the interdunal index (IDI):

IDI = (WIC)/(WS)

where,

WIC = Width of an interdunal corridor, and
WS = Width of a sand ridge.

The term 'interdunal corridor' is proposed because the genesis of longitudinal corridors separating longitudinal sand ridges result from deflation in a sand sheet. The sand ridges are residual dunes between two deflation corridors, where wind erosion is active.

The value of IDI is maximum in the central Sahara sand seas. Measurement on the Landsat images of Erg Check and Erg Iguidi show that the width of the sand ridges reaches 3 km. Both sand seas possess an increasing IDI in the wind direction.

Latitude	Value of IDI
29°	5
26°	6

In Egypt the WS reaches a maximum of 1,500 m between 25° and 28°N and 24° and 27°E and the WIC reaches 4,000 m (Skharet al Amud dunes). Further east, in the Abu Mingar sand ridges (25°30′-27°E) the maximum WS is 2,500 m and the maximum WIC 2,000 m. Thus, the IDI decreases from 2.4 in the west to 1.25 in the east.

Approaching the Sahel, south of the Sahara-Sahelian strip of ergs, the IDI becomes narrower and confirms the still positive sediment balance or a less advanced negative one. In Ouarane erg (22°N) the Space Lab image gives WS = 100 m, WIC = 250 to 1500 m and an IDI varying from 0.4 to 1. In the Maqteir sand sea (21°50′N-11°35′W), IDI is <1. North of Timbuktu (17°N, 13°W) in the Azaouad and in Niger (south of Erg de Fachi Bilma), WS = 750 to 1000, WIC = 250 to 1500 and IDI < 1.

All these longitudinal edifices correspond to a negative sediment balance, meaning that they are in areas previously of deposition with a positive sediment balance, but are now in a phase of deflation. In these areas the danger due to aeolian degradation lies in export of the finest particles and loss of soil and soil structure.

This fundamental difference between aeolian bedforms resulting from accumulation and others resulting from deflation explains the existence of two schools of thought. The first school believes that the shifting of dunes and the shifting over time of the dunefields and the sand seas are the main effects of wind erosion triggered by drought and man-induced land degradation. The second school is convinced that the general trend of progressing dunes is more or less a legend. This difference lies in the fact that the first have made their observations in barchan-infested areas with a positive sediment balance where the dunes are all mobile, whereas, the second have worked in areas of negative sediment balance in longitudinal dunefields where the dunes are not mobile, but nevertheless dangerous because even though not mobile, these dunes are sand reservoirs where sand particles can be set in motion. These two situations and diagnosis lead to two different strategies to combat wind erosion: the first which must avoid encroaching sand; the second which must avoid soil loss.

Criteria for wind erosion control

Combating wind erosion is an extremely difficult task, probably more difficult than combating water erosion. To explain this difficulty several reasons appear.

Difficulty of detecting wind action in the first phase of erosion

Wind is an invisible fluid, its action is diffuse and hypocrite in the preliminary phases, those which are the dangerous prodromes in the processes of land degradation. Wind can entrain particles of many sizes. The fine grained particles around 100 micrometres are the most erodible (Fig. 5).

The entrainment of unconsolidated surface material, its transport and redeposition are the three main facets of wind erosion. During the transport of the sand load by creep, saltation and reptation, other activities can take place, like corrasion on the aggregated soil surface and rock, abrasion of natural and human- made structures, and physical damage to plant stems and leaves of the low vegetation, thereby encouraging the spread of diseases.

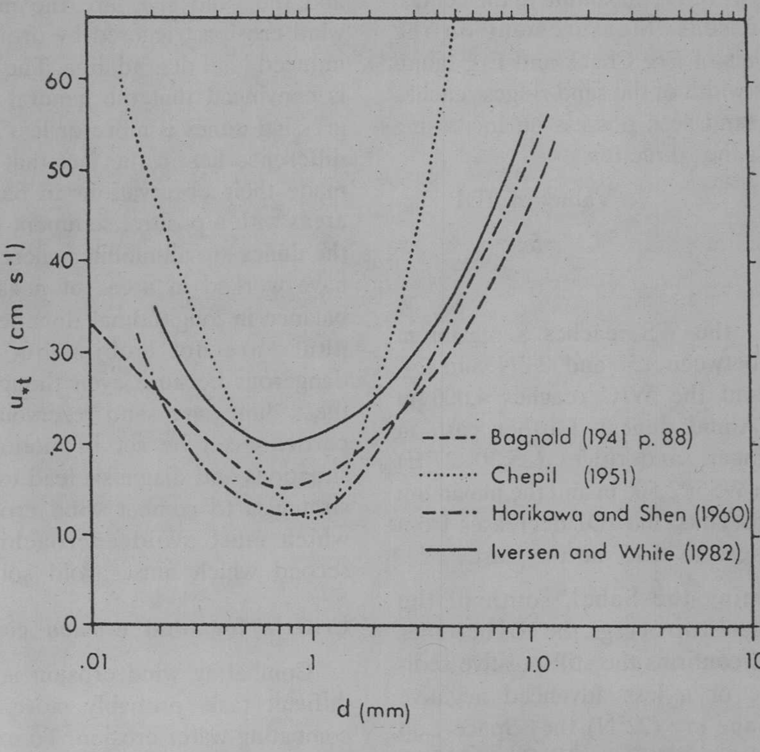

*Fig. 5. The threshold velocity (U*t) is maximum for sand particles around a diameter of 0.1 mm (After Pye and Tsoar, 1990).*

When transporting clay and silt by suspension, the visibility can be reduced severely. One index of the severity of dust storms is based on the visibility which may be less than 800-1000 metres and dangerous for aviation.

The sand flows organized as sand rivers are the most difficult questions to solve when they threaten human settlements because of the size and the distance of the source areas. That is why Mainguet (1992) proposed the notion of Global Wind Action System (GWAS).

Concept of Global Wind Action System (GWAS)

Combination of areas of sand deflation, sand transport and sand deposition, detectable on satellite imagery, allows one to define the concept of Global Wind Action System (GWAS). A GWAS is a dynamic aeolian system where, in a definite area, particles are exported, transported and accumulated, or re-exported in consequence of wind activity. A GWAS can be an open or a closed system.

A closed GWAS is an area where particles are imported and accumulated, but where export is negligible. The Taklamakan sand sea, because of its topographical site in a deep basin between high mountains (Tien Chan at its north, Kuen Luen at its south), is probably the best example of such a closed GWAS.

An open GWAS is defined as a system where, after import and accumulation, particles can be re-exported out of the system.

The Sahara which exports its aerosols towards the north until Greenland, towards the east until Kazakstan, towards the south until the tropical forest of the Gulf of Guinea, and towards the west over the Atlantic Ocean, the Bermudas and the *Nordeste* (Brazil), is the best example of an open GWAS. The correlation between the Sahara and the Sahel and how Sahara exports its sand particles towards the Sahel have been demonstrated (Mainguet, 1992). The active Tenere sand sea in Niger, for example, is continued without interruption by the fixed Hausa sand sea which has also received a part of its sand from a branch of a sand current which runs west of Air Massif and has loaded sand from the alluvium accumulated by the *dallols*.

In a GWAS, there is not a simple juxtaposition of these three units: erosion, transport, deposition, but a GWAS is the juxtaposition of multi-scale units. This multi-scale organisation should be answered by a multi-scale approach. Because of the complex nature of aeolian depositional processes, the investigation must be led at a multi-scale approach which means to investigate at the synoptic scale of the global wind action system; at a regional level in the area of the major sand sea; at a local level of villages and all kinds of other human settlements, roads, railways, plantations and projects. Choosing the right techniques to control mobile sand and moving dunes requires a knowledge of the whole system and to appreciate in which dynamical area of the GWAS the problem area is located, where sand control solutions are to be applied.

Control of sand deflation, transport and accumulation

Controlling wind action is often considered as mainly a programme of dune stabilization in its restricted sense, but it should also mean controlling the movement of particles in the different parts of a GWAS from the source area towards the areas of transport and accumulation.

The strategies to combat wind-blown sand and migrating or encroaching dunes are different. The effect of disturbance of dunes is not the same as the effects of disturbance of migrating sand. Control of wind-blown sand may have no effect on the rates of dune movement.

Stabilization of mobile sand through physical methods : In hyper-arid and arid ecosystems, with an almost limitless supply of sand and with frequent and strong winds, managers face the danger of mobile dunes and drifting sand. Mauritana, where the sand flows composed of barchans threaten the human settlements (road and railways), is the most significant example and probably the most difficult to control (Mainguet, 1991).

Blocking the sand in the source area and in the transfer area : The knowledge of the location, nature and extent of both the erosion area and the sand migration area is necessary. To determine the location and the extent of the source area is a priority because, without a knowledge of the size and the distance of the source area it may be impossible or impractical to solve the problem of sand and dune encroachment. In the Egyptian desert the wind flow brings sand to the Kharga oasis from Quatara depression, 700 km to the north-west. Along its way the transporting fluid takes its load of grains which can be a mixture of more or less autochthonous and/or allochthonous particles.

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

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

- reducing wind speed through windbreaks of dry or preferably live vegetation, if permitted by rainfall, or available water; the strategies are different according to the degree of aridity;
- increasing the cohesion of soil particles by planting vegetation;
- fixing the soil using chemical adhesives, or covering the loose particles with plastic sheets, nets or dead vegetation.

The strategies to control aeolian damages linked with drifting sand and mobile dunes can be summarized in two sets of action: blocking the shifting sand in the source area or at any step of transport by palisades or barriers with artificial material, plastic or organic, creating an artificial dune or fixing the loose sand by chemical measures. When the source area does not allow biological rehabilitation, blocking the sand may require repeated or permanent actions like stabilizing the loose sand by biological measures. In the transport area, the objective is to bring about a reduction in wind speed by increasing the roughness of the land. The resulting turbulence causes the airborne particles to settle. Deposition of sand in preselected areas will reduce the threat to human settlements.

Watson (1990) summarized the approaches which have been employed to reduce drifting sand as: (i) promotion of the deposition of drifting sand by ditches and barriers; (ii) plantation of vegetation belts to trap the sand moving away from source area; (iii) enhancement of sand transportation by shaping the land surface and treatment of the surface; and (iv) deflection of the sand stream.

The objective is to minimize the volume of particles transported, so as to encourage accumulation upwind of the area which requires protection. Nevertheless, to trap moving sand is a solution which needs an indefinite maintenance. The excavation of deep ditches upwind of human installations is based on sand entrapment and can bring temporary protection against encroaching sand. To be effective the ditches built at right angle to the main wind direction must be wider than the length of the jump of saltating grains that may reach 3-4 m (Watson, 1990). The ditch must have a depth which prevents aeolian deflation from the floor and must be regularly cleared of the entrapped sand or doubled by parallel ditches.

When the area of transport is underlain by unconsolidated material, techniques to reduce deflation should be applied, such as spreading coarse grained material over the surface so as to obtain a kind of desert pavement. The protection must be continuous, to reduce the scouring of underlying material. Moreover, mulching is necessary to prevent excessive movement of particles. It involves evenly covering of the sand, sand sheet or dune with natural or human-made materials. The objective of mulching is to break up the smooth surface of bare field into a rough surface which slows down with the speed and stabilizes the surface against wind erosion. Chemical methods of mulching can also be used and combined with biological methods if the rainfall is sufficient. The sand-fixing layer formed by chemicals should be maintained in good condition until the vegetation is established and takes over the controlling function of wind erosion.

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

During a long geological time the Sahel was a huge vegetated accumulation area, south of the Saharan active sand-exporting wind action system. In the 1950's, with increasing population and overgrazing, this vegetated fixed area with palaeosol began to be reactivated and the sand of the topsoil reworked. In the accumulation area, topsoil erosion should be avoided, mainly in the cultivated areas by shallow wind ridging, minimum tillage, pitting, covering the sand surface with clay, and creation of a checkerboard structure of barriers.

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

Biological stabilization of sand, sand sheet and dunes : In areas where rainfall reaches 300 mm year^{-1}, the biological stabilization should be favoured through a checkerboard pattern of low fences and development of a natural or planted vegetation cover. In areas of continuous sand deposition, like in the Chinese basin sand seas, the solutions are more difficult and more expensive because they are linked to mountainous geomorphology and a continuous sand supply. Permanent stabilization of sand, sand sheet and dune requires the development of permanent vegetation cover. There are three possibilities for rehabilitating the dry areas: natural regeneration of the vegetation cover if rainfall is sufficient; semi-natural regeneration of the vegetation cover, or creation of a vegetation cover. To these methods can be added biological shelterbelts, windbreaks and wind barriers.

Green belts, formed of several rows of trees or bushes, are a classic technique in China. The species are the locally adapted ones. In the oases, fruit trees like nut, apricot and mulberry are planted. In the oasis of Turfan (South Taklimakan), 16,000 ha of vineyard are surrounded and subdivided by green belts; 1130 ha were planted since 1964. Similar green belts were planted in Hetian to avoid a bidirectional wind regime.

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

Other biological techniques like intercropping or micro-crop shelterbelt consisting, for example, of three rows of tall-growing pearl millet planted across the prevailing wind direction by Central Arid Zone Research Institute (Anon., 1985) was found to be instrumental in increasing the water-use efficiency and productivity of summer-grown vegetables like lady's finger and cowpea. The pearl millet crop for micro-crop shelterbelt have to be sown about a fortnight earlier to the actual sowing of vegetable crops for providing the shelter effect.

Control of mobile dunes

According to Watson (1985) the problem of moving dunes can be tackled in three ways: removal, dissipation and immobilization. The question is not so simple. All the techniques to combat migrating dunes have their negative faces. Removal of the dunes is very expensive. Dissipation of a mobile dune by trenching, surface treatment (complete or strips) and transformation of the dune in shifting sand is feasible only in areas where shifting sand is not a ,disturbance for human activities. Reshaping of mobile dunes into a mobile sand mound is temporary; the sand mound will evolve very quickly towards the optimum aerodynamic form. Therefore, for permanence the surface of the reshaped dune must be vegetated.

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

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

Conclusion

The increasing human and livestock population in most parts of arid lands have led to an increasing use of sand dunes, loess areas and areas of wind erosion risk for grazing, agriculture, urban and industrial development. All these activities accelerate wind erosion.

Two main strategies need consideration for combating wind activities: the vertical ones like wind barriers, palisades, wind break, etc., and the horizontal defence which consist of checkerboard and trials to rehabilitate a vegetation cover.

The scarcity of information on wind dynamics, aeolian action and behaviour of sandy soils in the dry lands have made the control of wind erosion difficult. Secondly, the strategies for development in dry lands are more aimed towards development of irrigation than for rainfed agriculture. The cost of development of irrigation is very high, but comparable amount of money is not spent to control wind erosion. Can we suggest a change in the mind of the decision makers?

References

Anderson, R.S., Sorensen, M. and Willetts, B.B. 1990. *A Review of Recent Progress in Our Understanding* *of Aeolian Sediment Transport*. Department of Theoretical Statistics, University of Aarhus, Research report 213, 48p.

Anonymous, 1985. *CAZRI Research Highlights, 1959-84*. Central Arid Zone Research Institute, Jodhpur, 153 p.

Aufrere, L. 1931. *Le cycle morphologoque des dunes. Annales de Geographie 40: 362-385.*

Bagnold, R.A. 1941. *The Physics of Blown Sand and Desert Dunes*. Methuen, London.

Chepil, W.S. 1941. Relation of wind to the dry aggregate structure of soil. *Scientific Agriculture* 21: 488-507.

Chepil, W.S. 1945. Dynamics of wind erosion : I. Nature of movement of soil by wind. *Soil Science* 60: 305-320.

Chepil, W.S. 1951. Properties of soil which influence wind erosion : IV. State of dry aggregate structure. *Soil Science* 72: 387-401.

Chepil, W.S. and Milne, R.A. 1941. Wind erosion of soils in relation to size and nature of the exposed area. *Scientific Agriculture* 21: 479-487.

Chepil, W.S. and Woodruff, N.P. 1963. The physics of wind erosion and its control. *Advances in Agronomy* 15: 211-302.

Chudeau, R.G. 1920. L'étude sur les dunes sahariennes. *Annales des Geographie* 29: P. 334-351.

D'Almedia, G.A. and Schultz, L. 1983. Number, mass and volume distribution of mineral aerosol and soils of the Sahara. *Journal of Climate and Applied Meteorology* 22: 233-243.

Delany, A.C. and Zenchelsky, S. 1976. The organic component of wind-erosion-generated soil-derived aerosol. *Soil Science* 121: 146-155.

Ehrenberg, C.G. 1847. The Sirocco dust that fell at Genoa on the 16th May 1846. *Quarterly Journal of Geological Society, London* 3: 25-26.

Frank, A. and Kocurek, G. 1944. Effects of atmospheric conditions on wind profiles and aeolian sand transport with an example from White Sands National Monument. *Earth Surface Processes and Landforms* 19: 735-745.

Fryrear, D.W. 1981. Management of blank rows in dryland skip-row cotton. *Transactions of the ASAE* 24: 988-990.

Horikawa, K. and Shen, H.W. 1960. *Sand Movement by Wind Action*. US Army Corps of Engineers Technical Memoir 119.

Iversen, J.D. and White, B.R. 1982. Saltation threshold on earth, mars and venus. *Sedimentology* 29: 111-119.

Kar, A. 1993. Aeolian processes and bedforms in the Thar desert. *Journal of Arid Environments* 25: 83-95.

Kaul, R.N. 1985. Sand dune fixation and afforestation - Traditional procedures for dune fixation : The hedge system. In : *Sand Dune Stabilization, Shelterbelts and Afforestation in Arid Zones*. FAO Conservation Guide 10, Food and Agriculture Organization of United Nations, Rome, pp. 87-95.

Knottnerus, D.J.C. and Peerikamp, P.K. 1972. Wind erosion. What can be done about it? *Bedrijfontwikkeling* 3: 175-179.

Lockeretz, W. 1978. The lessons of the dust bowl. *American Scientists* 66: 560-569.

Mainguet, M. 1972. *Le Modelé des Grès. Problèmes généraux*. Institute Géographique National. 637 p.

Mainguet, M. 1991. *Desertification : Natural Background and Human Mismanagement*. Springer-Verlag, Berlin, 306 p.

Mainguet, M. 1992. A Global Open Wind Action System : the Sahara and the Sahel. In, *The First International Conference on Geology of the Arab World*, (Ed. A Sadek). Le Caire, vol. 2, pp. 33-42.

Mainguet, M. and Callot, Y. 1978. *L'erg de Fachi-Bilma (Tchad-Niger). Contribution à la connaissance de la dynamique des ergs et des dunes des zones arides chaudes*. Mémoires et Documents. CNRS, Paris, Vol. 19, 184 p.

Mainguet, M. and Jacqueminet, C. 1985. Le Grand Erg Occidental et le Grand Erg Oriental. Classification des dunes, balance sédimentaire et dynamique d'ensemble. *Travaux de l'Institute de géographic de Reims* 59-60: 29-48.

Mainguet, M. and Dumay, F. 1995. Transsaharan wind flows analysed on Meteosat 4 satellite imagery (in press).

McCauley, J.F., Grolier, M.J. and Breed, C.S. 1977. *Yardangs of Peru and other Desert Regions*. US Dept. of the Interior, Geological Survey, Flagstaff, 2255 No, Gemini Dr. A.Z. 86001, 177 p. (preliminary report).

McKee, E.D. (ed.). 1979. *A Study of Global Sand Seas*. U.S. Geological Survey Professional Paper 1052, 429 p.

Meigs, P. 1953. World distribution of arid and semi-arid homoclimates. In, *Reviews of Research on Arid Zone Hydrology*. UNESCO Arid Zone Programme 1: 203-210, Paris.

Meigs, P. 1961. *Map of Arid Zone*. UNESCO, Paris.

Merva, G.E. and Peterson, G. 1983. Wind erosion sampling in the north central region. *Paper, American Society of Agricultural Engineers* 83: 21-33.

Middeleton, N.J. 1985. Effect of drought on dust production in the Sahel. *Nature* 316 (6027): 431-434.

Orlovsky, N.S. 1982. Natural conditions of deserts in the USSR and desertification processes. In, *Combating Desertification in the USSR : Problems and Experience*. Center of International Projects, Moscow, UNEPCOM, 120 p. (Second edition).

Petrova, A.V. 1981. The content of various forms of potassium in eroded calcareous chernozems of the Krasnodar Krai. *Agrokhimiya* 7: 31-36.

Petrova, A.V. 1992. Changes in humus and nitrogen contents in calcareous chernozems caused by wind erosion. *Agrokhimiya* 8: 76-80.

Pewe, T.L. 1981. Desert dust : an overview. *Geological Society of America, Special Paper* 186: 1-10.

Prospero, J.M., Glaccum, R.A. and Nees, R.T. 1981. Atmospheric transport of soil dust from Africa to South America. *Nature* 289: 570-572.

Purvis, J.C. 1977. *Satellite Photos Help in Dust Episode in South Carolina*. Information Note 77/8, US National Weather Service. Natural Environment Satellite Service, Satellite Applications.

Pye, K. and Tsoar, H. 1990. *Aeolian Sand and Sand Dunes*. Unwin Hyman, London, 396 p.

Romanov, N.N. 1974. Sandstorms in Central Asia. *Tr. Tash GU 1960*: 178.

Sidhu, P.S. 1977. Aeolian additions to the soils of northwest India. *Pedology* 27: 323-336.

Thomas, D.S.G. and Middleton, N.J. 1994. *Desertification : Exploding the Myth*. Wiley, Chichester, 194 p.

Udden, J.A. 1894. Erosion, transportation and sedimentation performed by the atmosphere. *Journal of Geology* 2: 318-331.

Vasil'yev, G.I., Bulgakov, D.S., Gaavrilenko, L.N. and Kalinichenko, A.S. 1978. Conditions under which dust storms develop in the northern Caucasus. *Soviet Soil Science* 10: 60-69.

Watson, A. 1985. The control of wind blown sand and moving dunes : a review of the methods of sand control in deserts with observations from Saudi Arabia. *Quarterly Journal of Engineering Geology, London* 18: 237-252.

Watson, A. 1990. The Control of blowing sand and mobile desert dunes. In *Techniques for Desert Reclamation* (Ed. A.S. Goudie), pp. 35-85, John Wiley, Chichester.

Wilson, I.G. 1973. Ergs. *Sedimentary Geology* 10: 77-106.

Woodruff, N.P. and Siddoway, F.H. 1965. A wind erosion equation. *Soil Science Society of America, Proceedings* 29: 602-608.

Worster, D. 1979. *Dust Bowl*. Oxford University Press, New York.

Zingg, A.W. 1953. Quelques caractéristiques due mouvement éolien du sable par le processus de saltation. *Editions du Centre National de la Recherche Scientifique* 13: 197-208.

Zhao Sunqiao. 1986. *Physical Geography of China*. Science Press, Beijing and John Wiley and Sons, New York, 209 p.

Zobeck, T.M. and Fryrear, D.W. 1985. Chemical and physical characteristics of windblown sediment. *Paper, American Society of Agricultural Engineers*, 2539.