Sand Dunes: Their Formation and Stabilization In the Sahara with Special Reference to The Sudan

By

MOHAMED ABDEL MAHMOUD IBRAHIM

### B. Sc. Forestry (Hons.)

University of Khartoum, Sudan

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Declaration

I declare that this dissertation submitted in candidature for the degree of Master of Science at the University of Wales, Bangor, has not been submitted in whole or in part for any degree, and is not being submitted currently for any other degree. It is a result of my own review and any assistance is acknowledged.
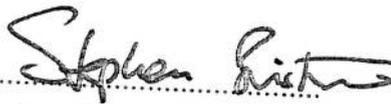
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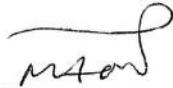
Candidate Name: MOHAMED ABDEL MAHMOUD IBRAHIM

Date ....26th September 1994

Signed ....

Supervisor

Mr. STEPHEN BRISTOW

Date 25th. Sept. 1994

Signed ....
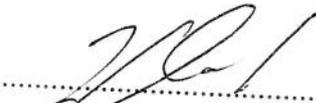
Course Director

Mr. JONATHAN CLARK

Date 26-9-74

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Dedication

To my family who has lost their home twice by the mobile dunes, and to those who are struggling with sand and sand dunes for their survival and livelihood.

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Abstract

The Sahara is the largest of the world's deserts, and is characterized by extreme aridity and the greatest number of sand seas. Sand dunes in the Sahara come in all of the many dune forms, and vary in size and shape. They are found as isolated dunes or in continuous series covering thousands of square kilometres. Wind velocity and direction, sand supply, vegetation cover and topography are major factors determining dune types. There are longitudinal dunes lined up parallel to the dominant wind direction, transverse dunes perpendicular to the wind, barchan dunes having the familiar crescent shape and others. The rate of dune movement depends on their size and sand flow rates, smaller dunes are usually fastest. Mobile dunes often pose a threat by invading agricultural lands and residential areas. Surveys by satellite imagery, aerial photography and ground checks seem to indicate that the Sahara is in progress southwards. However, some authors believe that sand shifting is a localized process in deserts. Therefore, regular monitoring of desert dune movement is essential for the planning of effective control measures. Also, the success of any such measures dependent upon the better understanding of the nature of dunes, their genesis, dynamics and reaction to dune determinant factors. There are a wide variety of possible control measures: dissipation techniques, mechanical fixation using fences, chemical treatment, and vegetation planting. The best measures combine several methods including use of vegetation, which lasts longer with relatively lower costs. Usually, vegetation needs a pre-fixation phase to reduce sand movement before establishment. Stabilization techniques are reported successful from several affected countries in the Sahara region. The selection of any control method depends on the magnitude of the threat, the objectives of control and other economic and environmental considerations. Conservation of natural vegetation on fixed dune areas is also important. The Sudan is one of the countries affected by the threat of mobile dunes. Monitoring and assessment techniques, stabilization experiments and control methods involving significant local participation have been attempted with some degree of success.

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Chapter 1: Introduction and objectives

1.1 Introduction

The Sahara is the largest of the world's deserts. Its central part, referred to as the "dead heart", extends for about 5150 km from the shores of the Atlantic Ocean to the Red Sea coast in Egypt and the Sudan. Its extent from north to south varies between 966 and 1287 km (Smith, 1984).

The global pattern of sand-fields and dunes largely corresponds to the regional distribution of arid climates as shown in Figure 1 (Hagedorn *et al.*, 1977). From another point of view, Ghose (1985) reported that sand and sand dunes are no measure of aridity in a region, although sand dunes are normally expected in desert landscapes. For example, in the extreme arid region of the Sahara sand occupies only 15 per cent of the area. Climate is not the only factor responsible for the formation of sand dunes, the source of sand supply is also one of the main factors.

Most dunes are gathered in vast areas termed "sand seas" or *ergs* in Arabic. These ergs are made up of coalesced complexes of geometrically arranged sand mountains called *draa* (aligned with the wind and rounded crests) and *oghrouds* (pointed peaks), where winds continually drift and mould the loose sand into dunes of various scales and forms. The largest sand seas are found in North Africa, Arabia and desert basins of central Asia. The greatest numbers of sand seas are found in the Sahara. Among the best examples are the ergs of North Africa, especially the Grand Erg Oriental, Grand Erg Occidental and Erg Chech of Algeria (Allan and Warren, 1993; Cooke *et al.*, 1993).

Sand dunes come in all sizes and shapes. They vary in height from 30 cm to over 400 m, and are distributed over areas consisting of isolated dunes on clay plains to continuous series covering thousands of square kilometres. There are longitudinal dunes lined up parallel to the dominant wind direction, transverse dunes in rows perpendicular to the wind, barchan dunes having the familiar crescent shape with horns pointed downwind, dome dunes having a roughly circular shape, and others (Bagnold, 1941; Hagedorn *et al*, 1977; Pye and Tsoar, 1990; Thomas, 1992; Cooke *et al.*, 1993).

Moving sands often pose a threat by invading residence and agricultural areas. This occurs on the largest scale north of Al Miniya and in the Kharga and Dakhla oases in Egypt, in the great bend of the Nile near Ed Debba in the Sudan and where the

Figure (1)
ARID LANDS AND SANDY DESERTS OF THE WORLD

Legend:
- DUNES AND SANDY DESERTS
- EXTREMELY ARID REGION
- ARID REGION
- SEMIARID REGION

Source: Hagedorn et al., (1977).

Grand Erg Occidental presses the Wadi Saoura against the eastern escarpment of the Hamada of Guir in Algeria (Mitchell, 1984).

The scale of the problems caused by moving sand precludes long-term prevention in many areas. The sand flow must, therefore, often be regarded as inexorable, since the source areas are too large or too distant to be stabilized (Watson, 1990). Also it has to be recognized that stabilizing barren dunes in arid regions is very difficult, whether mechanical or chemical treatment is given or vegetation establishment attempted. Quite often lack of water is the major problem in vegetation establishment (Dregne, 1976). However, significant achievements in dune control have been made in the Sudan where many villages in the Nile valley are suffering from sand encroachment.

1.2 Objectives of the study

The main objective of the study is to compile and analyse relevant information on sand dunes in the Sahara and reproduce it in such a form that it can effectively assist scientists, researchers and land managers in the arid and semi-arid zones. In particular the study is directed to the following:

_ To review current knowledge of the process of dune formation, dynamics and morphology, along with the adopted classifications.

_ To assess the major climatic and topographic factors determining the formation, morphology and movement of dunes.

_ To review and discuss dune stabilization techniques adopted so far, particularly in the Sudan, with consideration for dune morphology, dynamics and associated climatic factors.

It is hoped that this work will draw the attention of workers concerned with the problems of mobile sand dunes and that it will stimulate further research in this field to reveal some of the mysteries as well as contribute to the existing body of knowledge.

Chapter 2: Background

2.1 Sahara climate

Climatically the Sahara is a classic example of hot desert. The greater part of the region is free from surface water, is sparsely vegetated, and is exposed to dry, descending, north-easterly air streams. Its mean annual rainfall is less than 400 mm, and over vast areas less than 100 mm, and evaporation losses from free water surfaces and transpiration losses from vegetated areas are greater than anywhere else on the globe (Cooke *et al.*, 1993). Temperatures are also high, the mean annual temperature varies from 20°C to 25°C. The average maximum of the hottest month is 35°C to 45°C. The absolute maximum ranges from 40°C to 55°C (Le Houerou, 1986).

The Sahara is almost exactly bisected by the Tropic of Cancer. Its great extent and hyper-aridity is a consequence of a number of regional factors peculiar to North Africa. It is far removed from oceanic influences, a feature which makes it the most continental of all the hot deserts (Smith, 1984). Allan and Warren (1993) reported that the sub-tropical high pressure zones responsible for desert aridity are the result of a simple convection pattern called the "Hadly Cell" driven by the Sun's energy. Most deserts lie north and south of the equatorial rainforests around the 30°S and the 30°N latitude. Thus, African deserts are found in two bands; in the North the Sahara, and in the South the Kalahari and Namib.

2.2 Sahara history

With the object of trying to trace the various stages that are passed through in the production of sand dunes, some of the history of the Sahara must be considered. Work carried out since the late 1950s has revealed that many of the present-day ergs were very much more extensive during earlier periods of the Quaternary. Large areas of the African continent are covered by fossil dunes which are now degraded, cultivated, or forested (Figure 2). In West Africa, the limit of active dune formation in the late Pleistocene appears to have moved southwards about 500-600 km from its present position (Grove, 1958; Grove and Warren, 1968; White, 1971; Street and Grove, 1976; Sarnthein, 1978). Further east, in the Sudan, west of the White Nile, a series of fixed dunes extend as far south as 10°N and merge northwards, locally, with mobile dunes at about 16°N, suggesting that there has been a shift in the wind and rainfall belt about 450 km southwards in Pleistocene time (Grove and Warren, 1968; Goudie, 1977). Recently, Pachur and Kropelin (1987) reported that field research into the climatic history and shifting of the East Sahara desert have furnished evidence that during the Quaternary period the present extremely arid western part of Upper Nubia (northern Sudan) was temporarily linked to the Nile by way of a hitherto unknown 400

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Figure (2)
Sand dune formations on the borders of the southern Sahara

The 150 mm isohyet approximately marks the southern limits of mobile dunes, the 1000 mm isohyet the southern limit of fixed dunes.
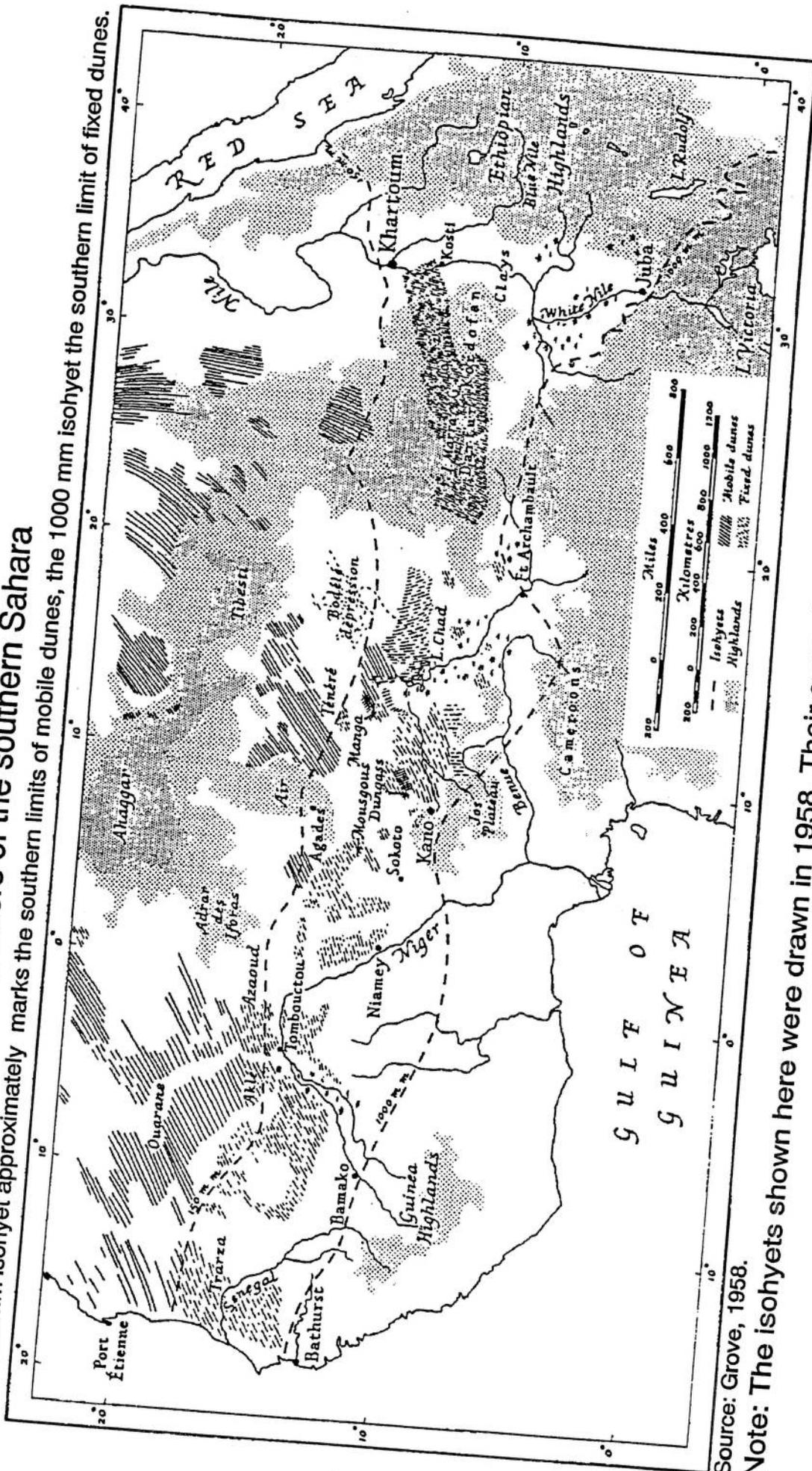
Source: Grove, 1958.

Note: The isohyets shown here were drawn in 1958. Their current position is not known with any certainty

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kilometre long tributary. From about 4,500-9,500 years ago, lower Wadi Hower flowed through an environment characterized by numerous groundwater outlets of freshwater lakes. Savanna fauna and cattle-herders occupied this region, which today receives at most 25 mm of rainfall per year. At that period the southern edge of the Eastern Sahara was some 500 kilometres further north than today.

The earth's climate is neither constant nor stable, and has fluctuated significantly over both short and long periods. Major expansions of desert conditions have also been experienced in association with climatic fluctuations, and there have also been occasions when wetter conditions penetrated into the heart of today's deserts. Short term climatic conditions in deserts, particularly rainfall, have also been subjected to considerable fluctuations. In the Sudan, for example, annual rainfall from 1965 to 1985 was 40 per cent less than from 1920 to 1940 (Allan and Warren, 1993).

2.3 Sand origin

It is important to understand the origin and source of aeolian dune sand. Bagnold (1941) stated that the bulk of the quartz sand grains found in the earth's crust have originated from the disintegration of quartz-bearing rock followed by some processes of mechanical abrasion. On the other hand Holm (1960), observed that in poorly cemented Palaeozoic sandstone, the carbonate cement tends to be extensively leached, whilst the weathered sandstone crumble easily to loose sands. Ghose (1985) expresses another view and emphasises that the source of the desert sand is mainly alluvium and dry river beds. Pye and Tsoar (1990) simply state that quartz and silicate grains released by weathering and erosion of crustal rocks are by far the most important sources of sand.

2.4 Sand dune movement in the Sahara

Wind is a major agent of erosion and deposition in the arid regions (Ben Salem, 1991). Wind hurls the finest particles into the atmosphere as dust. The largest particles remain behind and protect the surface from further erosion. Medium sized particles are winnowed away and deposited downwind as sand sheets and sand dunes (El-Baz, 1986a).

The movement of dunes is fuelled by wind, and depends on its direction and velocity. The rate of advance also depends on the size of the dune, the smallest dunes are usually the fastest in motion (Thomas, 1992). Wind seems to be very effective in deserts because of dry surfaces and sparse vegetation (Cooke et al., 1993). Serious wind related hazards such as burial by sand are thus common in arid and semi-arid areas, where both conditions often apply. In another study, Grainger (1990) reported

that, there are two main kinds of encroachment: the spreading of dunes on the fringes of deserts or in other desertified areas, and the movement inland of coastal dunes. According to Allan and Warren (1993) dust storms, migrating dunes and blowing sand are all potentially dangerous. Migrating dunes, for example, present a major threat to agriculture, forestry, roads, railways and pipelines that happen to get in their way. The most serious problems occur around towns and villages where the surface is more disturbed and the pressure on land is at its greatest.

Evidence of advance of the Sahara southwards had been reported by Stebbing (1937). He stated that, "the Sahara is far from stationary on its southern frontiers; that blown sand and desiccation are increasing in the colonies lying in juxtaposition of the Sahara". According to Stamp (1940) Stebbing formed the opinion that increasing desiccation was causing a rapid southward movement of the Sahara margin. These opinions were faced with opposition from many scientists, and the specific evidence of the Sahara advance southwards at an average rate of one kilometre a year during the past three centuries, had in Stamp's view, been refuted by B. Jones and Professor R. S. Troup.

On the other hand, Rapp (1976) has reported that an aerial reconnaissance survey including ground checks was carried out in the Sudan in 1975. Quoting Lamprey (1975), who stated that, "it is evident that the desert's southern boundary has shifted south by about 90-100 km in the last 17 years. The southward shift can be readily appreciated in the vicinity of the Wadi El-Milk in northern Kordofan". A similar shift of the boundary was observed along several transects in the air and on the ground. *Gizu* which is an ephemeral winter vegetation occurring in the Eastern Sahara Desert near Wadi Hower. For example, one of the main areas of *gizu* grazing in the Western Sudan had shifted 80 km southward since 1964 (Figure 3). Lamprey believes that the encroaching sand is transported over large distances, whereas other authors claim that sand shifting is a local process in deserts.

A different view had been expressed by Dregne (1987), who argues that although much has been written about desert expansion caused by mismanagement of natural resources, little data are available to substantiate or refute its occurrence. He added that recent studies involving ground, landsat and meteorological satellite observations demonstrate clearly the difficulty in drawing conclusions about the permanence of vegetation changes in arid Sub-Saharan Africa. He concluded that what is certain is that the idea of an encroaching Sahara expanding as a wave on a pond is untenable.

Figure (3)

Desert Encroachment in the Sudan, 1958-1975.
Based on reconnaissances by air and on the ground
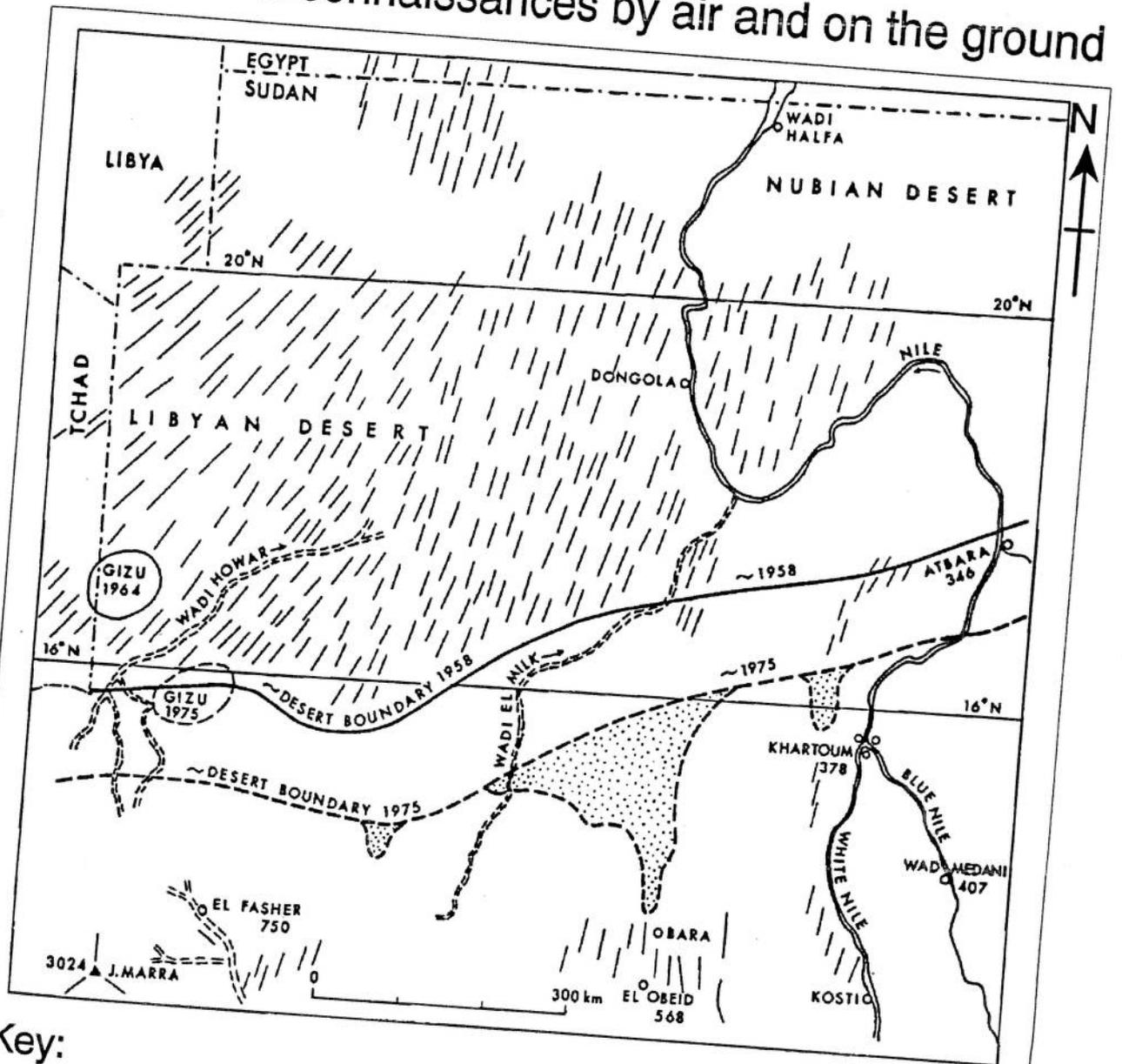
Key:

	Protruding areas with many mobile dunes in 1975
	Direction of longitudinal dunes, recent and fossile
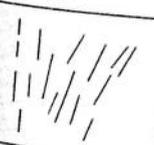
2.5 Control of sand and sand dunes

While discussing how to deal with shifting sand dunes, El-Baz (1986a) stated that one can either avoid them, try to halt their advance or learn to live with them, and even utilize them. It has become increasingly clear that avoidance of migrating dunes can be achieved by planning in advance. Hagedron et al. (1977) suggested the use of aerodynamic shapes for installations to avoid sand accumulation. This view is shared by Watson (1990) who recommended that the design of installations, whether roads, railways, individual buildings, or whole complexes must allow a degree of through-flow of sand.

Sand dune fixation is designed to prevent the movement of sand to enable either natural or planted vegetation to become established. The technique is often based on the principle of reducing the threshold velocity of wind at the dune surface by establishing a pre-planting mechanical system (Kaul, 1985).

Mechanical dune fixation appears to be effective and has successfully been applied in most of the Sahara countries, for example, Egypt (Ibrahim, 1969; Hagedorn et al, 1977; Tag-El-Din, 1986), Sudan (Rapp, 1976; Laird, 1990; Ibrahim, 1991), Libya (Messines, 1952), Senegal and Niger (Grainger, 1990), The Spanish Sahara (Benito and Le Roux, 1976), Mauritania (Ben Salem, 1991; Gaye, 1987). The major problem with the technique is that it is labour intensive and therefore slow. In countries where labour is in short supply the method can prove costly. Moomen and Barney (1981) have reported that rising costs of erecting barriers and heavy use of plant material that also threaten to denude and accelerate erosion prompted the search for other dune stabilization methods. Recently, equipment and technique for stabilization of dunes with bitumen spray, considered to be faster and more economical than the older method has been developed in Libya.

On the other hand, sand dune stabilization with plant species has been reported to be more permanent than the mechanical and chemical fixation techniques which are largely regarded as temporary measures. The choice of vegetative species for planting, however, requires studies of the natural vegetation in the area and on the environmental conditions (FAO, 1989) if a reasonable degree of success is to be attained.

Vegetation will not grow, however, as long as there is still strong movement of sand. Effective stabilization therefore means the combination of mechanical (or chemical) and biological methods at least for the initial phase of vegetative growth (Hagedorn et al., 1977).

Chapter 3: Sand Dune Genesis, Development and Classification

3.1 Definition of sand dunes

Dunes are defined as mobile heaps of sand piled up by wind, whose existence is independent of any surface feature. They appear to retain both their shape and identity indefinitely (Bagnold, 1933). Their shapes are adjusted to ambient wind conditions by the piecemeal deposition of sand-size particles (Cooke et al., 1993). The maximum linear dimensions of individual dunes range from less than 1 m to several tens of kilometres, while the height ranges from a few tens of centimetres to more than 400 m (Pye and Tsoar, 1990). Dune dimensions and the standard nomenclature of its different parts, are shown by sketch in Figure 4. Very large dunes, on which smaller dunes may be superimposed, are referred to as megadunes or "Draas". Dunes may also be linked together to form dune chains or networks (Hagedorn, et al., 1977; Kocurek et al., 1991).

3.2 Dune Initiation

In this context, initiation means the formation of a single dune on a reasonably levelled firm surface, as opposed to the replication of dunes downwind of parent dunes or on extensive sandy surfaces. Wind blown sand has the propensity for self-accumulation into dunes in the absence of topographic obstacles (Pye and Tsoar, 1990).

Bagnold (1941) explains these in terms of saltating grains that bounce off hard desert surfaces (pebbles or bedrock) more effectively than over a bed of loose sand. It is believed that the sand transport rate over a random sand patch is, therefore, relatively lower than over its surroundings, leading to accretion of the sand patch and extension of its upwind margin. This process is effective only if there is a constant supply of sand from upwind and under conditions of strong winds that can transport the sand over a rough surface and deposit it on the sand patch.

An alternative explanation, widely known as the wave-form theory, suggests that sand becomes concentrated into dunes owing to the existence of a wave-like motion or secondary circulation in the atmosphere. These secondary air motions, which may be intrinsic to the flow or generated by bed irregularities further upwind, cause variations in the surface shear stress and may therefore generate spatial variations in sand transport rate. This produces alternating transverse or longitudinal zones of erosion and deposition, which lead to the formation of regular series of ridges and troughs (Wilson, 1972; Folk, 1976).

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Figure (4):
Sketch showing dune parts
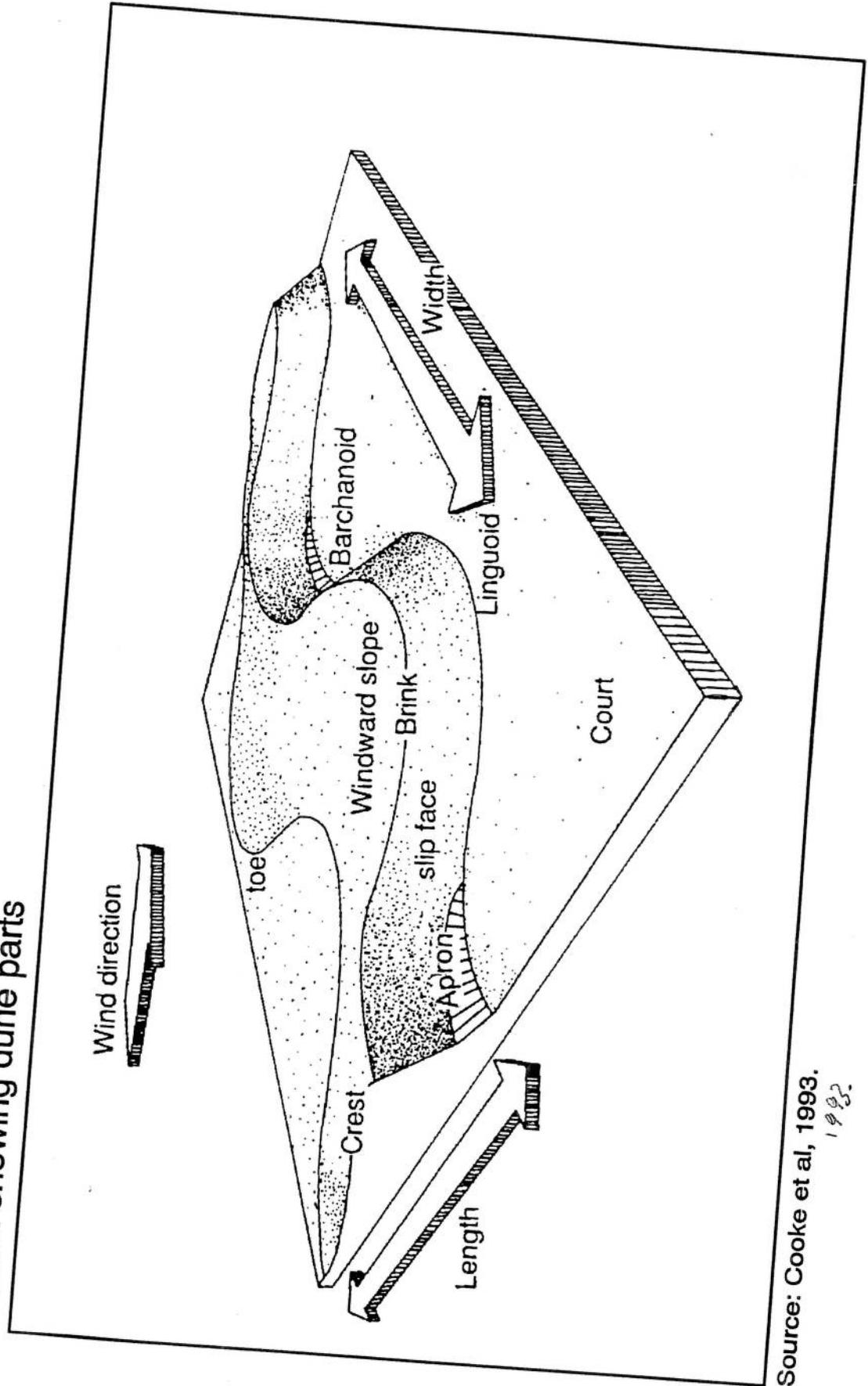
Source: Cooke et al, 1993.

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Cooke *et al.* (1993) have described three ways in which sand dunes may be initiated, namely: surface roughness, calving and formation of ground jets. Each of these is examined further.

3.2.1 Contrast in surface roughness

This occurs when dunes are initiated on flat surfaces. Sand is trapped by small differences in roughness of the surface, or in slight hollows. When wind meets a contrast between a rough desert surface and a smooth one, there is often a sudden drop, which induces the deposition of sand that the wind has been carrying over the desert surface. When a dune initiated, grow to a certain "equilibrium" size, it moves away from its template. Another dune starts to grow in the same spot and in its turn follow the first.

3.2.2 Calving

Many mobile dunes are "calved" or separated from the ends of the anchored dunes, and they then migrate downwind as free dunes.

3.2.3 Ground jets

It has been observed that the break-up of waves in an early morning atmospheric inversion, was capable of sweeping sand from limited areas and depositing it when dissipated. These patches have been suggested as templates for dunes.

3.3 Growth from sand patches to dune shapes

Sand travelling over a hard, pebbly desert pavement moves more rapidly than over a newly formed patch of sand (however initiated). The sand carried towards the new sand patch is therefore deposited on its surface and a dune begins to grow (Bagnold, 1941). As the sand patch grows upwards and becomes a dune, its upper parts are subjected to faster winds than the lower ones and they move forward to produce an asymmetrical shape (Cooke *et al.*, 1993 quoting, Graf, 1971).

Usually sand flow rate increases with height, and therefore increases erosion towards the higher sections of the upwind slope. Dunes can grow vertically as long as the rate of sand supply to the crest is not exceeded by rate of sand removal. After sometime a steady state is achieved in which the form of the dune balances with the rate of sand transport over it (Bagnold, 1941; Hagedorn *et al.*, 1977; Howard *et al.*, 1978). For a dune to maintain a steady-state profile (equilibrium) in the medium term, the rate of sand input to the dune must be equal to the sand output. If the two are not in balance the dune either grows or shrinks in size. A change in dune dimensions

resulting from a change in sand volume may have an effect on the dune morphology (Pye and Tsoar, 1990).

As a dune grows, the upper margin of deposition moves relatively closer to the summit until the lee slope becomes over-steepened. When the angle of repose for dry sand is reached downwind, slipping results and the slipface is formed. Slipface angles reported in the literature vary from 32° to 34° (Hagedorn et al., 1977).

For a dune to maintain itself in steady state, the rate of sand transport should steadily increase up the windward slope towards the crest. When a steady state is achieved, sand eroded from the windward side of the dune is deposited in equal volume on the lee side, and the dune advances without substantially changing its shape (Tsoar, 1986b).

3.4 Dune minimum size

Bagnold (1941) has stated that a dune can not be smaller than the zone of readjustment in sand carrying capacity, as wind passes over the edge of sand patch. The results of his study show that in order for the in-coming wind may be sufficiently checked to cause deposition, the sand surface must extend over a certain minimum distance downwind. He concluded that a minimum length of 4 to 6 metres is required for a dune to form and that the smallest true dune found in nature is of this size. However, Cook et al. (1993) noted that the lag distance of Bagnold's argument is less important to the survival of a dune than an adequate supply of sand. Therefore, his model cannot apply to dunes in continuous sand, which are by far the most common form of dune. They concluded that in reality there is minimum size for dunes, because those less than 1 m in width have not been reported.

3.5 Flow separation and lee eddy

As a dune grows upwards, there comes a point, depending on flow characteristics, at which wind no longer follows the form of the dune, and flow separates from the bed (Cooke et al., 1993). Micro-wind measurements by Tsoar (1986b) revealed that when wind encounters a dune body perpendicular to the crest line, the streamlines are separated from the surface over the brink, and are reattached to it a certain distance downward. This physical phenomenon is known as "separation of flow". In the space between the point of separation and the point of attachment, a light reverse flow is formed as a result of the vortex there (figure 5). At the point of attachment the velocity of the wind is zero, because from that point the streamlines are split into two contrary directions: streamline that are moving to the crest and streamlines that continue in the

Figure (5):
Flow separation

Legend:
•••••••• Boundary layer
———— Dune profile

Labels in figure:
Upper boundary layer
Internal boundary layer
Reattachment point
Flow separation
dune brink
Separation bubble
Reverse flow

After: Cooke et al. (1993).

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general wind direction. The drastic fall of velocity on the lee side of the dune leads to deposition of sand there, and to a creation of slip face.

In the lee of aeolian dunes, ripple patterns and small shadow dunes show that wind velocities are great enough to move fine sand back towards the slipface, at least in high ambient wind speeds. But, there is no evidence to show that lee eddies affect the morphology of the slipface in any significant way. Their only accomplishment is low angle accumulation of fine sand at the base of the slipface (Hoyt, 1966).

3.6 Factors determining the morphology of sand dunes

Pye and Tsoar (1990) stated that at the broadest level the form and scale of aeolian sand accumulation is governed by at least six factors: (a) Sand availability, (b) Grain-size distribution, (c) Wind energy, velocity distribution, and directional variability, (d) Vegetation cover, (e) The presence or absence of topographic obstacles, and (f) Sequential climatic changes.

3.6.1 Sand availability

From their experiment, Wasson and Hyde (1983) have shown that wind regime is not the only determinant of dune type, but sand supply has a major role as well. They conclude that barchans occur where there is very little sand and almost unidirectional winds; transverse dunes occur where sand is abundant and winds moderately available whilst longitudinal dunes occur where the winds are more variable but there is little sand. Star dunes occur where sand is abundant and wind variability is at maximum. Robin (1984) commented on Wasson and Hyde's model. He agrees with them on the barchans but not the other three dune types, and argues that transverse dune forms even in areas with little sand cover. He further observed that if longitudinal dunes can occur only where sand is scarce, they should be unable to produce deposits without causing their own destruction or evolution into other types of dunes. Pye and Tsoar (1990) believe that sand availability exercises some control on dune morphology although it is not directly related to the size or spacing of individual dune forms in an area. However, even where sand is scarce, as indicated in Wasson and Hyde's (1983) method, individual barchans may still assume megadune proportions. In many sand seas the largest and most widely spaced dunes are found furthest away from the sand source.

3.6.2 Wind velocity and directional variability

The nature of movement of particles by wind in deserts has been investigated by Bagnold (1941), who distinguished three types of movement namely suspension, saltation and surface creep. Only very fine particles with diameters less than 0.2 mm are carried in suspension by the winds. Thomas and Tsoar (1990) stated that wind

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velocities must not only be sufficient to overcome the resistance exerted by the particles themselves, but also the effects of other ground obstacles such as vegetation. El-Baz (1986b) reported that, "in most deserts meteorological stations are placed in oases, which are located in depressions. Cliffs and scarps that surround these depressions exert a marked influence on wind direction and velocity. Therefore, it is important to consider local topographic effects when comparing wind and dune orientation".

3.6.3 Grain size

Warren (1972) stated that dunes of different morphologies are associated with sands of different grain characteristics. An investigation by Tsoar (1986b) reveals that grain size is a significant factor governing dune profile. Quite often coarser-grained sand dunes have a greater difference in threshold velocity between their crest area and the lower levels than finer-grained sand dunes of a similar profile. Coarse-grained sand dunes have longer periods of erosion taking place at or near the crest, thus lowering the dune profile. This explains why all dunes composed of bimodal coarse-mode grains such as "sand sheets" and "zibar" (para. 4.3.2) are flat and low.

3.6.4 Vegetation cover

Hack (1941) noted that vegetation is a third major variable (besides sand supply and wind) which influences dune development. In another study Buckley (1987) observed that the precise effect of sparse plant cover on the transport of dune sand by wind is a critical factor in understanding the morphology, evolution and global distribution of aeolian dunes. Therefore, vegetation has considerable practical importance in sand stabilization, rehabilitation and restoration ecology.

One of the most spectacular aspects of ecosystem deterioration in arid regions is the movement of sand subsequent to decrease in, or disappearance of, the plant cover (Bendali *et al.*, 1990). Recent studies by Thomas and Tsoar (1990) indicate that the morphology of vegetated dunes is usually influenced by the strongest winds that are unidirectional.

3.6.5 Topographic obstacles

The formation of true dune forms like barchan, transverse and seif dunes, is usually initiated on the flat ground desert surface (Bagnold, 1941). On the other hand, there are other dune forms that relate to topographic obstacles, which will be discussed further in the next chapter.

3.6.6 Sequential climatic changes

Climatic changes may bring about fluctuations in any of the first four factors, and lead to the modification of existing dune form (Pye and Tsoar, 1990). Relict (fixed) desert dunes have been identified in many deserts, and pre-desert areas and have been widely interpreted as indicators of climatic change (Thomas and Shaw, 1991). For example, the ancient erg of Hausaland in Nigeria, and other similar formations in Niger, Chad basins and the *Qoz* formations in the Sudan (Grove, 1958; Goudie, 1977).

Difficulties in assessing the factors that determine dune morphology arise because several of the factors are interdependent. For example, the stronger or more frequent the wind, the less vegetation is found on dunes. This is especially true for transverse and barchan dunes (Illenberger and Rust, 1988).

3.7 Dune memory

For aeolian dunes, with their potentially long reconstitution times, the concept of dune reconstruction is better expressed as "dune memory" (Cooke *et al.*, 1993 quoting, Warren and Kay, 1987). Small dunes appear to "memorize" the events of a few hours, days or weeks. Larger ones memorize the events in a series of annual cycles whilst the largest ones memorize or integrate into their form, the events of thousands of years. Memory appears not to be everywhere related in the same way as size, for example, in annual wind regimes of gentle winds, quite small dunes have meso-memories, while in variable regimes of violent winds, quite large dunes are reoriented (Cooke *et al.*, 1993). Thus the shape of a dune can yield valuable information on the conditions it experienced during its development.

3.8 Classification of sand dunes and other aeolian sand accumulations

A considerable number of names have been used to describe dunes, and the use of different names for basically similar features in different parts of the world has resulted in some confusion (Pye and Tsoar, 1990).

Many attempts have been made, however, to classify dunes based on a combination of shape, number and orientation of slipfaces relative to the prevailing wind or resultant sand drift direction, and degree of form mobility (e.g. Bryan, 1932; Melton, 1940; Hack, 1941; Holm, 1960; Wasson and Hyde, 1983; Ghose, 1985; Mainguet, 1985; El-Baz, 1986a; Pye and Tsoar, 1990; Thomas, 1992; Cooke *et al.*, 1993).

Hack (1941) designed a schematic diagram to illustrate the relationships between vegetation, wind strength, sand supply and dune type (Figure 6). Ghose (1985) summarised the aeolian sand into sand sheet, minor forms, free dunes, and dunes related to obstacles.

Figure (6)

Hack's schematic diagram of the relation between vegetation, wind strength, sand supply and dune type
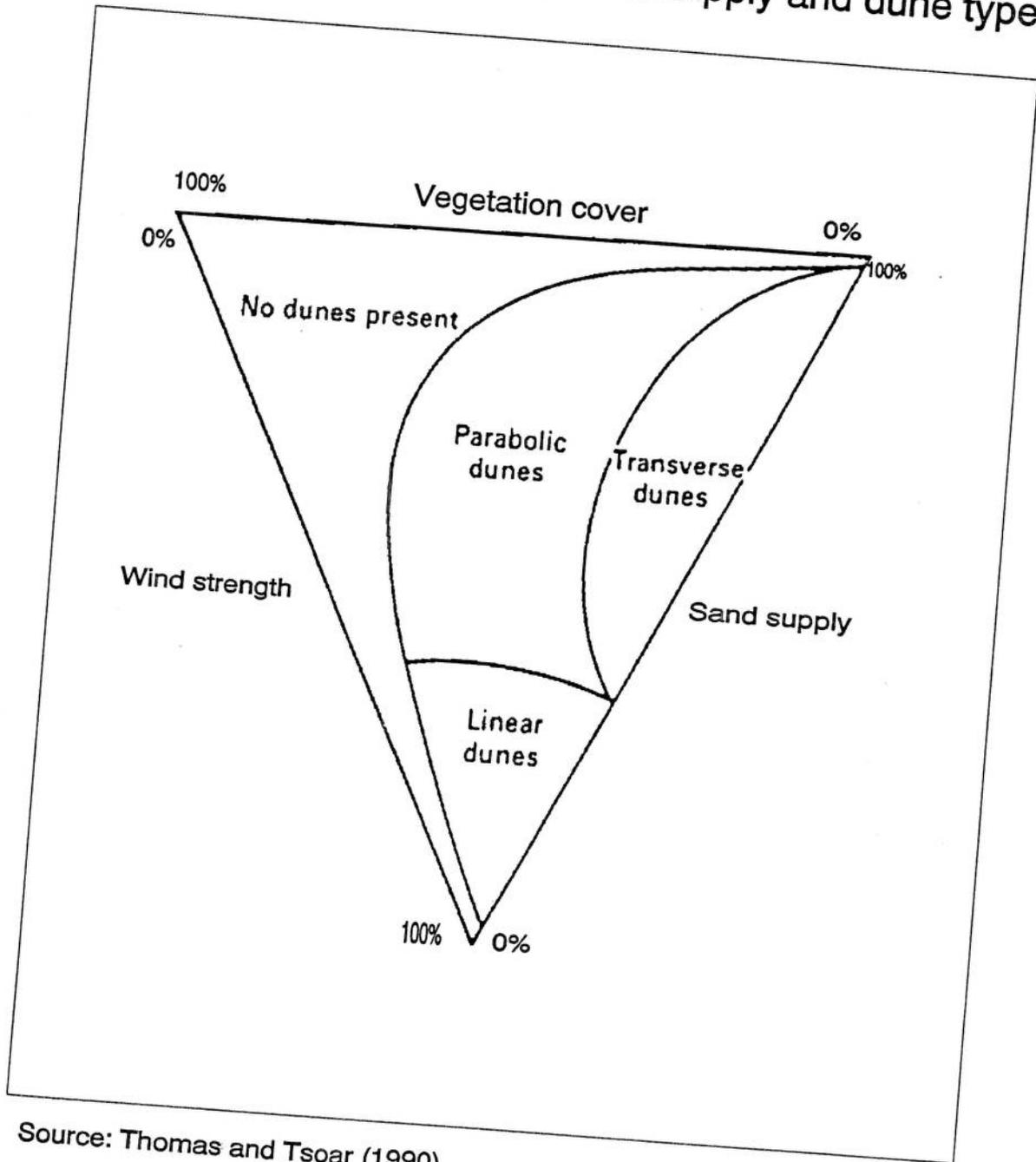
Source: Thomas and Tsoar (1990).

Studies of aerial photographs that have become available for large dune areas since the 1950s, always reveal that complicated patterns of dunes are the rule, and that transverse, longitudinal, and oblique dunes (by their angles with the prevailing winds), even in more than one shape, are likely to occur simultaneously in most of the large dune areas of the world. Seasonally changing winds also seem to complicate patterns, as well as the existence of dunes of different ages in one area. A simplified classification of the dunes making up these often complicated patterns have been given by Cooke and Warren (1973), and was widely adopted in subsequent studies (Hagedorn et al., 1977).

The relationship between wind regime, slipface orientation, and direction of dune movement (or extension) is complex, and descriptive terms such as "longitudinal" and "transverse" are frequently used inappropriately. In practice, it is often difficult to classify dunes accurately in this way because long-term wind data are not available from the dunes' areas, and local sand transport directions usually deviate significantly from those predicted using data from the nearest weather station owing to the effects of topography and secondary circulation in the atmosphere (Pye and Tsoar, 1990).

A useful distinction had been shown by El-Baz (1986a) who used satellite imagery for dunes investigations in the Western Desert of Egypt. He stated that accumulation of sand takes numerous forms, for example, it may be simple, compound or complex: Simple dunes are those where the individuality of each dune is clear and separable. Compound dunes are those in which two or more of the same type coalesce or combine by overlapping each other. Complex dunes are those that result from the combination of two different types of shapes.

3.8.1 Simple classification of major dune types

Pye and Tsoar (1990), in their dune classification system shown in Figure 7 stated that simple dunes are divided into three basic groups:

(a) Those whose development is related to topographic obstacles.

(b) Those which can be regarded as self-accumulated.

(c) Those whose development is strongly influenced by vegetation.

The first category is divided into windward accumulations, which include *climbing dunes* and *echo dunes*. Also there are the leeward accumulations that include *lee dunes*, *falling dunes*, and *cliff-top dunes*. Self-accumulated simple dunes include *barchans*, *transverse (barchanoid) ridges*, *unvegetated linear dunes (seif dunes)*, *dome dunes*, and *star dunes*. Dunes formed by accumulation of sand related to the presence of vegetation include *parabolic dunes*, *vegetated linear dunes*, and *coppice* or *hummock dunes*.

Figure (7)
DUNE CLASSIFICATION

SIMPLE DUNES

SAND ACCUMULATION RELATED TO TOPOGRAPHIC OBSTACLES
- Windward accumulations
  - Echo dunes
  - Climbing dunes
- Cliff-top accumulations
  - Cliff-top dunes
- Leeward accumulations
  - Lee dunes
  - Falling dunes

SAND ACCUMULATION RELATED TO BED ROUGHNESS CHANGES OR AERODYNAMIC FLUCTUATIONS
- Dunes composed of fine sand
  - Barchans
  - Transverse (barchanoid) ridges
  - Unvegetated linear dunes
  - Dome dunes
  - Star dunes
- Forms composed of poorly sorted and bimodal sand
  - Sand sheets
  - Zibars

SAND ACCUMULATION RELATED TO VEGETATION
- Parabolic dunes
- Hummock dunes
- Vegetated linear dunes

Source: Pye and Tsoar (1990)

Recently, Cooke *et al.* (1993), stated that dunes have immense variety. The diversity is attributed to infinite variation in the intensity and combination of dune-forming processes such as diurnal and annual wind patterns, atmospheric stability and stratification, wind strength, sediment size, sediment supply, plant cover and plant shape, hard-rock topography, rainfall, and recent geological history. There may be other controls, such as secondary flow patterns, of which little is yet known. They also added that, with so little of this variety explained, a comprehensive genetic classification must underlie any attempt at explanation. It is clear from their report that any appropriate variables can be used as a basis to produce a dune classification, such as type of sedimentary structure or even the going-conditions for vehicles.

Although Cooke's classification of dunes is simple, it will not be pursued further in this chapter because it includes some components such as "clay dunes" that are irrelevant for this study. Furthermore it is quite similar to Pye and Tsoar's (1990) classification, which will be examined further in the later chapters of this study.

Chapter 4: The Dynamics of Desert Sand Dunes

4.1 Introduction

Modern investigation technology such as aerial photographs and satellite imagery has enabled an understanding of the dynamics of dunes and their collective organization to develop significantly in the last decade. In view of the actual process of sand dune encroachment, particularly in the sub-Saharan region, and the need for expanding sand dune fixation activities, a better understanding of dune dynamics is essential, so that more efficient control measures can be designed. This can be achieved through proper assessment of the relationships between sand supply, wind regimes and the other factors determining dune types. Desert sand dunes dynamically react to formative wind regimes, as well as to other determinant factors, in terms of formation, orientation and movement (Figure 8). These processes vary according to the type of dune concerned. This chapter is devoted to an overview of the variations that exist within, and between, different desert dune types.

4.2 Dune accumulation influenced by topographic obstacles

Topographic obstacles such as escarpments and hills induce zones of airflow acceleration and enhanced turbulence. Consequently, there is erosion or accumulation of sand, or both simultaneously in different places. The resulting dunes are often static, i.e. they do not advance or elongate once they have attained a steady state (Pye and Tsoar, 1990). Large topographic prominences such as mountains also cause major variation in wind flow. These variations result in the formation of different types of dunes on the windward, leeward and on either side of a topographic barrier (El-Baz, 1986a).

4.2.1 Lee dunes

Lee dunes are best developed under a nearly unidirectional wind regime. They break-up downwind, at a distance where the topographic obstacle is no longer effective, into individual barchan dunes which is the most typical dune form in open areas of unidirectional wind (Cooke et al., 1993).

Bagnold (1941) observed that accumulation of sand can also occur in the lee of a gap between two obstacles. The sand flow is accelerated and funnelled through the gap, but fans out and decelerates on the lee side, leading to sand deposition.

Figure (8)
Desert dune types based on formative wind regimes and morphology

Dune type		Number of slip faces	Major control on form	Formative wind regime	Nature of movement
Zibar		0	Coarse sand	Various	Limited
Dome dune		0	"	"	"
Blow out		0	Disrupted vegetation cover	"	May extend down wind
Parabolic dune		1	"	Transverse Unimodal	Slow, nose migration
TRANSVERSE DUNES					
Barchan dune		1	Wind regime and sand supply	"	Forward migratory
Barchanoid ridge		1	"	"	"
Transverse ridge		1	"	More directional variability than for barchans	"
LINEAR DUNES					
Linear ridge		1 - 2	"	Biomodal / wide unimodal	Extending
Seif dune		2	"	Biomodal	"
Reversing dune		2	"	Opposing biomodal	May migrate if one mode dominant
Star dune		3+	"	Complex Multimodal	Vertical accretion
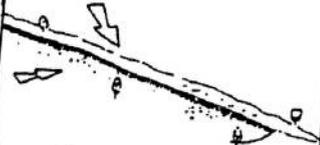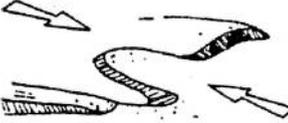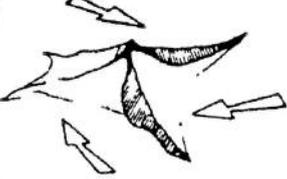
Source: Thomas (1992).

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4.2.2 Echo dunes

Echo dunes form some distance upwind from a major relief feature such as a scarp (El-Baz, 1986a). Pye and Tsoar (1990) reported that echo dunes can only be maintained in the long term if sand is moved laterally along the cliff line by vortices located between the cliff and the echo-dune. When the echo dune is small, the forward wind velocity on the echo dune crest is lower than that of the reverse flow of the vortex in front of the bluff body. Consequently, the echo dune grows in height by sand deposition until a condition of steady state is achieved. From observation and experiments with wind tunnels, Tsoar (1983) has shown that this steady state is reached when the height of the echo dune is about one third of that of the obstacle. Sand arriving at the crest is then moved into the trough between the dune and the cliff.

Kadar (1934) in his early study on Libyan dunes reported that neither tail-dunes (lee dunes), nor the sand dams (echo dunes) are moving formations of sand like the barchans. They remain in the same place, sand stops and rests on them because they are in calm spots.

4.2.3 Climbing dunes

If the escarpment is initially not steep, a vortex with strong reverse flow will not develop and sand is able to climb the escarpment as a climbing dune. Simulation work has shown that initial slope angles of less than 60° bring about the formation of climbing dunes (Tsoar, 1983).

4.2.4 Falling dunes

These are formed when the sand-carrying winds deposit the sand as they descend the slopes of hills or plateau (El-Baz, 1986a).

4.2.5 Cliff-top dunes

A zone of reduced wind velocity is frequently observed just below the crest of escarpments. Sand often accumulates at such sites forming cliff-top dunes. Since sand can be blown up slopes as steep as 60°, the formation of cliff-top dunes does not necessarily require cliff recession or erosion of a sand ramp (Pye and Tsoar, 1990).

4.3 Sand accumulation related to bed roughness and aerodynamic fluctuations

Wind-blown sand has a natural tendency to accumulate into dunes in the abscence of topographic obstacles. These self-accumulating dunes are classified on the basis of sand texture into two groups, dunes composed of fine sand and forms composed of poorly sorted and bimodal sands.

4.3.1 Dunes composed of fine sand

Dune sand grain size determines the threshold velocity for sand movement by the wind, and strongly influences dune alignment (Lancaster, 1981). Grains are generally described as sand when their diameter lies between 0.063 and 2 mm (Hagedorn et al., 1977). Dune fine sand lie in the range 0.3-0.65 mm (Pye and Tsoar, 1990).

4.3.1.1 Simple barchan dunes

Barchans are isolated cresentic dunes on a firm, coherent basement, with horns pointing downwind (Kadar, 1934; Bagnold, 1941; Mckee et al., 1964; Ghose, 1985; El-Baz, 1986; Pye and Tsoar, 1990; Thomas, 1992; Cooke et al., 1993). The windward slope is typically convex with an average maximum slope of 12°, while the leeward slope is characterized by a slip face at 33°-34° (Kadar, 1934; Khalaf, 1989; Pye and Tsoar, 1990). Smaller barchans tend to be flatter than larger ones and have smaller angle between the windward flanks and the desert floor (Khalaf, 1989; Pye and Tsoar, 1990). Bagnold (1941) observed that the relative length, width and height of barchans vary greatly. The maximum length and width of barchan dunes in the Libyan Desert are about 400 metres. The height of these big dunes varies up to 30 metres.

There is a general agreement that barchans form in vegetation-free areas, where sand supply is limited and the winds are almost unidirectional (Bagnold, 1941; Hagedorn et al, 1977; Howard et al., 1978; Wasson and Hyde, 1983; Pye and Tsoar, 1990; Thomas, 1992; Cooke et al., 1993; Allan and Warren, 1993). Meso- and mega-barchans are commonly confined to directionally constant annual wind regimes (Bagnold, 1941; Kar, 1990).

Patches of sand migrating over a land substrate develop a cresentic plan form even before they are high enough to develop a slip face, because sand is transported more rapidly across and around the sides of the sand patch than across its centre (Howard et al., 1978; Khalaf, 1989). As more sand is trapped in the middle of the patch, it grows in height until it is sufficiently high to induce flow separation and form slip face. The precise form of the dune is determined by the rate of sand supply, degree of sand flow saturation, and wind regime (Howard et al., 1978). These studies agree with Bagnold's (1933) assumption that the barchans are the true forms of dunes.

According to Hagedorn et al. (1977) a barchan dune is the optimal aerodynamic form for a migrating sand body. Further investigations have revealed that barchans can migrate long distances downwind without major changes in size or shape (Shehata et al., 1992; Thomas, 1992). In some instances they act almost as a closed system, in which sand is prevented from escaping from the dune by reverse flows associated with vortices on the leeward side of the dune. However, in most cases migrating barchans act as an open system in dynamic equilibrium, in which the input of sand from upwind is equal to the downwind losses from the horn tips (Pye and Tsoar,

1990). A change in wind direction or sand supply causes the barchan to change its size and probably its shape (Thomas, 1992). In barchans, the unavoidable loss of sand from the wings, must be replaced by sand from upwind if the barchan is to maintain its size. Without sand a barchan slowly diminishes and vanishes. Thus, barchans are continuously renewing stores of sand (Cooke et al., 1993).

The rate of barchan advance is directly related to the rate of sand transport over the brink, and inversely related to brink height (Bagnold, 1941). Smaller barchan dunes move forward more rapidly than large ones (Thomas, 1992). Migration rates more than up to 30 m yr^{-1} have been recorded for small barchans, but 5-10 m yr^{-1} is more typical for larger dunes (Howard et al., 1978; Thomas, 1992).

Very small barchans have memories of the order of no more than hours, barchans about 1 m high with memories of a few months (before a seasonal change of wind). Meso-barchans 3-10 m high, with memories of 1-30 yrears, are far less common. Mega-barchans, with memories of thousands of years, are even more rare (Cooke et al., 1993).

4.3.1.2 Transverse (barchanoid) dunes

Mainguet (1985) has stated that transverse dunes are formed when a slowing process groups them in chains or strips, while the sand continue to feed them. She added that contrary to isolated barchans, they are not very mobile. While Cooke et al. (1993) assume that transverse dunes are formed in the same kind of wind regime as barchans, but where there is more sand supply. In transverse dunes the barchanoid sections are joined by linguoid links that are usually lower and sometimes of coarser grain size than the barchans.

Transverse and barchan dunes in a reversing wind regime change their profile dramatically as the slip faces alternate from one side of the dune to the other (Bagnold, 1941). In another study, Illenberger and Rust (1988) observed that barchans arise from transverse pattern if sand supply declines or wind speed increases. On the other hand, Lancaster (1985) revealed that wind velocity varies with dune shape and height. Changing ratios of base to crest sand-transport rates on transverse dunes tend to reduce dune steepness as overall wind velocities increase.

4.3.1.3 Unvegetated linear dunes

Linear dunes are those parallel to the prevailing wind. They may be hundreds of metres high and hundreds of kilometres long (Ghose, 1985). From their study, Wasson and Hyde (1983) concluded that linear dunes in general occur principally in areas of limited sand supply and moderately variable wind regimes. Tsoar (1986a) observed that linear dunes use wind from all directions and elongate in their direction. He considers this could partly explain why longitudinal dunes are the most widespread type in the

world's deserts. According to Pye and Tsoar (1990) linear dunes have sharp crests that give them the name *seif* (sword in Arabic). They occur in many African sand seas, where they are often referred to as *silk dunes, irg, elb, draa* and *habil* (Pye and Tsoar, 1990; Cooke *et al.*, 1993).

Early studies by Bagnold (1941) have revealed that seif dunes are modifications of barchans produced by strong cross winds transverse to the prevailing wind direction. While Price (1950) argues that the occurrence of the small inter-dune longitudinal ridges in all parts of Sahara desert indicates that longitudinal dunes originate in all parts and not only the windward borders, as some writers have assumed. Tsoar (1986a) believes that linear dunes are not the creation of the initial response of the sand to the wind. The first forms are barchans and transverse dunes (initial aeolian bedforms) from which the linear dunes develop. While Kar (1990) suggested that vegetation may also play a role in retarding the progress of the barchanoid dunes and the formation of the longitudinal ones under the prevailing unimodal environments. On the other hand, many authors have supported the theory that linear dunes develop with the presence of parallel helical vortices in unidirectional wind regimes.

Studies by Livingstone (1989) tend to suggest that linear dunes are associated with bi-directional wind regimes that are often seasonal. Preliminary evidence from his studies confirms that a seasonal aeolian regime induces seasonal responses due to the dynamics of sand transport on the dune. Thomas (1992) reported that investigations performed by Tsoar (1986a) and Livingstone (1989) on the dynamics of seif dunes, have demonstrated how *seifs* develop under the influence of two principal wind directions, and how dune-induced airflow modifications lead to maintenance of the dune form parallel to the two wind directions. Clearly, these field studies have provided evidence that longitudinal helical vortices are not required.

According to Tsoar (1986a) longitudinal dunes do not advance, but elongate. This view is shared by Allen and Warren (1993) who noted that linear dunes are not mobile and can offer a habitat in which vegetation can become established.

4.3.1.4 Dome dunes

Dome dunes are gently sloping mounds, often without slip faces, which are circular or elliptical in plan. They are typically 150-200 m in diameter, and 6-10 m high (El-Baz, 1986a; Pye and Tsoar, 1990). Cooke et al (1993) added that dome dunes are built of fairly fine grained uni-modal sand.

El-Baz (1986a) stated that dome dunes occur in strong wind regime. For example, at the southern terminae of linear dunes in the Western Desert of Egypt.

Shehata et al. (1992) noted that dome like shield dunes with relatively small slip faces are believed to transform in time into cresentic dunes.

4.3.1.5 Star dunes

Star dunes are the largest aeolian bedforms in many modern sand seas, and they contain a greater volume of sand than any other dune type (Lancaster, 1989). They are characterized by their pyramidal morphology and three or more sinuous arms radiating from a central peak with multiple avalanche faces, and a broad gently sloping plinth forms the basal parts (Mainguét, 1985; El-Baz, 1986a; Lancaster, 1989; Pye and Tsoar, 1990; Cooke et al., 1993). They are the highest of the mobile dunes, reaching up to 400 m, and have a mean width of 500-1000 m (Pye and Tsoar, 1990).

Star dunes occur in many African sand seas, where they are known as *demkhas, ghourds, rhourds* or *oghourds*. They are found in the North-western Sahara, the Fachi-Bilma Sand Sea in Chad and Niger (Mainguet, 1985; Lancaster, 1989; Pye and Tsoar, 1990; Cooke et al., 1993), and in North-eastern Sahara as well (Thomas, 1992). The greatest continuous area of star dunes is in the Great Eastern Sand Sea in Algeria, where they cover about 12,000 km^2 (Cooke et al., 1993).

Holm (1960) noted that the stellate form of star dunes is a response to sand transporting winds which blow from different directions at different times of the year. While the Wasson and Hyde's (1983) hypothesis relates star dunes to regional wind regimes commonly called the "multimodal wind regime hypothesis". Recently, Cooke et al. (1993) reported that the best authenticated hypothesis is that which relates star dunes to regional wind regimes known as the "multimodal wind regime hypothesis".

On the initiation and development processes of star dunes, Wilson (1972) speculates that they might develop under depositional process, where wind systems overlap. While Lancaster (1989) suggested that star dunes may be initiated and developed as a result of the modification of other dune types as they extend or migrate into areas of seasonally changing wind directions. He added that the effects of multidirectional wind regimes are in part influenced by dune size. It is clear from several reports that the processes responsible for the initiation and subsequent early development of star dunes are still uncertain.

Lancaster (1989) concluded that whatever the process that initiates them, star dunes are characterized by a high degree of interaction between dune form and airflow as winds change direction seasonally. This plays a major role in the formation and maintenance of this dune type. Such interactions often lead to deposition of sand in the central parts of the dune, giving rise to its pyramidal shape, as well as extension of the linear arms. Star dunes are immobile dunes and their arms only change position and elongate (Mainguet, 1985). On the other hand, Thomas (1992) reported that star dunes can move 1-3 m year^{-1} but that this movement is probably not a long-term trend.

4.3.2 Sand forms composed of poorly sorted and bimodal sand

These forms are often of low amplitude, dominated with coarse grain mode. Tow main types, "Zibars" and sand sheets that will be discussed further.

4.3.2.1 Zibars

Zibars are long wave-length, low amplitude migrating bedforms without slip faces whose surfaces are usually covered by ripples or megaripples (Holm, 1960; Wilson, 1972). The low, flat typical form of zibar is governed by the presence of a coarse sand mode in the sediments that comprise them (Cooke et al., 1993). On the other hand, Warren (1972) has reported that some of the zibars in the Tenere Desert in Niger are higher than nearby seif dunes, reaching over 5 metres.

Most zibars are aligned at right angles to the strongest winds, presumably the only ones able to move the coarse sand. They are common upwind of sand seas, in zones from which finer material has been winnowed. Individual fields of zibars are extensive, for example, in Mauritania they cover 10,000 km^2(Warren, 1972; Cooke et al., 1993).

Many zibars are active, even when covered by sparse vegetation. No flow separation occurs in the lee of zibars, only flow expansion (Cooke et al., 1993). This agrees with Bagnold's (1941) statement that dunes composed of fine sand have steeper slopes than dunes composed of coarse sand.

4.3.2.2 Sand sheets

Sand sheets are defined as areas of predominantly aeolian sand where dunes with slip faces are generally absent. Their surface may be rippled or unrippled (Pye and Tsoar, 1990). Ghose (1985) stated that sand sheet's coarse grains usually remain at the surface, which are resistant to surface creep and saltation.

The thickness of sand sheet deposits range from a few centimetres to several tens of meters, depending on their environment of formation (Maxwell and Haynes, 1989).

The largest sand sheet, over 100,000 km^2, is the Selima Sand Sheet on the borders of Egypt, the Sudan and Libya (Maxwell and Haynes, 1989; Cooke et al, 1993). The most important control on the formation of the large desert sand sheets such as in the Sahara is the coarseness of sediments (Khalaf, 1989; Maxwell and Haynes, 1989). Also sand sheets could be formed in the presence of vegetation, where some are kept fairly level because vegetation curtails sand movement and dune growth (Khalaf, 1989).

Investigations by Maxwell and Haynes (1989) on the Selima sand sheet in south-western Egypt using landsat images acquired between 1972 and 1988 indicated that these features move as discrete bedforms at a rate of up to 500 meters per year.

4.4 Sand accumulation related to vegetation

Wasson and Hyde (1983) regarded vegetation as a modifying factor for example, from transverse to parabolic dune, rather than a primary determinant.

4.4.1 Influences of vegetation on desert dunes

Thomas and Tsoar (1990) stated that the presence of vegetation on desert dunes influence their geomorphological dynamics, by modifying the aerodynamic roughness of the ground surface. These influences of vegetation on desert dunes can be grouped into three categories; vegetation as a surface stabilizer, vegetation as an accretion focus and vegetation as a determinant of dune morphology. Each of these will be discussed further:

4.4.1.1 Vegetation as a dune surface stabilizer

The criterion which has received most application is the presence of dune vegetation cover, based on the reasonable concept that as vegetation cover increased on the ground surface, so dune development became less likely (Hack, 1941; Thomas and Tsoar, 1990; Thomas and Shaw, 1991). The widespread identification of desert dunes, both within today's arid lands and in extra-arid locations, possessing a partial or near-complete vegetation cover, has commonly been accompanied by their interpretation as inactive, or fossilized features (Sarnthein, 1978; Lancaster, 1981; Thomas and Shaw, 1991). The vegetation cover is therefore considered to act as a buffer between potentially effective sand-moving winds and potentially entrainable sediments (Thomas and Tsoar, 1990).

4.4.1.2 Vegetation as an accretion focus

Vegetation can contribute to the genesis and development of dunes by acting as a focus for sand accumulation. This may occur when the vegetation cover is incomplete (Thomas and Tsoar, 1990). As stated by Hesp (1981) whenever sand transporting wind interacts with a discrete roughness element projecting above the bed, sand deposition and hence bedform construction often result. Deposition may also occur if the plant is sufficiently large, or of low wind porosity on the windward side. When plants obstruct sand, coppice dunes can form, which develop through the trapping of sand within the body of the plant.

4.4.1.3 Vegetation as a determinant of dune morphology

The complex interaction of environmental variables which contribute to the development and characteristics of desert dune fields means that it is possible to consider the role of vegetation as more than simply inhibiting sand movement or encouraging its deposition (Thomas and Tsoar, 1990). Spatial variations in plant cover

allow adjacent communities to act as surface stabilizers on dune arms and to permit deflation in the central corridor where plants are absent. The widespread occurrence of parabolic dunes in some deserts provides evidence of the importance of vegetation as a determinant of dune form. A reduction in the vegetation cover of these dunes has been noted to result in significant changes in the morphology of the dune crestal zones and in dune alignment (Tsoar and Moller, 1986). Morphological degradation may be in the form of a reduction of dune height, which in the case of linear dunes, may result in relict dune forms being lower for a given spacing than active counterparts, assuming that a dynamic relationship exists between sand supply, wind regime and dune field morphology (Thomas and Shaw, 1991).

4.4.2 Dune types related to vegetation

Because there is a substantial scattering of bushes or clumps of grass in many deserts, dunes associated with plants are very common indeed.

4.4.2.1 Vegetated linear dunes

Vegetated linear dunes range in height from several metres to a few tens of metres, and typically have a rounded cross-sectional profile. The vegetation cover is thickest on the plinth and lower slopes and is usually sparse or absent on the crest (Pye and Tsoar, 1990). Many, if not most, linear dunes are vegetated to a point where sand movement is severely restricted (Allen and Warren, 1993).

Cooke *et al.* (1993) reported that many of the linear dunes in the West African Sahel have clearly been stabilized following climatic change, for they are now covered by dense vegetation. The bimodal wind regimes that favour linear dune formation may be more characteristic of desert margins, and these are more likely to experience the critical climatic change between dune activity and inactivity, than are the desert cores.

Destruction of the vegetation cover can turn vegetated linear dunes into *seifs* or braided linear dunes, the latter being linear dunes on which small secondary transverse dunes are superimposed. This has occurred in some parts of Sinai (Tsoar and Moller, 1986), and the Sudan (Davies, 1991).

There appear to be at least two modes of vegetated linear dune development. The first is by slow down wind movement of sand along the crest of a dune ridge whose flanks are largely vegetated, and the second is by more rapid movement of sand along an essentially bare sand ridge, followed by vegetation colonization of the ridge when the sand transport rate is reduced due to an increase in rainfall or reduction in wind energy downwind (Pye and Tsoar, 1990). Partially vegetated linear ridges displaying crestal sand movement, are a normal active type of dune in desert environments (Thomas and Tsoar, 1990), and should not always be regarded as

palaeoforms, although climatic changes have probably played an important role in their development.

4.4.2.2 Parabolic and elongated parabolic dunes

Simple parabolic dunes are U- or V- shaped in plan with two trailing arms pointing upwind (Mainguet, 1985). Many have a large sand mound with a steep lee slip face at the downwind end, the outside slopes of the trailing arms are partly or wholly vegetated (Pye and Tsoar, 1990). According to Mainguet (1985) these dunes are formed on levelled surfaces which are stabilized by open vegetation cover under a unidirectional wind regime. While Ghose (1985) observed that in regions with excessive sand supply, vegetation is partly or almost fully buried and the resulting form of the dune is parabolic. In an early study, Price (1950) described the transition from barchan to parabolic dune where vegetation retards only the wings of the barchan.

Maximum rates of forward movement of 2.8 to 6.4 m per year for parabolic dunes have been reported by Pye and Tsoar (1990).

4.4.2.3 Hummock dunes

The term hummock dune as used by Pye and Tsoar (1990) describes any irregular shaped mound of sand whose surface is wholly or partially vegetated. Hummock dunes can reach up to 30 m high and 100 m across, but a height of less than 10 m is more typical.

The morphology of hummock dunes is strongly dependent on the shape, density and growth characteristics of the associated vegetation. The formation of well developed hummock dune terrain is favoured by a discontinuous plant cover and high winds (Cooke et al (1993).

4.4.2.4 Nabkhas dunes

This kind of dune has many ethno-geomorphological descriptions such as "bush mounds", "shrub-coppice dunes" and "rebdou". The concise, and now widely recognized North African word "nabkha" is the most preferred (Cooke et al., 1993). Shrub-coppice dunes form on the leeward side of vegetation. Isolated mounds or shrub-dunes are formed around low trees and shrubs with limited sand supply (Mainguet, 1985). From observations and experiments, Hesp (1981) assumed individual plants need to be higher than 10-15 cm before they can begin to trap sand effectively. Saxena and Singh (1976) repotred that in the Saharo-Sindian belt from Mauritania to India, bushes of species of Calligonum, Calatropis, Zizyphus, Tamarix and Salvadora build dunes up to 5 m high and 10 m in radius.

Chapter 5: Control of Drifting Sand and Mobile Dunes

5.1 Introduction

Sand dune encroachment is prevalent throughout the countries within and at the borders of the Sahara. The process has been further accentuated by the destruction and depletion of natural vegetation over past centuries (Ibrahim, 1969; Moomen and Barney, 1981; Mainguet, 1986). Moving sand and sand dunes cause a number of problems. Sand accumulates in calm zones around obstacles such as roads, railways, and buildings or walls. Also, sand deposits within depressions can result in losses to agricultural lands mainly in the fertile basins. Mobile dune problems may even include the burial of buildings, industrial installations and any object that may get in their way (Khan, 1983; Watson, 1985; Al-Nakhshabandi and El-Robee, 1988). Approximately 65 million ha of productive land at the southern borders of the Sahara are estimated to have become desert in the last 50 years (Eckholm, 1975; Novikoff, 1989). According to Mainguet (1986) sand-laden winds manifest themselves mainly in the Saharan region where the yearly rains are less than 100 mm, but their secondary effects spread into the Sahel.

Attempts to limit the damage caused by blowing sand and mobile dunes have a long history. Measures to control the movement of desert sand have been employed in the Nile valley for millennia (Pye and Tsoar, 1990). However, the need for more effective measures of sand control has become more apparent in the past 40 years owing to economic growth and urban development (Jones et al., 1986; Watson, 1985), and to increased concern about the human and environmental consequences of desertification (Rapp, 1976; Hagedorn et al., 1977; Le Houreou, 1986). The author considers that increasing rates of population growth, shortage of fertile cultivable lands, and the related expansion onto marginal lands may be counted as major factors that have raised awareness of the need for sand stabilization in areas where mobile dunes are found.

The aim of this chapter is to review and discuss the the fundamentals of aeolian sand control. These will include methods for controlling drifting sand and those for dealing with mobile dunes. Generally, five main approaches have been employed to avoid or reduce the problems associated with sand movement:

1- Reduction of sand supply and elimination of sand sources.

2- Enhancement of sand transport.

3- Deflection of moving sand.

4- Enhancement of sand deposition.

5- Control of mobile dunes.

Most of these methods have been applied in several projects, and good results have been reported by Grainger (1990), although much earlier, Finkel (1959) was very critical of these methods, from his experience in southern Peru. His views are discussed in para 5.8.

5.2 Assessment techniques

In order to combat drifting sand and mobile dunes an understanding of the physics of moving sand is required together with an effective data collection system (Stipho, 1992). In most cases, the techniques for controlling blowing sand and mobile dunes are well established. However, implementation of these procedures under field conditions frequently proves difficult (Watson, 1990). One reason for this is that empirical data on the rate of sand and dune movement are often scarce (Jones et al., 1986). Another is that the environmental phenomena of topography, aeolian dynamics, and the physical characteristics of sand are far more variable than those assumed by theoretical or simulated estimations of sand movement (Watson, 1985; Pye and Tsoar, 1990).

It is important to develop a broad scale for the types of sand dune movement, so that the conditions at a particular site can be placed in a regional setting (Jones et al., 1986). It is in this context that examination of satellite imagery may yield valuable information on the distribution of surface sand accumulations and the major stream lines of sand movement (e.g. El Baz, 1986a; Mainguet, 1986; Jones et al., 1986; Watson, 1990). Aerial photography is, normally, a better source of information on the direction and the rate of the mass transport of sand (Rapp, 1976; Laird, 1990; Ibrahim, 1991). The author is of the opinion that ground checks are of equal importance to aerial photography and satellite imagery, and need to be done on the basis of systematic field monitoring to assure useful and durable stabilization methods. On the other hand, Jones et al. (1986) recommend that care needs to be taken when assessing the field evidence in order to ensure that the features recognized represent contemporary forms evolving under present environmental conditions. Many dunes are in fact stabilized palaeo-forms and give false indications of both the direction and magnitude of present sand migration.

Ibrahim (1969) stated that all methods of controlling sand drift should be based on sound ecological studies carried out on both micro-climate and macro-climate scales.

5.3 Reduction of the sand supply

In areas where intense sedimentation occurs, enhancement of sand deposition or transport may be impractical or impossible. In such instances it may prove preferable to

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identify the main sources of sand and stabilize the deflating sand body which is often most cost effective (Watson, 1985; Pye and Tsoar, 1990). Three main methods of source area control are employed:

1- Treatment of the surface.

2- Reduction of wind velocity.

3- Restriction of human and livestock activity in sand source area.

5.3.1 Surface stabilization by mulches

A wide variety of materials have traditionally been used to protect surface sand from erosion, such as stones, corn stalks, brushwood, and domestic refuse. In more recent years these materials have been widely replaced by oil, bitumen, lime, resins, latex and other commercially formulated chemicals (Hagedorn *et al.*, 1977; Moomen and Barney, 1981; Watson, 1985; Kaul, 1985).

5.3.2 Reduction of wind velocity

Physical barriers to the wind create regions of low flow velocity both infront of and behind the barrier. Barriers built upwind can thus be used to reduce the friction velocity over a potential sand source area (Pye and Tsoar, 1990).

5.3.2.1 Artificial barriers

Artificial barriers can be constructed from any material sturdy enough to withstand strong winds. For example, reeds, palm fronds, brushwood, slat-fencing, planks, stakes and synthetic nylon mesh have all been used (De Banito and Le Roux, 1976; Hagedorn *et al.*, 1977).

Nearly all barriers provide maximum percentage reductions in wind velocity at leeward locations near the barrier, with a gradual decrease downwind. The height of barriers is a very important factor influencing effectiveness because it governs the limits of influence. Expressed in multiples of barrier height, the zone of wind velocity reduction on the lee side of a barrier may extend a distance equal to 40 or 50 times the height of the barrier. These distances are insignificant in terms of wind erosion control, therefore if complete control is desired, barriers must be spaced at relatively close intervals (Chepil and Woodruff, 1963). The fence height should be determined on the evidence of annual rates of sand movement. Once the fenced area has been buried by sand, the next fence is installed on top of the sand mound (Watson, 1985).

5.3.2.2 Vegetative barriers

Alternatively, tree shelterbelts can be created by planting rows of trees or shrubs perpendicular to the dominant sand flow direction, for example in northern Sudan

(Ibrahim, 1991). The greatest drawback with this approach to sand stabilization in deserts is the problem of selecting plant species capable of withstanding severe drought (Watson, 1985). The author is of the opinion that groundwater table depth and irrigation techniques are, also, a major part of the problem.

5.3.3 Restriction of human activity in sand source area

Trampling by pedestrians, vehicles, livestock, and overgrazing are major factors leading to enhanced sand blowing in deserts. Restriction or even banning of such activities altogether, can often reduce the need for other sand control measures (Mainguet, 1985; Jones et al., 1986).

5.4 Enhancement of sand transport

In some instances where the supply of sand cannot be controlled, or where it is not possible or desirable to trap moving sand, it may be preferable to enhance the transport rate of sand across an area, and to reduce the amount which is deposited, by increasing the sand-transporting capacity of the wind or by reducing the ability of the surface to trap moving grains (Pye and Tsoar, 1990). The erection of panels to enhance sand transport and channel airflow over a road surface or around an installation has been reported by Walls (1982). This method has widely been used in the Sudan to prevent sand deposition on the railway line between Atbara and Karima (personal observation).

5.5 Diversion of moving sand

This system is designed to divert or deflect sand around individual structures (Kaul, 1985; Khan, 1985). Two types of fence alignment have been used. In the first, the sand fences are slanted at an angle of 45° to the direction of sand drift. In the second, the fences form a V-shaped barrier pointing into the sand stream. To be most effective, and to maximize their useful life, the fences should have low permeability, thereby limiting the amount of sand deposited in their lee (Pye and Tsoar, 1990). Fences need not be very high as about 95% of the sand is transported within the first 30 cm above the ground (Hagedorn et al., 1977; Stipho, 1992). The system is advisable in those areas where the distance between the threatening dunes and the area to be protected is too short to permit the creation of normal foredunes (Kaul, 1985).

5.6 Enhancement of sand deposition

This involves reducing the sediment load of the wind by decreasing the wind energy. This can be achieved by the construction of ditches, sand fences, planting vegetation, or by a combination of methods (Watson, 1985; Pye and Tsoar, 1990).

5.6.1 Ditches

The excavation of pits and trenches upwind of an installation can provide a high degree of temporary protection from wind-borne sand (Watson, 1990). While ditches will trap all sand grains moving as surface creep, they must be wider than the maximum horizontal jump of saltating grains (Stipho, 1992). This may reach 3-4 metres, and the ditch must be sufficiently deep to prevent scouring of sand from its floor. The trench must be cleared of sand when its minimum effective depth is reached, or new ditches must be excavated (Watson, 1985).

5.6.2 Sand fences

Fences designed to accumulate sand are always set up at right angles to the prevailing wind direction (Hagedorn et al., 1977). They take up or deflect a sufficient amount of the wind force to lower the wind velocities on the leeward side to below the threshold required for sand movement (Chepil and Woodruff, 1963). The amount of sand trapped is dependent on the fence height, its porosity, the shape and arrangement of the gaps through which the air can pass, and the wind velocity (Jensen, 1985). However, individual fence designs have different sand trapping abilities at different wind velocities. For this reason the fence design must be tailored to local environmental conditions (Kaul, 1985).

A fence with less than 20% porosity behaves almost as a solid obstacle to the wind flow, inducing upstream and downstream separation bubbles. Most sand deposition occurs on the upstream side, forming an echo dune. Maximum sand deposition is achieved by fences with 36% to 40% porosity, regardless of the structure (Pye and Tsoar, 1990). Field tests have shown that a wooden slat fence with 50% porosity is more effective and have the advantage that they are more easily lifted for re-use after being partially buried by sand (De Banito and Le Roux, 1976). Multiple rows of sand fencing can trap more than 80% of wind-borne sand, even under variable wind conditions, if optimal alignment and porosity for the specific area are employed. Hence, the fences must be located in areas where the creation of a large artificial dune will not pose problems (Watson, 1985). On the other hand, Hagedorn et al. (1977) recommend a three fence system, spaced about 1500 m away from each other. Sand will largely accumulate at the first upwind fence. An increasing accumulation rate at the second fence indicates a decrease in effectiveness of the first one. In this case the first fence has to be raised higher. Sand accumulation at the third fence, the one closest to the protected area, calls for raising of both the other fences. Watson (1990) stated that the use of fences over a long period constitutes a commitment to a sand control policy based upon dunes building. Very large dunes may be created which require careful management to prevent any encroachment on the installation downwind.

5.6.3 Vegetation planting

Vegetation can be used to trap sand in several different ways; First, belts of trees or shrubs can be planted to act as a self-renewing fence system. Second, vegetation can also be planted to trap sand over large areas rather than in discrete belts (Watson, 1990). However, since dunes are dynamic bedforms, the pattern of sand transport and form evolution must be properly evaluated from geomorphological perspectives before planting. Also, shifting sand presents a hostile environment for many seedlings and young plants, and it is therefore important to identify areas of net sand erosion and accretion in order to plan the correct pre- and post-planting management measures (Pye and Tsoar, 1990).

The establishment and evolution of vegetation are, in part, influenced by physical and chemical properties of the sand which include thermal regime, moisture retention characteristics, salt concentration, cation exchange capacity, and nutrient availability. This interaction between vegetation and sand substrate is of great importance in management and conservation of sand dunes (Hagedorn et al., 1977; Pye and Tsoar, 1990).

5.6.3.1 Moisture and temperature characteristics of dune sand

The maximum quantity of water which can be retained by surface tension and granular absorption against the pull of gravity is defined as the field capacity. The field capacity of active dune sand which contains less than 1% fines and less than 1% organic matter varies from about 4% to 10%. While stabilized dune sands which contain more fines and organic matter can retain up to 35% moisture at field capacity (Brady, 1974).

Temperature variations have little effect below 30 cm of sand surface. Therefore, when water reaches a depth of 20 to 30 cm it remains there as a moist unsaturated zone for several years because, sand being a very poor conductor of heat, the temperature is constant, and virtually no direct evaporation loss occurs (Bagnold, 1954). The author believes that this is true, where he observed that in the Sudan, a dune area at El-Rekabia village (figure 11) had been flooded in 1988. Field tests carried out in 1993 revealed that the unsaturated moisture is at a depth of about 50 cm. On the other hand, Alizai and Hulbert (1970) stated that the effect of texture on evaporation varies with the amount of water added. If rainfall is plentiful so that all soils are wet below the root zone, the storage capacity is more important than evaporation. In semi-arid conditions most rains do not wet to the root zone, and then the amount of water available to plants is determined by evaporation, and not storage capacity.

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5.6.3.2 Protection against sand blasting and burial

Over a monitoring period of several months, 25% of all sand movement occurred during one storm lasting only 43 hours. In such conditions rapid sand accumulation may bury the plants precluding their survival (Watson, 1990). Survival of plants in these mobile areas may be enhanced, however, if the surface is covered with brush matting, protected by fences, or spraying with a binding agent (Pye and Tsoar, 1990). In the Sudan (Ibrahim, 1991) fences are a prerequisite for the survival of trees planted to prevent sand drift and dune stabilization. Also starting the planting season after the period of maximum sand movement has been found to have an effect on the survival rate up to 15%.

5.7 Control of mobile dunes

Relatively few investigations of the methods of combating the problems posed by encroaching dunes have been undertaken (Stipho, 1992). In some ways the problems associated with mobile dunes are less severe than those posed by drifting sand. This is because, while sand will drift from any direction that the wind blows at velocities greater than 5 m/s, dune movement requires the mobilization of a large volume of sand and, therefore, the direction of movement is more or less constant on an annual basis (Watson, 1990). Rates of dune movement vary considerably, not only from desert to desert but also from dune to dune. Bagnold (1941) argued that there is an inverse relationship between rate of movement and dune size. The larger the dune the slower it would move.

The problems posed by the movement of sand dunes have been tackled in three ways; removal, dissipation, or immobilization of the dunes. The selection of one of these options depends on the type of installation being protected, the distance of the dune from the installation and the size of the dune.

5.7.1 Removal of the dunes

The only practical method of dune removal is mechanical excavation and transportation to a new site (Hagedorn et al., 1977). The costs are high since a 6 m high dune may incorporate 20,000-25,000 m³ of sand, weighing between 30,000 and 45,000 tonnes depending on the volumetric porosity of the material (Watson, 1985).

5.7.2 Destruction of the dunes

Mobile dunes can be destroyed and the sand removed by natural processes. This is practical only if the endangered area can stand through-transport of sand (Hagedorn et al., 1977). This can be undertaken in four ways:

5.7.2.1 Dissipation

This is achieved by setting up panels in a random way on a dune. The turbulence results in the gradual deflation of the dune. The panels have to be moved frequently because they become undermined and tend to topple over (Hagedorn et al., 1977).

5.7.2.2 Reshaping

Dune movement involves the deflation of the windward side of the dune and accretion of the slipface. If the slipface of a barchan dune is removed mechanically and prevented from reforming, sand will flow beyond the dune. However, reshaping will be temporary since the sand mound will tend to evolve toward the optimum aerodynamic form. The surface of the reshaped dune must be stabilized if the treatment is to be permanent (Watson, 1990).

5.7.2.3 Trenching

This is achieved by excavating a trench parallel to the direction of movement, through the axis of the dune. The trench will allow unrestricted air flow through the centre of the dune removing sand from its core. This method can only be adopted in areas where sand drift will not create a hazard since it is possible that the deflating sand could form a mobile parabolic dune or two smaller barchans (Watson, 1985).

5.7.2.4 Partial surface treatment

This involves fixing the arms of a barchan allowing deflation of the central portion. The stabilizing materials include oil, chemicals, gravel, or fences (Watson, 1990).

5.7.3 Mechanical dune stabilization

In areas where mobile dunes pose an immediate threat, destructive techniques are inappropriate. If complete removal of the dune is not possible on economic grounds, several methods of dune immobilization can be employed to combat the threat of encroachment.

5.7.3.1 Total surface treatment

This method is similar to dune surface treatment in para 5.3.1. Also armouring the surface with aggregates or coarse grained particles can prevent sand entrainment. The method is valuable in areas where the material is available and where the environmental conditions preclude the use of oil or chemical stabilizers (Stipho, 1992).

5.7.3.2 Fences

When protection is required from dune encroachment, the most effective stabilization policy involves the erection of sand fences to supplement dune immobilization

(Hagedorn *et al.*, 1977). Kaul (1985) recommends parallel line fences for unidirectional winds and a checkerboard system for multidirectional winds (figure 9). Two ways identified for the use of fences to stabilize dunes are:

1) If the dunes are more than approximately 1 km from a property, fences can be erected upwind of the dune to trap incoming sand (Watson, 1990). Fences should be built on the windward side of a dune as, the wind-blown material will be deposited there instead of on the dune. While the dune migrates, with its sand supply cut off, it will grow smaller and eventually disappear (Hagedorn *et al.*, 1977). However, the distance the dune will travel before it disappears completely depends on the size of the dune, its rate of movement and the rate of sand loss. The greatest problem with this approach to dune control is that the fences that inhibit sand supply will accumulate sand. Dunes built by sand fencing are permanent features which must be periodically re-fenced as sand accumulates (Watson, 1985).

2) When encroaching dunes present an immediate threat, two methods have to be combined to stop the dune (Hagedorn et al., 1977). The windward slope has to be stabilized by fences, and another sand collecting fence has to be erected in front of the dune. Stipho (1992) stated that the precise location of fences can be determined by field monitoring of lines of sand movement or by the identification of the paths from aerial photographs. The rate of growth of the artificial dune and the scheduling of fence replacement can be determined by using field measurements of the rate of sand transport. Under severe conditions and where sand drift must be minimized (Watson, 1990), fences can be erected on the dune itself. In this case the optimum location for fences relative to the crest of the dune should be determined with consideration to the fence height and wind velocity.

5.7.4 Vegetative dune stabilization

In the author's opinion, permanent stabilization of dunes can only be achieved by the development of vegetation cover of the dune area. Vegetative control techniques have been widely implemented because they are often relatively inexpensive and are less disruptive to the environment than other methods of stabilization. Vegetation will not grow, however, as long as there is still a strong movement of sand. Effective stabilization therefore means the combination of mechanical or chemical methods with biological methods at least for the initial phase of vegetative growth. In many cases the mechanical methods used against moving sand will no longer be needed, once the vegetation has been firmly established (Hagedorn *et al.*, 1977).

Figure (9)
Fence designs:
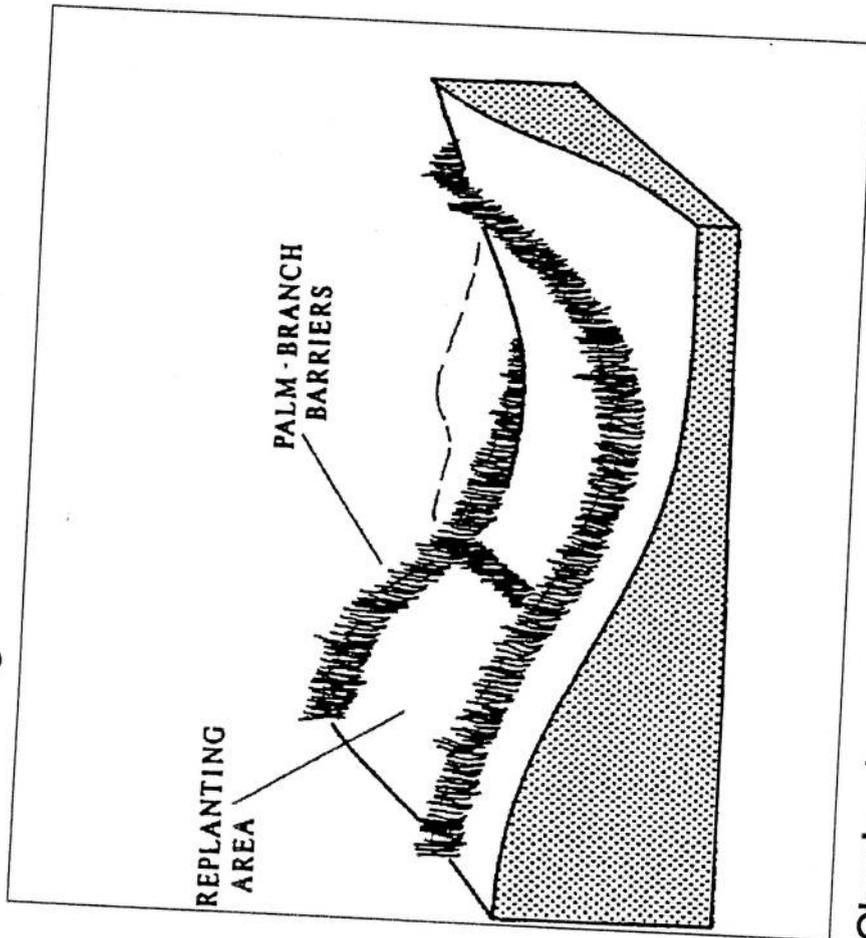
Checker-board system.
Source: Gaye (1987).
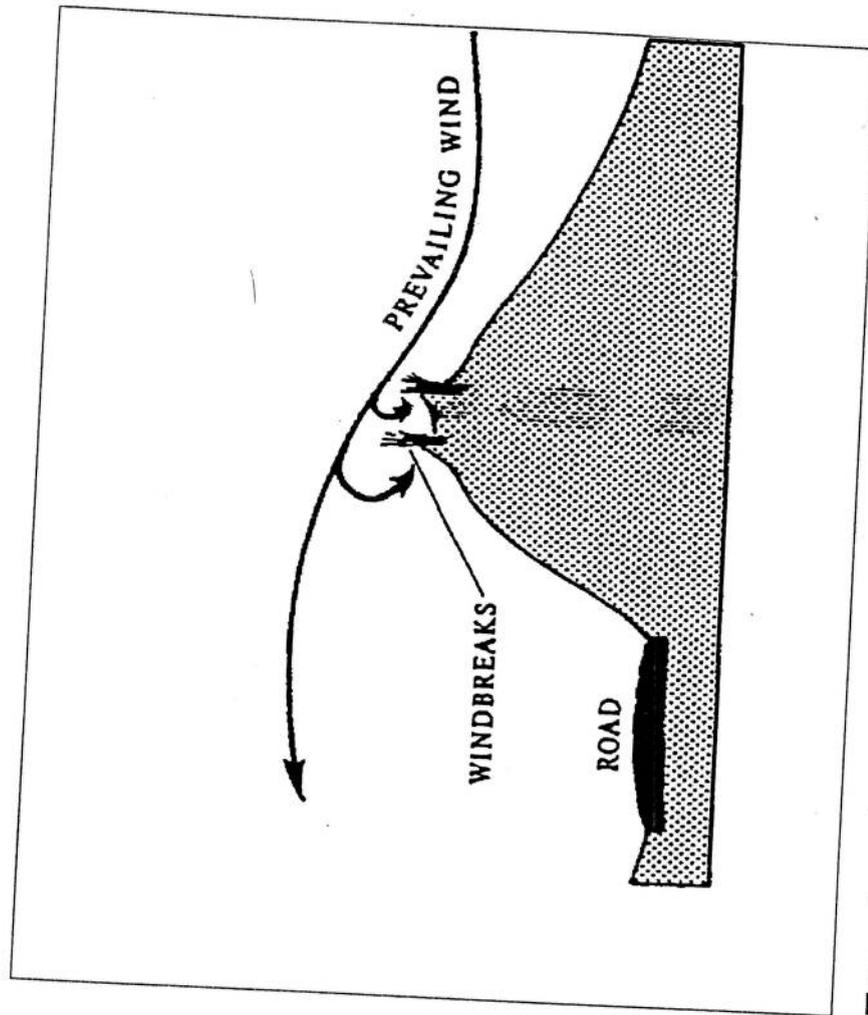
Fore-dune built by fences (windbreaks).

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As described in paragraph 5.6.3, establishing vegetation on sand dunes will be hindered by certain limitations such as water, wind and the physical and chemical properties of sand itself. The author stresses that dune sand depth and suitable plant species choice should also be considered as major determinants of vegetation establishment on dunes.

5.7.4.1 Dune sand depth

Walls (1982) reported that where irrigation is possible and dunes are no higher than 10 m with depressions between them, plants for protection against sand are generally arranged in belts and patches. Sand dunes are thus surrounded and partitioned off, and dune movement halted. Even without further measures, dunes 4-5 m high will decrease 1-2 m in height within three or four years. Kebin and Kaiguo (1989) recommend that tree shelterbelts have to be planted behind mobile dunes to erode their upper parts. When the tops of the dunes have been reduced, they too are planted with shrubs. Later, trees can be planted among the shrubs.

5.7.4.2 Irrigation

Supplementary irrigation is sometimes used for trees and shrubs planted for dune fixation (El-Houri, 1989). Irrigation at the initial establishment stage may be required for the plants' survival until they have sufficiently deep root systems. If water is not available in adequate quantities for long term irrigation, it is advisable to irrigate at least during the first two or three months, after planting, at weekly intervals (FAO, 1989a). From field experience the author has found that when rainfall is negligible, irrigation is essential. Its duration depends on ground water availability and its level below the surface. There are two factors that determine the length of the irrigation period required: First, groundwater depth and second, soil structure, as loose soils allow free percolation of water and easier growth of tree roots.

5.7.4.3 Choice of species

Plants used for sand stabilization must often cope with prolonged droughts and very high summer temperatures, in addition to sand mobility during periods of high winds (Pye and Tsoar, 1990). Tree species suitable for dune fixation must have a well developed root system which is capable of deep vertical penetration to reach the lower moisture layers of soil, or of considerable horizontal spread to take maximum advantage of the scanty precipitation (Kaul, 1985). It is essential to select trees species which have growth rates greater than the rate of sand accumulation and which also have a bushy shape (Watson, 1990). From observation and experiments Bendali *et al.* (1990) showed that desert plants which do not have deep root system cannot survive on shifting sand.

5.7.5 Combining different stabilization techniques

Effective control often requires the combination of mechanical and vegetative techniques. The building of parallel and grid-like barriers, usually made of dead plant material, clay and asphalt felts, to halt moving sand, is often carried out first. Shrubs are then planted in the centre of the grids (Kebin and Kaiguo, 1989; Gaye, 1987). Moomen and Barney (1981) reported that in Libya bitumen is applied in a layer about 2-3 mm thick immediately after a good rain (annual rainfall 300 mm). Survival of trees in treated areas has been about 20-30% greater than on comparable areas using barriers.

5.8 Discussion

Although in recent years the techniques described have proved effective in many situations, Finkel (1959) reached several interesting and controversial conclusions from field work and experiments with barchan dunes in Peru:

i) The control of wind-blown sand may have no effect whatsoever on the rate of dune movement.

ii) Dunes cannot be tolerated in the same way as blown sand might.

iii) Source areas are often very distant, so stabilization of the sand source may prove impractical or impossible.

iv) Ditches are useless since they fill with sand almost immediately while having little effect on dune morphodynamics.

v) Mechanical disturbance is often ineffective.

vi) Physical barriers are also ineffective.

vii) Vegetative stabilization techniques are usually impractical because they require irrigation.

viii) Techniques that reduce the height or volume of the dunes may merely aggravate the problem by increasing the rate of advance.

The author's own view is that sand dune control in desert regions has never been an easy task. It is important to mention that several of the methods discussed above are not just theoretical hypotheses, but are the result of the experiences of many workers in this field, and have been reported as successful measures. Finkel's views are therefore probably the result of specific local conditions which made success particularly difficult. Shelter-belts and wind-breaks (mechanical) assume great importance in North Africa because of the need to fix dunes and protect agricultural land and human settlements. About 282,000 ha are already under the protection of various types of stabilizing techniques (FAO, 1989b). For example, vegetative measures such as shelterbelts or dune fixation practices have been established successfully in the Sudan where the water table can be 15 metres below ground surface

(e.g. Ibrahim, 1991). Also, different types of fences have been used successfully with the involvement of voluntary community participation to protect their houses and agricultural lands. High levels of commitment from the beneficiaries have been reported where it is their last resort (Laird, 1990). In Mauritania, a combination of methods has been used, including mechanical stabilization and dune fixation by planting at sites under particular threat where mobile dunes have completely buried homes, roads and agricultural lands. The results have been successful and the local people were able to move back after the sand had been cleared and the dunes stabilized (Gaye, 1987). According to Grainger (1990) in Senegal shelterbelts of *Eucalyptus camaldulensis* and *Acacia* trees were planted on mobile dunes. Woven brushwood panels of the local shrub *Guiera senegalensis* were established on the windward of the dunes to protect the planted trees. Rows of trees were planted at spacing of 2-3 metres starting at a distance of 20 metres from the panels. The work has been considered a substantial achievement in dune stabilization. Eckholm (1975) reported that Algeria is setting an example with it's bold plan to plant a 15 km wide great barrier all the way across its 1500 km expanse. On the other hand, Stewart (1993) argued that the climatic effects of the Green Dam will not be felt more than a few kilometres away, and northern Algeria will go on turning to desert wherever over-exploitation and deforestation continue to degrade the environment. The author believes that the protection of dune plantations and the conservation of natural dune vegetation are the first priorities for success. For example, in Tunisia as reported by Novikoff (1976) the stabilized vegetated dunes are grazed by animals in the dry season. With excessive overgrazing and destruction of trees, the dunes have started to move.

According to Tagel-Din (1986) in the extreme arid climates such as the Western Desert of Egypt, mobile dunes cover vast areas. In this case, protective methods are almost impossible, because vegetative stabilization can only be done with permanent irrigation, which is not feasible due the scarcity of water in the region. As the application of chemicals is costly, he added that even if the dunes within the oases were fixed at a high cost, there still remained an unlimited source of mobile dunes that could invade and cover the stabilized dunes. He recommends the only economical way to handle the migrating dune chains is to get out of their way.

Each method has its advantages and disadvantages. The adoption or rejection of any method should not be necessarily based on its technical aspects only. There are other criteria that govern the decision such as the method's costs and the value of the area in need of protection, and the attitude of the local population.

Chapter 6: Sand Dune Encroachment and Stabilization in the Sudan

6.1 Introduction

Sudan is the largest country in Africa, covering some 2.5 million km^2 and stretching from 4° to 22° N. It has a population of approximately 23 million (1986) and an annual population growth rate of 2.2% (El-Mangouri, 1990). The area threatened by desertification and mobile sand dune hazards lies between 12° to 18° N, extending across the country from east to west. It includes northern parts of Kordofan and Dar Fur, and the Nile valley up to the Egyptian border between 30°-32°E (figure 4), covering a total area of 650,000 km^2 (El-Karouri, 1986). This area (the study area) will be discussed further with emphasis on sand and sand dune genesis and movement, and the control measures adopted so far.

6.2 Climate

The climatic contrasts within the Sudan reflect the great N-S extent of the country and can be explained in terms of the migratory Inter-tropical Discontinuity (I.T.D.) at different times of the year (Walsh, 1991). The rainfall within the study area ranges from 75 mm in the north to about 400 mm in the south (El-Karouri, 1986). At Jebel Tageru (16°N to 17°N) and the greater part of Wadi Hower the annual rainfall is less than 50 mm. At Malha (figure 10), the annual rainfall varied between 53 and 326 mm in a measurement period of 16 years (Neumann, 1987). The relative humidity in the area for most of the year is below 20%. Summer shade temperatures can regularly reach 45-50°C, and soil surface temperatures in full sun can reach 70-80°C (Bristow, 1989). Also, El-Karouri (1986) stated that the annual potential evapotranspiration in the extreme north is over 2500 mm. Thus, the whole region suffers from a large water deficit, the annual water balance being -2500 mm. The seasonality of the rainfall, its variability and unreliability as well as the general water deficit combine to to make this region vulnerable to desertification and dune movement.

6.3 Desert encroachment

In several areas of Northern Kordofan and Northern Dar Fur, moving sands and sand dunes from the Libyan Desert have degraded consolidated sandy clay rain-fed lands and some settled areas (El-Karouri, 1986; El-Mangouri, 1990). Also the whole of the north and north-east-facing banks of the Nile in the Northern Province are now seriously threatened by encroaching sand, where sand dunes are engulfing productive agricultural lands and human settlements (Rapp, 1976; Bristow, 1989; Ibrahim, 1991). In northern Sudan, major rivers which in the past had eroded large valleys, have dwindled and dried up, have become choked with mobile dunes (Mitchell, 1991). The

Figure (10)
THE SUDAN
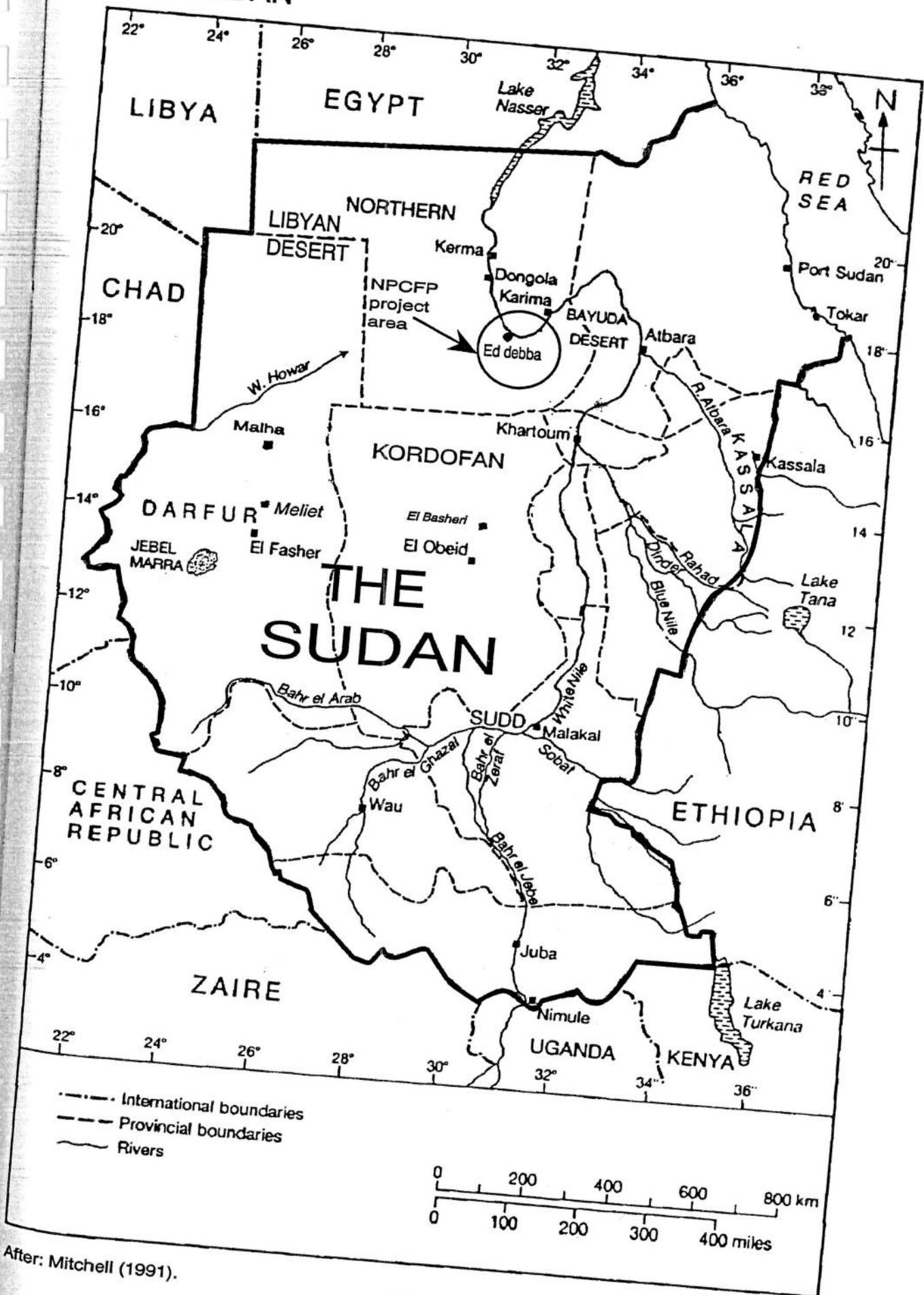
After: Mitchell (1991).

importance of the protective role of natural vegetation cover which has been expressed by several other authors, is that the process of desertification and sand dune movement has been exacerbated by the removal of ground vegetation, which exposes sandy soils to wind movement and leads to sand accumulation.

6.4 Sand dune types in the Sudan

Broadly two main types of dunes can be identified in the region; the fossil fixed dunes in Kordofan and Dar Fur, and the mobile dunes further in the North. At some sites the fixed dunes are reactivated by the removal of vegetation, presumably by the recent droughts and human activities.

6.4.1 Fixed dunes

Andrew (1948) stated that the *Qoz* is an accumulation of dune-sands consisting almost entirely of quartz-grains derived from the Nubian series. During the early Pleistocene period the limits of the *Qoz* to the north were found to be on the frontier with Libya (19^ON and 24^OE) and near Wadi Howar. Grove and Warren (1968) assume that dune sands forming the *Qoz* have been derived partly from the Umm Ruwaba beds and associated thinner deposits that formed during the Pleistocene period.

Fixed dunes border the White Nile right bank between Hshaba and Jebel Aulia, and occupy about 160,000 ha. They extend for over 150 km between latitude 14° 15' and 15° 15'N, and near El Geteina dunes extend up to 20 km from the river (Williams, 1968). They probably originated as channel deposits laid down by the former sandy tributaries of the Blue Nile. At about 6000 BP discharge diminished, perhaps due to climatic change, and the channels became redundant. Their bed loads were resorted by wind action (Williams, 1966; Williams and Adomson, 1974).

6.4.2 Mobile dunes

In the Sudan, the chief geological formation is the continental Nubian sandstone which covers about one-quarter of the country (Mitchell, 1991). In the Northern Province, Jensen (1993) considered the origin of mobile dune sand to be from the Nubian sandstone. The quantity of sand coming to the area varies considerably from site to site according to the nature of the Nubian sandstone situated upwind. He also stressed the importance of topography, where valleys may concentrate the transport of sand, while mountains may produce shelter. The author agrees with this opinion, where the complex barchanoid dunes in the area, for example, in Argi, were attributed to the deposition of sand in the lower old river flood basin from the surrounding plateau, which is relatively higher.

6.5 Pilot projects for dune fixation

A thorough and well founded plan for analysing and counteracting desert encroachment in the Sudan was worked out by the General Administration for Natural Resources in 1975. Three representative sites were proposed in the mobile zone for experimentation in sand dune fixation, two in Kordofan (El-Basheri and Umm-Badir) and one in Dar Fur (Meliet). The project has been operating since 1969/70. It is based on the protection of dunes from grazing, the planting of *Acacia senegal* and other tree species and facilitating the growth of grass between them (Rapp, 1976). On the other hand, rehabilitation of natural vegetation on Kordofan fixed dunes has been tried using the enclosure system. Rapp (1976 quoting Kassas, 1970), stated that although plant growth varies in response to annual rainfall, protection is only partial and fences are often broken through, there is a tendency toward improvement of plant cover.

6.6 Sand dunes in the Northern Province

The area most affected by sand drift and mobile dunes in the Northern province, lies on the eastern bank of the main Nile bend (figures 10 and 11). The author assumes that dune development determining factors were all represented in the area. The Nubian sandstone which is considered to be the parent material, stretches across 200 km upwind (Jensen, 1993). Winds are mainly unidirectional N and NW for most of the year (Table 1).

Table 1: Monthly dominant wind direction and mean wind speed (10 years) for Atbara, Karima and Dongola

| Month	Atbara		Karima		Dongola	
	Dir	mile/h	Dir	mile/h	Dir	mile/h
January	N	6	N	11	N	11
February	N	7	N	11	N	11
March	N	6	N	12	N	11
April	N	5	N	11	N	11
May	N	4	N	11	N	11
June	N	5	NNW	10	N	11
July	SW	5	NNW	9	N	9
August	SSW	5	N	9	N	9
September	SSW	4	N	9	N	11
October	N	4	N	9	N	10
November	N	5	N	12	N	11
December	N	6	N	11	N	10

Source: Jensen (1993).

The inevitable result is that great sand drifts dominate the area and mobile dunes, mainly barchans and transverse forms, are the main dune types (plate 1). Massive lee dunes extending from escarpments, and echo dunes behind jebels, hills and buildings are also common features in the landscape.

The author believes that the abundance and continuity of sand drift and dune movement in one direction from N to S is reasonably explained by Bagnold (1941) who stated that the mean wind direction indicates indirectly the direction of sand movement. However, sometimes, strong winds from the opposite direction for short periods may cause a notable sand drift and significant changes in the shape and orientation of dune forms, but normally such changes do not last for long periods and the dune shape and net advance rate are always governed by the dominant winds which are Northern and North-eastern. Periodical monitoring of sand dune movement carried by the Northern Province Community Forestry Project (Implemented by the Sudan Government and SOS Sahel in 1988 and still running) at the project sites (figure 11), showed that an average advance rate for El-Hau barchans (up to 6 m high) is 30 m year^{-1}, and El-Rekabia barchans (up to 10 m high) is 20 m year^{-1}. Relatively lower rates had been recorded for the barchanoid complex dunes at Argi (up to 40 m high) where the advance rate is only about 5-10 m year^{-1} (NPCFP, 1993). The author considers the massive lee dunes in the lee of the nearby escarpments and jebels as a source of sand for barchans and dome dunes. It has been observed on the upwind side of Argi, Affad and north of El-Bar (figure 11) that small barchans and dome dunes are calved from the ends of the longitudinal lee dune at the point where the effect of shelter is no longer significant.

6.6.1 Historical background of sand dunes

The history of the area shows that sand drift and sand dunes are not new events. Traditionally, local people of the Northern Province used to cope with the sandy environment by self-learning and inherited knowledge. In some places they have managed to initiate their own control techniques that have helped them to avoid or fix moving sand and sand dunes on a limited localized basis. For example, the invention of round or elliptical building designs instead of the normal square ones, have been observed in many of the villages of the province. Very old high foredunes built by fences have been seen at Abkur and Tergis villages. Wind dissipating panels made of local wooden materials and protective mud walls are common in Kuri and Rekabia villages.

Figure (11):
Site of The Northern Province Community Forestry Project, Sudan
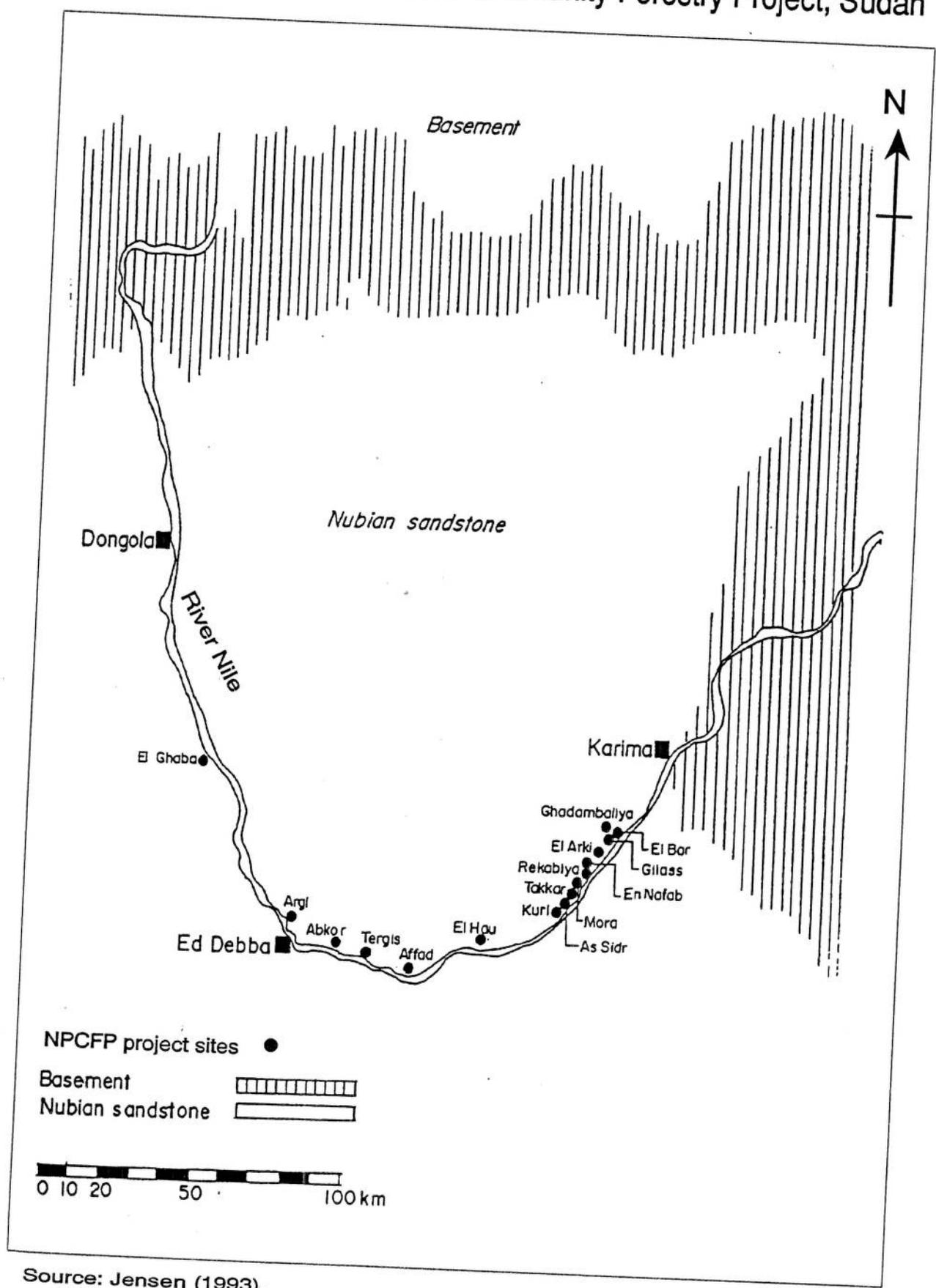
Source: Jensen (1993).

6.7 The Northern Province Community Forestry Project (NPCFP)

This project in the Ed-debba area is jointly funded and implemented by the Government of Sudan and the British NGO SOS Sahel. Project activities include seedling production, shelterbelt planting, dune fixation and training the local community in these activities, with follow up by extension services. The NPCFP has adopted several techniques to control moving sand and mobile dunes. Major limitations to the project strategy are the low level of precipitation (less than 50 mm y^{-1}), physical features specific to the project area, and the project budget, all of which lead to the exclusion of some of the techniques mentioned in the previous chapter, for example, the control of sand drift and sand dunes at the potential source areas. A system of mechanical and biological control has been implemented in the project area which will be discussed further.

6.7.1 Mechanical barriers

The erection of mechanical barriers in the project area is usually done for either of two purposes; first, the building of foredunes, which is implemented only on a limited scale, because they need a long-term commitment in terms of continuous maintenance with careful management. Second, the erection of mechanical fences as a necessary stage before tree planting in shelterbelts and dune plantations.

6.7.1.1 Fore-dune fences

This type of fence is practised on a very limited scale, mainly where the fertile agricultural land is in acute shortage and threatened by mobile dunes and sand drift. The local people have traditionally applied this system for example, in Abkor and Tergis. Sometimes the farmers use this system to clear some of the buried fertile land. As a general rule, fences designed to build foredunes are made to be of low porosity (but not less than 20%) to minimize sand spilling on the lee side of the fence. Materials used from the available local vegetation in the area, include date and dom palm fronds, *Leptadenia pyrotechnica* and *Tamarix* branches.

6.7.1.2 Windbreak fences

These are usually used in flat terrain before planting seedlings in shelterbelts. The system is widely accepted because of its notable effect on increasing survival rates of the planted trees (up to 20% increase). These fences break the wind force, and prevent leaf defoliation and stem abrasion by saltating sand particles. In the case of the NPCFP it has become a prerequisite for planting in open lands. One of the advantages of this system is that it can be abandoned as soon as the planted trees are established. From field observation, NPCFP has found that the three row fence system is more effective and, therefore, is highly recommended when fencing material is available. Material used

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is more or less similar to the foredune fences, the only difference is that some strong posts of local material will need to be erected at reasonable distances to support the fence which, in most cases, is installed on a hard surface or where there is little sand. The porosity of the fence needs to be no less than 50% to allow the trapping of sand on both the windward and the leeward of the fence. This high porosity is needed to extend the life-span of the fence long enough before renewal.

6.7.2 Biological fixation

The use of trees to control drifting sand and mobile dunes is more sustainable where the planted trees become self renewing barriers. In the project area there is no reliable precipitation, and so irrigation sources need to be identified before the planting of trees. The ground water table is another factor to be considered, as with deep ground water more time for irrigation will be needed before establishment is attained. Generally, the water table lies at a depth of 8-15 metres. Moisture is usually found at about 2 metres above the level of the water table (Ibrahim, 1991).

The author divides the types of plantations in the project area into two groups: First, shelterbelts on levelled terrain, and second, trees on sand dunes.

6.7.2.1 Shelterbelts

The purpose of planting shelterbelts is to prevent sand from invading agricultural lands and residential areas. One type of shelterbelt is located close to farm lands, by the edge of the fertile land at the foot of the dunes or drifting sand to provide immediate protection. These are locally known as *internal shelterbelts*. The second type of shelterbelt is located further to the back of the properties requiring protection, in an attempt to trap the moving sand and dunes far enough from the agricultural land and houses. These are locally known as *external shelterbelts*.

In the case of *internal shelterbelts* (plate 2), establishment is relatively easy, where the fertile and moist soil accelerates the growth of seedlings, and in addition to that the effect of wind blasting and desiccation are found to be at a minimum. Irrigation is required only for a short period at the first stage for no more than 6 months, and normally such small amounts of water are provided from the farm irrigation source. These shelterbelts are well protected from damage by animals as they are in the vicinity of the farms.

The *external shelterbelts* (plate 3), which are relatively far behind the village and farms, and have more difficult growing conditions. The soil is poor, the water table in most cases is relatively deep and the wind energy is high and loaded with sand causing burial, defoliation and blasting of the newly planted seedlings. Irrigation requirements are much greater due to the high rates of evapotranspiration compared to *internal shelterbelts*. Windbreak fences here are crucial before planting seedlings. The

optimum distance for fences from the nearest row of seedlings has been found to be about 12 metres for fences of 1 metre high. Irrigation techniques in use are either furrows receiving water from a shallow well with pump (a matara), or pit irrigation using portable water source e.g. lorry tanker, horse cart or manual irrigation. The selection of any of these depends on the topography and the scale of the proposed shelterbelt. Normally, establishment is achieved between 15 to 24 months, with frequent irrigation throughout the period, starting with intensive irrigation (e.g. once a week) at the early stages, extended to one irrigation fortnightly after the first four months. By the end of the first year, the irrigation interval is extended to once a month as the tree roots will be approaching the ground water table.

Tree species used in the internal and external shelterbelts are dominated by *Prosopis chilensis* locally known as "Mesquite", which was introduced from South America more than 60 years ago (Bristow, 1989). On a limited scale other species were tried such as *Acacia tortilis*, *A. nilotica*, and *Prosopis juliflora*. Generally, the Acacias have lower rates of growth compared to "Mesquite".

The effectiveness of these shelterbelts is very high, as they trap almost all the surface moving sand. The land to the lee of the shelterbelts is kept clear of sand, because the wind at this point is free of sand. It has been observed that with an increase in height of these shelterbelts more sand will be cleared. Some data on sand deposition in these shelterbelts is shown in table 2.

Table 2: Accumulation of sand within and behind shelterbelts and sand fences at some selected sites in the project area:

Locality	Accumulation volume m^3/ml	Period months	Speed of accumulation m3/ml/year
Affad internal shelterbelt	11.30	43.00	3.15
Affad external shelterbelt	5.60	6.00	11.20
Affad/Tergis shelterbelts	26.00	24.00	13.00
Takar external shelterbelt	3.60	3.00	14.40
Mora external shelterbelt	3.00	6.00	6.00
Weighted mean	7.24		

ml = metre length along shelterbelts.
Source: Jensen (1993).

6.7.2.2 Tree planting on sand dunes

As has been described in para. 5.7.4, it is not possible to plant vegetation on mobile dunes while they are still in motion. The use of fences here is a prerequisite for planting. From field work and experiments the NPCFP has revealed that the survival and establishment of trees is only guaranteed on dunes no more than 4 m high. On the other hand, due to the poor fertility of dune sands, the project has adopted the local technique of adding loamy soil. The fertile soil is packed in pits dug in the shape of cylindrical columns in wetted sand, about 20 cm in diameter and 60 cm in depth before planting. A significant difference in survival rates of about 15-20% had been observed in the treated sites.

Irrigation is possible only by portable means including lorry tanker and portable storage tanks due to the undulating nature of the dunes. The amount of water added is between 40 to 60 litres per plant at each irrigation for about 2 years. Irrigation starts with short intervals of once a week at early stages, and extends to once a month after 2-4 months. On his consultancy to the NPCFP, Jensen (1993) recommended the use of 200 litres of water once at the planting stage, instead of periodical irrigation in small amounts. This has not yet been tried.

The most popular type of dune plantings are the inter-dune shelterbelts. The farmers prefer this type of shelterbelt because it is easy to establish and has the advantage of opening some of the buried fertile land, which can be used for small scale agriculture and date palm orchards. Plate 4 shows an example of inter-dune shelterbelts.

The species used in dune planting is almost entirely *Prosopis chilensis* which is well adapted to arid conditions (El-Houri, 1986). Other species include *Leptadenia pyrotechnica*, *Tamarix nilotica* and *Salvadora persica* which have only been used on a limited scale.

6.7.3 Cost benefit analysis

A cost benefit analysis study for the project was carried out by Ibrahim *et al.* (1992). It showed that the costs of establishing internal shelterbelts are low compared to the other shelterbelt types. The costs of the external shelterbelts using furrow irrigation from a shallow well (a matara) are less than those where irrigation is by lorry tanker. However, the latter had the advantage of reaching planting sites which are not feasible for furrow irrigation. On the other hand, the storage tanks which are fed by a lorry tanker are the most expensive, therefore their use is justifiable only for the most difficult sites, and those that have a higher priority for stabilization.

Generally, vegetative stabilization techniques have a relatively high cost when compared with local incomes. However, costs of other stabilization methods such as

mechanical and chemical, are significantly higher still. In the case of the NPCFP the costs of vegetative methods were found to be acceptable when compared to the value of the agricultural land being protected. There is no available information on dune stabilization costs from similar sites for comparison.

Plate (1)
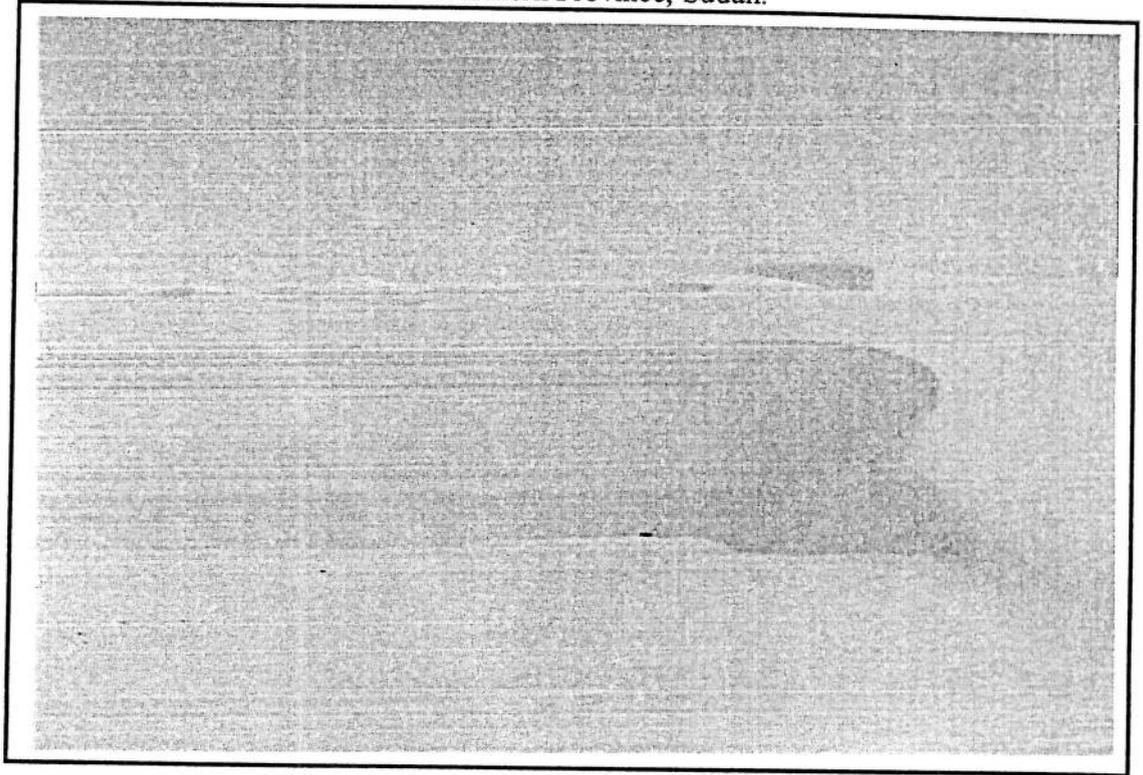Barchan and Transverse dunes- Northern Province, Sudan.

Plate (2)
Internal shelterbelt between the foot of the dunes and the agricultural lands- an example from Argi village, Northern Province, Sudan.

Plate (3)

External shelterbelts with irrigation channel appear on the foreground- an example from Affad village, Northern Province, Sudan.
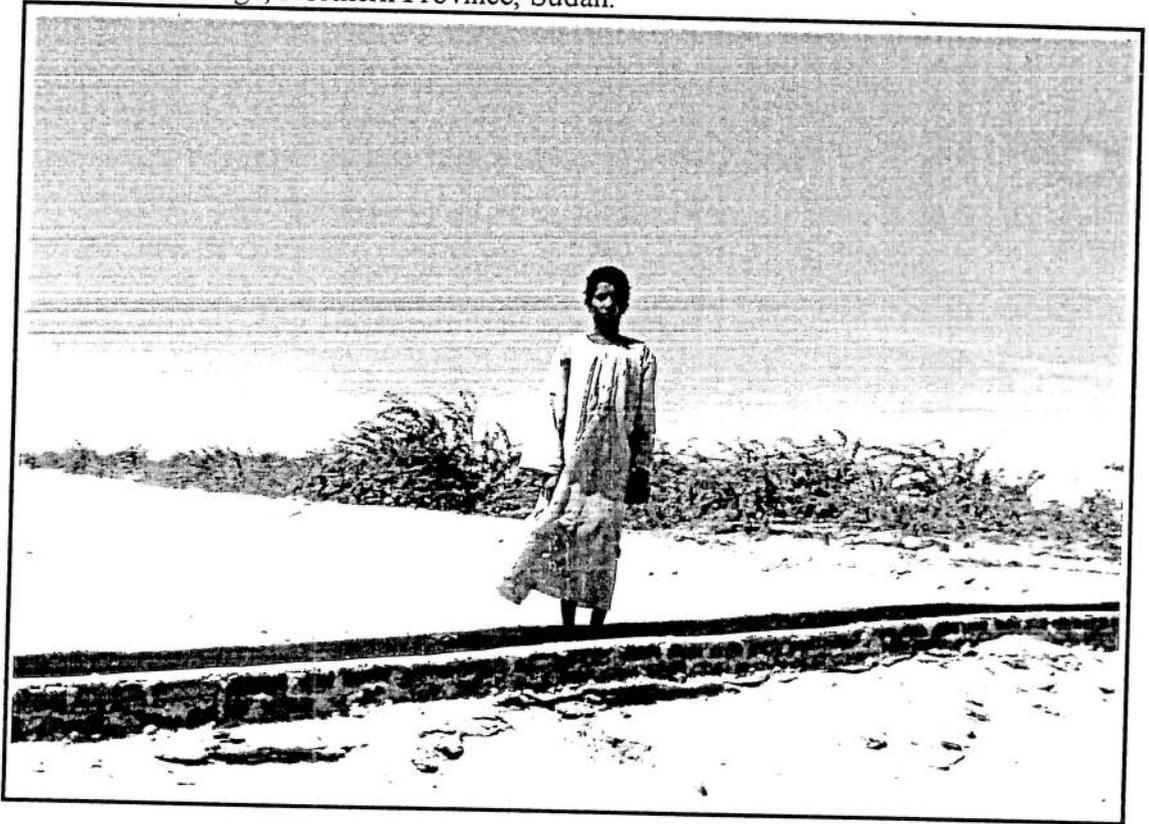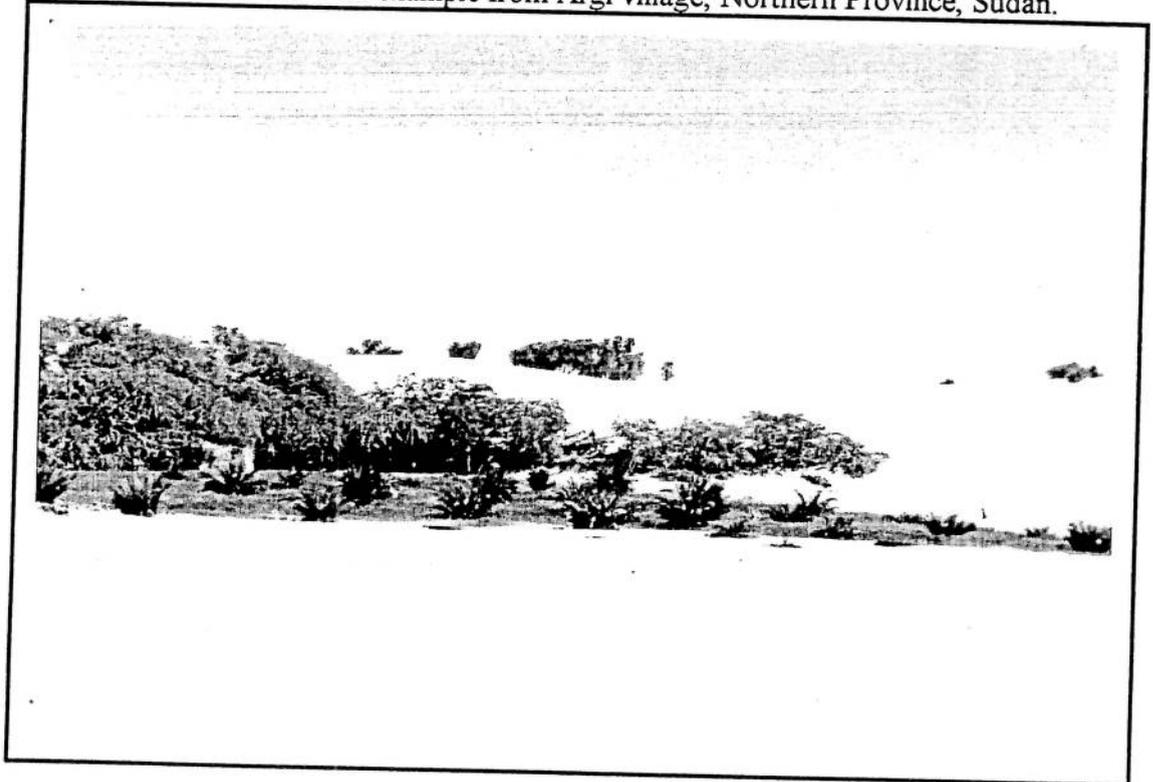

Plate (4)

Inter-dune shelterbelts- an example from Argi village, Northern Province, Sudan.

Chapter 7: Conclusions and Recommendations

7.1 Conclusions

Dune genesis remains one of the least understood components of aeolian geomorphology, but once having occurred the interactions between a dune and the atmospheric boundary layer will tend to result in the perpetuation of the dune form unless there are determinant changes in sediment availability or climate.

The degree and nature of dune activity is closely related to dune type, formative wind regimes and sand supply. Barchan and transverse dunes can be considered as migrating forms, linear dunes as sand-passing or extending forms and star dunes as sand-accumulating forms.

The rate of transverse and barchan dune migration is generally a function of the wind-determined total sand transport potential, together with dune size.

The orientation, direction and magnitude of most palaeo-form fixed dunes is attributed to ancient climatic conditions.

Only limited and scattered data on desert sand movement are available at present.

The success of any sand control scheme is dependent upon detailed monitoring of sand flow and dune dynamics. This includes mapping of geomorphological features and characteristic vegetation cover from aerial photographs or satellite imagery. Such information may be supplemented with field checks and meteorological data in order to estimate potential rates of sand flow.

Identification of wind direction is of great importance for implementation of dune fixation programmes. Usually, unidirectional wind regimes are relatively easy to deal with, while multidirectional wind regimes often complicate dune patterns, and relatively sophisticated control measures will be required.

In desert regions with strong winds and abundant sand supply, a complete arrest of sand and sand dunes has often proved very difficult.

In areas where intense sedimentation occurs, enhancement of sand deposition or transport may be impractical or impossible.

In the case of mobile dunes on a limited scale, the best remedy to the problem is their removal. However, this is not always practical. In practice they must be either dissipated or immobilized. Because of the threat from drifting sand, destructive procedures can be implemented only with dunes at some distance from a facility. Those dunes that pose an immediate threat must be immobilized by treating their surfaces. The way in which this is undertaken depends upon economic and environmental considerations.

Employment of fences, or vegetation belts, constitutes a commitment to dune building. The accumulation of sand will continue indefinitely and the fences or trees must be maintained accordingly.

The most common types of fences are those made from plant material that is locally available. For large projects a supply problem is likely to occur in most areas. There is also the problem that the removal of too much vegetation from a given area for fence construction purposes may diminish the protective function of that vegetation, so that new dunes start to move where others are being stabilized.

For protection from drifting sand the three fence system in conjunction with shelterbelts between the last fence and the area in need of being protected has shown in the Sudan to be very effective and long-lasting at comparatively low costs.

Permanent stabilization of dunes can only be achieved by the development of vegetation cover of the entire dune area.

Plant species with shallow roots are less successful on mobile dune types, where species with anchoring tap roots are able to tolerate both deflation and accumulation of sand.

Effective dune stabilization requires the combination of mechanical and biological methods at least for the initial phase of vegetative growth.

The destruction of natural vegetation cover can lead to rapid sand movement. Traditional grazing systems accelerate erosion mainly on fixed dunes. The enclosure system has proved to be effective and is highly recommended in sensitive dune areas.

7.2 Recommendations

Regular monitoring of dune movement rates and direction is recommended if good protection is to be obtained.

For most palaeo-form fixed dunes, recent meteorological data should be obtained for any intended control activities in such sites where such dunes have been reactivated.

In the case of strong winds and abundant sand supply, the long-term solution is to design facilities in a way to allow the free movement of sand across them.

In areas where intense sedimentaion occures, it may prove preferable to identify the main sources of sand and stabilize the deflating sand body.

Chemical sand stabilizers are not recommended without subsequent planting of vegetation cover, because they only last for a limited period.

Vegetative stabilization of dunes is highly recommended where trees and other vegetation cover can become a self-renewing measure. This method has the potential for long term cost effective control of moving sand.

Detailed ground water surveys should be undertaken prior to drawing up afforestation and shelterbelt plans for vegetative dune fixation programmes.

Irrigation is the most costly item in vegetative fixation of dunes and is required wherever rainfall is insufficient. Better techniques to economize in the use of water will be necessary if the high costs of dune stabilization are to be reduced.

More research work is required on vegetative dune stabilization, particularly in the selection of suitable plant species and plant irrigation requirements.

More research is required on mechanical dune fixation, especially the selection of reasonably cheap non-plant materials.

Sand dune stabilization efforts are less likely to be successful if implemented in isolation from local communities. Therefore, it is most important to consider the motivation, training and participation of local residents for long-term maintenance and conservation of such programmes.

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