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Sand Dune Stabilization in the Thar Desert of India: A Synthesis

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Abstract : Sand dune stabilization programme in the Thar desert of India is based on an understanding of the edaphic characteristics of the dune-interdune systems, as well as on the soil-water-plant relationships of the major dune types. A number of physical and chemical methods of stabilization have been tried during the last four decades. It has been found that the more lasting effects are achieved through a careful plantation of trees, shrubs and grasses at appropriate sites and using proven technologies. There is, however, a need to further refine the techniques to suit the different dune environments and to make the venture economically more viable.

Key words : Thar desert, dune ecology, chemical stabilization, physical stabilization, biological stabilization.

Sand dunes cover extensive area of the Thar desert which lies between the Aravalli hill ranges in the east (in Rajasthan state of India) and the Nara river in the west (in Pakistan). In India, the northern limit of the Thar is along the Indo-Gangetic plains in the states of Haryana and Punjab and its southern limit is along the north Gujarat plains. Sand dunes of many different types have been recognised in the Thar, the major ones being the longitudinal (linear), transverse, parabolic, network, star, barchan and barchanoid, with height ranging from ~2 m to 50 m or more (Kar, 1993). Low sand streaks and sandy hummocks are also numerous. Based on their age of formation, sand dunes have been classified as the dunes of 'old system' and 'new system' (Pandey *et al*., 1964). Usually the high sand dunes are of old system. These were formed in an earlier dry climate and have a greater stability than the dunes of new system which are forming now.

The major causes of the formation of many low sand streaks, sandy hummocks and barchans are over-grazing, faulty agricultural practices, including ploughing along the dune slopes, as well as destruction of natural vegetation cover on dunes and sandy plains for fuel and fodder. Such activities are also leading to the advancement of old dunes in many parts of the desert. In fact, very high human and livestock densities in the desert are leading to mismanagement of the sandy terrain, causing sand reactivation and land degradation. The total area affected by sand drift in Rajasthan, Gujarat and Haryana states is estimated as 88,078 sq. km. The ultimate result is sand encroachment upon productive agricultural fields, human habitations, canals, roads and railway tracks. In order to control the menace of sand drift it is necessary to undertake effective sand dune fixation programme.

Ecology of Sand Dune Ecosystem

For successful fixation of inland sand dunes it is necessary to understand the ecology of sand dune system, particularly factors affecting soil-water-plant relationship. Success of biological sand dune fixation largely depends upon the delicate balance between the availability of soil moisture and its use for plant growth over a period of time. This balance has to be considered in the context of climatic, edaphic and hydrological factors vis-a-vis plant adaptability as it influences the choice of plant species and the planting techniques, viz., direct seeding vs. transplanting, age of seedling, spacing, depth of planting, etc.

Climatic characteristics

The climate in the Thar desert is characterized by extremes of variation in diurnal and annual temperatures, scarce and erratic rainfall and high evaporation. Drought, due to lack of moisture, is quite frequent. Monsoon arrives here by the last week of June or first week of July. The annual rainfall varies from as low as 100 mm to 150 mm with 11 dry months in the west (Jaisalmer in Rajasthan) to 400-450 mm with 9 dry months in the east (Sikar in Rajasthan; Mahendragarh in Haryana). Bulk of the rainfall occurs during the south-west monsoon season between June and September with a peak in August. Although not much rainfall is received in the desert, the atmospheric humidity is unusually high and is comparable to that in places of higher rainfall in the semi-arid and sub-humid zones (Krishnan, 1968). The mean monthly temperature during the hottest months (May and June) is 40°C, but it often goes as high as 45°C which is very detrimental for plant growth. In this period dry and hot dust-raising winds, popularly known as '*loo*' and duststorms (*andhi*) occur very frequently (Krishnan, 1977). The potential evapo-transpiration during summer varies from 7 to 9 mm day^{-1}. Winter is very cold. Normal minimum temperature varies from 1°C to 5°C and in exceptional cases, it goes down to as low as -4°C. In severe winter, frost occurs frequently.

Edaphic characteristics

Physical : Dune soils are single-grain, noncoherent and structureless, and are, therefore, highly erodible. Their apparent specific gravity ranges from 1.62 to 1.75 as compared to 1.4 to 1.5 in the case of other soils. The total pore space is, therefore, less in the dune soil and the pores are of very large size.

As a result, during rainfall or irrigation, water movement is free and rapid (infiltration rates being 10 to 16 cm h^{-1}), leading to heavy percolation losses. Water retention capacity of dune sand is very low, ranging from 4.0 to 6.0% at 0.1 bar and 1.5% at 15 bar. The available water holding capacity of the dune sand ranges from 3.0 to 4.5% (w/w).

Pores being of large size in sand, there is negligible unsaturated hydraulic conductivity; these are too big to hold any water against the force of gravity. Therefore, the only places where water can be held in sand are the spaces where pores acquire sufficiently narrow size. This is possible at points of close contact of sand grains with each other. Since such pore spaces account for only a small fraction of the total pore space, the dune soils have field capacity values of 3.5 to 6.0% only. This gives them a moisture retention capacity of 50 to 90 mm m^{-1} depth. Of this, 12 to 20 mm is too tightly held to be available to plants. The maximum water that can be retained by these soils is 38 to 70 mm m^{-1} depth (Dhir, 1985).

There is hardly any crust formation on shifting sand dunes due to low percentage of silt and clay, whereas, on stabilized and semi-stabilized sand dunes, soil crust is formed because of the presence of organic matter and algal growth. Gupta (1976) reported that the soil crust so formed on these sand dunes at Bikaner attained a strength of 3 to 4 kg cm^{-2} which provides stability to these dunes.

Chemical and microbiological : Even though insufficiency of soil moisture is a limiting factor in plant establishment and subsequent growth, soil fertility is important for

Table 1. Certain chemical characteristics of dune soils of Bikaner

Locality/ stabilized & unstabilized dune	pH	E.C. (mmhos cm^{-1})	O.C. (%)	N (%)	C/N (ratio)	P (%)	NH_4+NO_3 N (ppm)	NH_4+NO_3 N of total N (%)
Beechwal								
Stabilized								
0-30 cm	8.7	0.07	0.10	0.009	9.9	0.013	30.8	34.0
30-60 cm	8.5	0.07	0.04	0.014	3.6	0.020	22.4	16.0
Unstabilized								
0-30 cm	8.9	0.07	0.30	0.006	5.0	0.013	30.8	50.0
30-60 cm	8.5	0.08	0.03	0.011	2.7	0.020	26.0	–
Sheobari								
Stabilized								
0-30 cm	8.6	0.09	0.12	0.015	7.8	0.020	35.2	16.8
30-60 cm	8.8	0.07	0.04	0.004	9.8	0.025	22.4	51.0
Unstabilized								
0-30	8.7	0.08	0.03	0.006	5.2	0.025	28.0	46.6
30-60	8.8	0.07	0.02	0.006	2.7	0.007	28.0	46.6
Shrikolayat								
Stabilized								
0-30 cm	8.7	0.09	0.09	0.014	6.4	0.013	30.8	22.0
30-60 cm	8.7	0.09	0.07	0.015	4.7	0.025	25.2	16.8
Unstabilized								
0-30 cm	8.2	0.10	0.02	0.005	4.6	0.025	33.6	67.0
30-60 cm	8.5	0.12	0.03	0.007	4.4	0.020	36.4	52.0

Source : Aggarwal and Lahiri, 1981.

an optimum utilization of this limited moisture. Aggarwal and Lahiri (1981) reported that in both the stabilized and unstabilized dunes EC was comparable, but pH varied between 8.2 and 8.9 (Table 1). Although the organic carbon content was generally low in stabilized dunes, it was consistently more than that in unstabilized dunes. The surface soils of stabilized dunes had marginally higher organic matter compared to that in the subsurface. The C/N ratio was nearly 10:1 in the surface soils of stabilized dunes, but quite low in the subsurface layers (2.7 to 4.7). This suggests slow, but a definite trend of soil fertility improvement, at least in the surface layers of the stabilized dunes with a possible involvement of microbial activities, despite the prevalence of high temperature, low soil moisture (Lahiri, 1964) and hazards of wind erosion. Venkateswarlu and Rao (1981) showed an increase in C/N ratio in stabilized dunes. Population of fungi, actinomycetes and bacteria were considerably higher in the stabilized dunes than in the unstabilized dunes.

A study by Dhir and Gajbhiya (1973) on the distribution of various major nutrient elements revealed that the soil in the immediate vicinity of grass clumps had nearly 25 to 40%

Table 2. Nutrients depletion/addition as affected by sand movement under different land use conditions from 5.4.77 to 24.6.77

Locality/ Treatment	Sand depletion/ addition (t ha^{-1})	Nutrients (kg ha^{-1})				
		Organic matter	Total nitrogen	Mineral nitrogen	Total phosphorus	Total potassium
Beechwal						
Bare sandy plain	-1449.0	-724.5	-115.90	-44.9	-231.8	-2159.0
Pearl millet stubble	-22.5	-38.3	-2.25	-0.7	-3.8	-34.9
Grass	+13.5	+35.8	+1.62	+0.4	+2.7	+22.4
Udairamsar						
Bare unstabilized sand dune	-5560.5	-2780.0	-333.60	-166.8	-1000.0	-6282.8
Stabilized sand dune	+151.5	+2121.0	+227.30	+30.3	+333.3	+1818.0

more humus, phosphorus and potash than in the soil away from the rhizome. Under an arid environment, the plants, particularly the trees, utilize nutrients perhaps from the deeper soil layers, and enrich the fertility of surface soil, possibly through a nutrient cycling mediated by vegetal residues. In other words, the soil in the immediate vicinity of the plant has higher contents of available form of various nutrients. Studies by Gupta and Aggarwal (1980) showed that maximum sand depletion took place from bare unstabilized sand dunes (5560.5 t ha^{-1}), followed by bare sandy plains (1449.0 t ha^{-1}). Fields with grass cover and stabilized sand dunes recorded accumulation of sand (13.5 t and 151.5 t ha^{-1}, respectively). The trends were similar in the case of organic matter, total N, mineral N, total P and total K (Table 2).

Soil-water-plant relationship of shifting and stabilized dunes

Singh and Shankarnarayan (1986) reported higher moisture on the leeward side of sand dunes as compared to their windward side. Moisture content was also higher at the crest. These variations may be due to the nature and thickness of sand and the size of sand grains. Sand dune fixation studies carried out in the late 50s and the early 60s (Bhimaya *et al.*, 1961; Kaul, 1970) revealed that soil moisture regime in shifting dunes (without vegetation) was more favourable as judged by the increased establishment and growth of the planted seedlings, compared to the semi-stabilized (with vegetation) dunes. The accumulation of soil moisture in shifting dunes may be due to absence of transpiration losses and the mulching action of the loose surface sand (Lahiri, 1977). Studies by Krishnan *et al.* (1966) revealed that in the unstabilized (shifting) sand dunes, a sharp discontinuity in moisture content occurred in the layer 1.5 to 2.0 mm below the soil surface. Below this layer, the soil moisture reached more than 5% by weight (i.e., field capacity) throughout the year. However, in the stabilized sand dunes, the moisture content up to 3.0 m depth was generally less than 1.5%, although the moisture content, as such, increased with depth. The moisture below 3.0 m profile in stabilized dune was highly variable due to the differential extraction pattern of trees, shrubs and grasses over the stabilized sand dunes.

Since the moisture status of the profile is influenced by the rainfall received during the rainy season (i.e., July to September), soil moisture contents during the rainless period (i.e., October to June) are of particular interest. In unstabilized (shifting) dunes, reasonably high soil moisture may be encountered within 5 to 30 cm of the surface, while in stabilized dunes, moisture content above the permanent wilting point may be found (Mann *et al.*, 1976; Table 3). Thus, unstabilized dunes offer better soil moisture condition for plant establishment and growth and also support the usefulness of deep planting in shifting sand dunes as is being practiced in Israel (Kaplan *et al.*, 1970) and in Egypt and Yemen (Costin *et al.*, 1974). Deep planting also provides favourable temperature for root growth during summer at the early stages of plantation.

The low unsaturated state hydraulic conductivity of sandy soil not only influences the rate of evaporation but also the rate of soil moisture movement within the profile and its utilization by vegetation. Since the inter-site movement of moisture is very small, the degree of moisture utilization in dunes will be, to a large extent, dependent upon the degree of direct access of the roots to the points of entrapped moisture. Bhimaya and Kaul (1965), while studying root systems of *Acacia senegal*, *Albizzia lebbek*, *Prosopis cineraria* and *Tecomella undulata*, reported that the rooting pattern of these species in different soil types was somewhat different. It was also observed that the root morphology may change with changes in environmental conditions. On undisturbed dunes, Kaul (1970) observed that *Acacia tortilis*, which develops lateral roots at a much greater depth in other soils, developed a deep root system

Table 3. Soil moisture (%) status of unstabilized and stabilized dunes at different times of the year in Barmer (recorded 1963-64)

Depth (cm)	March		September		June		January	
	Unstabilized	Stabilized	Unstabilized	Stabilized	Unstabilized	Stabilized	Unstabilized	Stabilized
0-5	0.3	0.1	0.0	0.1	0.4	0.8	0.9	0.1
5-15	0.9	0.3	1.9	0.5	0.8	0.5	0.8	0.3
15-30	3.2	0.8	2.3	0.3	1.5	0.8	1.5	0.1
30-45	2.8	0.4	2.8	0.7	1.7	0.9	2.4	0.4
45-60	2.6	0.8	3.1	0.8	2.1	0.8	2.1	0.4
60-75	3.5	0.5	2.6	0.6	2.7	1.4	2.4	0.3
75-90	2.8	0.7	3.3	0.9	3.9	1.7	2.2	0.6
90-105	2.6	1.1	4.3	0.9	2.2	1.3	3.4	0.4
105-120	3.3	1.6	3.8	1.1	4.3	0.9	4.2	0.8
120-135	3.2	1.7	4.1	1.3	3.3	1.0	4.8	0.7
135-150	3.6	1.5	4.2	1.6	3.4	2.6	3.7	0.9
150-165	4.1	2.0	5.1	1.5	3.2	3.1	4.2	1.2
165-180	4.7	1.8	5.8	1.4	3.5	2.0	5.5	1.3
180-195	5.1	2.1	5.0	1.6	4.1	2.2	4.2	2.2
195-210	4.8	1.9	5.1	1.7	5.0	1.9	5.0	2.3
Moisture content (mm) upto 105 cm depth	41.0	10.2	44.8	10.3	33.3	16.9	33.5	6.6
Moisture content (mm) upto 210 cm depth	105.6	38.5	119.5	33.3	93.6	47.9	104.9	27.7

Source : Mann *et al.*, 1976.

with extensive spread of lateral roots relatively close to the surface, perhaps to make use of surface moisture for initial establishment and active growth. During the remaining dry months the deep root system helps in extracting moisture from deeper layers. Therefore, plants having a fibrous root system are better suited to sandy habitats.

Vegetation

Various stages of development or degradation of plant communities on sand dunes are encountered in the Thar desert. Out of those stages, Saxena (1977) reconstructed the successional pattern of natural vegetation (Fig. 1). According to him, *Cyperus arenarius, Aristida funiculata, Cenchrus biflorus, Tribulus terrestris, Citrullus colocynthis, Indigofera cordifolia, I. argentea, Farsetia hamiltonii, Crotalaria burhia*, and *Aerva pseudotomentosa* are the colonising species. Initially, a large-scale coverage by *Crotalaria, Aerva* and *Cyperus* sps. brings about the stabilization of sand to a great extent. This makes the substratum more suitable for succession of undershrubs, shrubs and perennial grasses, e.g., *Sericostemma pauciflorum, Leptadenia pyrotechnica, Clerodendron phlomoides, Calligonum polygonoides, Calotropis procera, Panicum turgidum, P. antidotale, Lasiurus sindicus* and *Cenchrus ciliaris*. Subsequent stabilization and undisturbed conditions bring about *Acacia jacquemontii, Lycium barbarum, Balanites aegyptiaca* and *Maytenus emarginatus*. The last three species form the penultimate stage for the climax community of *Prosopis cineraria*. The grassland development in the low-rainfall zone (below 300 mm) gets arrested up to *Panicum turgidum* type only, whereas, in the higher-rainfall zone (above 350 mm), the same stage is surpassed by *Saccharum* species. The highest grass community is represented by *Saccharum bengalense*.

From the foregoing discussion, it is apparent that with increasing depth in the unstabilzed dunes, soil nutrient depletion is greater, soil moisture content is higher and soil temperature decreases faster, as compared to those in the stabilized dunes. Likewise, soil fertility also declines more with depth in the unstabilized dunes. These observations are of considerable significance for further refinement of the technology for greening sand dunes.

Stabilization of Sand Dunes

Prerequisites for sand accumulation and dune building include wind velocity above a threshold that induces sand movement, availability of sand prone to erosion and presence of an obstruction around which moving sand tends to accumulate. The formation of dunes may be prevented or slowed down by adopting measures like : (a) reducing the velocity of wind by erecting barriers, (b) restricting sand movement through chemical sprays, and (c) encouraging the development of vegetation that binds sand. Depending on the convenience and the availability of materials, dunes have been stabilized through use of water, chemicals and sealants, erection of physical barriers and through afforestation.

Water is a fairly good stabilizer for short period. Frequent watering leads to formation of crust that can tolerate erosive force of average wind speed. This practice may be adopted in regions where water is available and the area to be stabilized is limited.

Chemical stabilization

Sand dunes have been fixed through spraying of byproducts of petroleum on dune surface, use of chemical mulches and sealants. Ben Salem (1985) reviewed the techniques and the products available for sand dune stabilization.

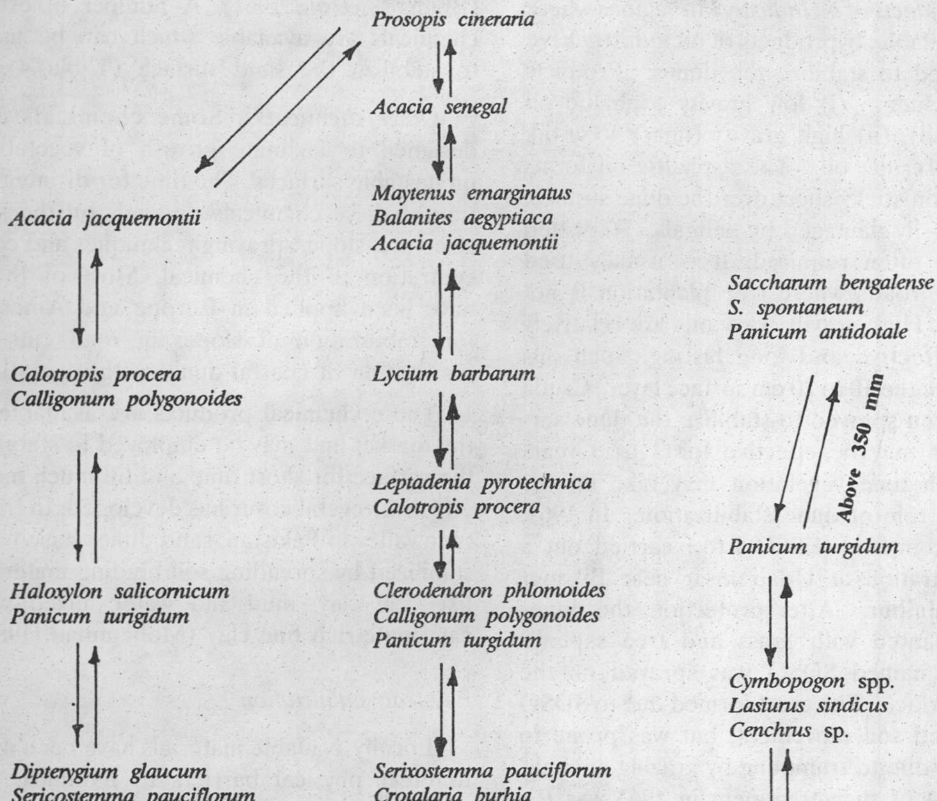

Fig. 1. Stages of development/degradation of plant communities on sand dunes (Source : Saxena, 1977).

Byproducts of oil industry : In regions where oil is available, byproducts of oil industry have been used to stabilize the dunes. Products used include: (i) low gravity asphaltic oil (heavy oil), (ii) high gravity (light) waxy oil, and (iii) crude oil. The asphaltic oil forms a thin, non-sticky sheet over the dune surface, but is easily damaged by animals. Repeated spray is often required. It is usually used near the roads where tree plantation is not possible. High gravity waxy oils are relatively more effective and long lasting. Such oils penetrate the 10 to 20 cm surface layer. Crude oil is often sprayed to stabilize the dune surface. It may be effective for 2 to 3 years by which time vegetation may take up the primary role of dune stabilization. In 1963, an oil company (ESSO Ltd.) carried out a demonstration at Udairamsar near Bikaner and at Jaipur. After protection, the dunes were planted with grass and tree saplings and oil named SDSO was sprayed on the dune surface. The crust formed due to SDSO prevented soil movement, but was prone to damage due to trampling by grazing animals. The cost of such treatment in 1963 was Rs. 184 ha^{-1} as against Rs. 197 ha^{-1} for conventional vegetative method developed by CAZRI (Bhimaya *et al*., 1961). A number of other chemicals are available which can be used to stabilize the sand surface (Table 4).

Other chemicals : Some chemicals are designed to facilitate growth of vegetation on unstable surfaces. The time for disintegration of these chemicals depends on the soil structure, slope, spraying techniques and concentration of the chemical. Most of these have been applied in Europe and America for stabilization of slopes in road cuts or for fixation of coastal dunes with vegetation.

These chemical products are available in the market and may be employed to stabilize the surface for short time and till much more effective vegetal cover has developed. In Mastung valley in Pakistan, sand dunes have been stabilized by spreading soil binding materials like fine clay, mud and water mixed with carbonate-rich fine clay (Mohammad, 1988).

Physical stabilization

Locally available materials have been used to erect physical barriers to minimize the wind velocity and prevent sand movement. These usually include parts of locally available plants or other wastes like rail road sleepers,

Table 4. Major chemical products available in the market and their characteristics

Market name	Form	Application	Rate of application	Effect
Sand stop	Powder	Spray	20-25 g m^{-2}	Powder absorbs moisture and forms a coating
Uresol 156 E	Colourless liquid	Spray	Concentration in water between 3.4 and 6.4%; 1.5 L m^{-2}	Penetration from 4-5 mm aggregate formation
Uresol 310 EA	Clear, pale yellow	Spray	–	–
Hulus 801	Dark-brown concentrate of white emulsion	Spray	10-40 g of concentrate for 2 L of water 10-15 g m^{-2}	Solidifies within 2 hours by reacting with SO_2
Agro fix	Milky white	Spray	30-50 g m^{-2}	
Unosol	Latex base product	Spray mixed with crude oil and after dilution with water	150 g m^{-2}	
Texand D	Mesh of very fine strands		5 g m^{-2}	

Table 5. Pattern adopted and materials used to erect microwind breaks in certain countries

Country	Design	Material used
India	Checkerboard (2 to 3 m^2)	Local material : *Leptadenia pyrotechnica, Ziziphus nummularia, Calligonum polygonoides, Lasiurus sindicus, Panicum turgidum, Erianthus munja*
Iraq	Checkerboard (2 to 5 m^2)	Palm posts 80 cm long
Libya	Checkerboard	Burrying 15 cm deep, stalks of dry grass/stubble. *Imperata cylindrica, Aristida pungens, Artemisia herba-alba*
Madagascar (Coastal)	Parallel strips 250 cm apart	0.75 to 5.09 m high *Aleos sisa*
Poland	Checkerboard	1 m high palisades of local brushwood, straw, etc.
Romania	Parallel rows	Reed fences
Somalia	Parallel rows (15 m apart)	Local plant material, *Comniphora bilderbrandtii, C. muyrrha, C. gowlello* and *Besamotnamnus busseanus*
Sudan	Checkerboard (6 sq. m)	Dry branches of *Leptadenia pyrotechnica*
Syria	–	Branches of *Pinus brautia* used for mulching dune surface
Tunisia	Parallel rows (200-300 m apart)	Palm branches, now often replaced by asbestos, cement corrugated sheets
Yemen	Parallel rows (20 40 m apart or checkerboard)	Dry reed fencing (palisades), 0.5 m high

telephone poles, used oil drums, etc. When these materials are inserted vertically in the ground, called 'palisades', they act as micro-wind breaks and when spread over the surface, called 'thatching', they act as mulching and prevent sand movement. Kaul (1985a) listed the different types of barriers being used the world over (Table 5).

Mechanical dune fixation is effective and has been applied over extensive areas in most of the developing countries. It is, however, labour-intensive and is therefore slow. In countries where labour is in short supply, mechanical dune fixation will prove costly.

Biological stabilization

Establishment of vegetative cover on sand dunes is often the best, most permanent and the most effective method of stabilization. Before any attempt is made for afforestation, it is imperative to undertake preplanting measures so that sand movement is minimized. These measures prevent burial of seedlings due to sand deposition and exposure of roots due to soil loss.

Planting technique : Before planting of vegetation on sand dunes, the usual practice is to erect long parallel barriers (or micro-windbreak) of low height, using locally available plant material. The barriers are put at 5 m to 10 m interval across the prevailing wind direction. Where wind direction is variable, cross-barriers are also erected, thus creating a grid pattern. The pattern, i.e., distance between parallel lines and the size of checker board and the height of barriers, depends on a number of factors like velocity of wind, steepness of slope and type of sand dune. The sand within the grids/squares is usually stable enough to allow establishment of the transplanted seedlings. At times castor is sown as a nurse crop. It serves as a micro-windbreak, and in addition provides extra income through sale of castor seeds.

In the interdune plains sand movement is not much and, therefore, no micro-windbreak is erected.

Species selection : While selecting plants for afforestation the species having the following characters are desirable : (a) a mixture of plants having deep vertical roots to tap moisture from lower moist zone, and those having surface roots that can take advantage of moisture in the surface layers after light showers, and at the same time, possess high root binding index, (b) ability to withstand abrasive action of blown sand and high wind velocity without being uprooted, (c) ability to tolerate extremes of temperature, both frost and hyperthermia, and (d) capability of self regeneration. Kaul (1985b) listed trees, shrubs and grasses commonly used in afforestation programmes in different countries.

Seedling production : In deserts, the period of favourable soil moisture regime is extremely short. To take maximum benefit of this favourable soil moisture, it is desirable to develop a nursery to raise the seedlings. It should be ensured that regular water supply is available in the nursery and that it is near the site of plantation. Seedlings may be developed, depending on their availability, in polythene tubes or earthen tubes or in beds. The sowing in nursery should be done so as to get saplings of desirable age/height at the time of transplantation in July.

Planting time : In order to ensure a higher survival rate, the planting of seedlings in Haryana and in Indira Gandhi Nahar Pariyojna (IGNP) Stage II areas in Rajasthan is done after the onset of rainy season (July to September), when the sand is moist. In IGNP Stage II areas, planting is done from July to October. It can even be done as early as April and May, since adequate irrigation facilities are available, and take the full advantage of the following rains.

Planting depth : Experiments carried out at Bikaner have shown that planting 35 to 40 cm deep resulted in higher seedling survival (Kaul, 1983). In Haryana and Rajasthan, the standard practice is to plant in pits 40-45 cm deep. Since soil moisture increases with depth, it is important that planting be done as deep as possible, depending upon the tolerance of species to deep planting. For example, in Israel, large-sized balled nursery stock of *Acacia cynophylla* is planted at least 60 cm deep in the sand with only the upper two to three leaves emerging (Mayerson, 1961). Costin *et al*. (1974) obtained better results by deep planting (up to 150 cm down) of long cuttings of *Tamarix aphylla*, having diameters not less than 1.5 to 2.0 cm in the upper part of the dune. They found that it was economical to resort to shallower (50 to 70 cm) planting in depressions, with deep planting on high sites, e.g., 80 cm to 120 cm on slopes and 150 cm on high dunes.

In the interdune plains where hard pan exists close to the surface, it is necessary to break the pan to a depth of at least 45 cm to 60 cm by a tractor auger for better seedling establishment and growth.

Espacement : The fluctuations in the moisture regime of sand dune at different sites, the water consumption of plant species, their root system characteristics, and purpose of plantation should be taken into consideration while determining the spacing of plants. As a rule of thumb, the lower the rainfall and longer the dry period, the wider the spacing to be adopted to minimize competition for moisture and to reduce development of high moisture stress in plants. In the case of *Acacia tortilis* and other tree species, a spacing of 4 x 2 m has been adopted, while in the IGNP Stage II area, the spacing is 3 x 3 m. In other areas of Rajasthan, a spacing of 5 x 4 m is adopted. It has, however, been felt that a spacing of 4 x 4 m would be more appropriate for IGNP Stage II areas (Soni, pers. com.). Observations have, however, revealed that *Acacia tortilis,* in spite of irrigation for four years, has not put on commensurate growth. It is, therefore, suggested that instead of raising pure plantation of *A. tortilis*, it should be planted wide apart and in the intervening spaces *Calligonum polygonoides* and *Lasiurus sindicus* may be planted, as these are the dominant components of the natural vegetation of the area. These species are equally effective in controlling sand drift and in providing fodder and fuelwood. In interdune areas, a spacing of 5 x 5 m is usually adopted. In the areas with annual rainfall of 100 to 150 mm, a wider spacing needs to be adopted.

Watering : The scarcity of water may make raising of irrigated plantations difficult. In exceptionally dry years, life-saving irrigation of seedlings becomes necessary for survival and for the development of sufficiently deep root system to tap available soil moisture. The sand should be deeply moistened to prevent the development of superficial roots which would later die. No information is available on irrigation water requirement of transplanted tree seedlings except for neem seedlings under Jodhpur conditions (Burman *et al.*, 1991). Its importance is generally realised and such watering has even been practiced in Haryana and Rajasthan, by adopting arbitrary norms. For example, in the region receiving 248 to 393 mm annual rainfall in Haryana, three waterings at the rate of 16 L $plant^{-1}$, one at the time of planting, the other in October, and the third during December-February, are given. Even though a provision for two waterings of plants in the second year and one in the third year has been made, these irrigations are generally not required if timely planting of well developed healthy seedings is done. This amount of water makes the sand moist down to a depth of about 25 cm. A thin layer of dry sand should be spread around the seedlings after each watering, as it acts as mulch and reduces evaporation losses.

It is felt that until the research results are obtained relating to actual water availability in the field, such as how much water the trees really need, when and for how long it is needed, and how long a tree can survive without irrigation in different months of the year, several plant water-stress indicators can be used as a general guide to irrigation requirement, viz., darkening of leaf colour in some species, curling or changes of angle of leaves, and reduction of stomatal aperture (Armitage, 1985).

It has been observed that growth of planted seedlings on the windward slope of the dune varies in relation to site. This variation is shown in Table 6. The variation in seedling growth is possibly due to variation in soil moisture content at the four sites. The variation in moisture content at different sites is due to the nature and thickness of the sand and the size of sand grain (Singh and Shankarnarayan, 1986).

Table 6. Seedling growth performance in relation to site

Growth	Sites on windward slope of dune			
	1/3 from heel upward I	Mid II	1/3 up to the crest III	Interdune flats IV
Excellent		X	X	
Good	X	X		
Poor	X			X

In the interdune plains, the presence of hard pan near the surface contributes to poor performance of seedlings. Deep soil working, as mentioned earlier, will considerably improve seedling performance.

Inter-culture operations : In the initial stages, when the root growth of the plant is limited, there will be competition for moisture with weeds. Therefore, in Haryana, three weedings and hoeing in the first, two in the second and one in the third year, have been prescribed. If the plantation has been properly raised, no weeding and hoeing is generally required in the second and the third year of planting. If other vegetation is vigorous during the second year, it becomes necessary to undertake weeding. In Rajasthan, however, no weeding or hoeing has been prescribed.

Casualty replacement : As a normal practice, a provision of 20% is made for casualty replacement. It has, however, been observed that replacement planting in the second year, even if it survives, does not put on growth and tends to stagnate. All efforts should, therefore, be made to achieve as high a percentage of seedling establishment as possible in the year of planting itself. This should be possible particularly in the IGNP Stage II areas where provision of copious irrigation has been made. The calendar of activities for planting seedlings and grass slips is given in Fig. 2.

Aerial seeding

The Indira Gandhi Canal passes through vast stretches of parched (100 to 150 mm rainfall) dune country. Due to sand-laden wind, this prestigious canal is getting covered by invading sands. The less accessible dune track with low moisture is so large that it will take too long to afforest it by the conventional methods. With the assistance of the National Wastelands Development Board, Ministry of Environment and Forests, aerial seeding was, therefore, undertaken in July 1987 at two sites having average annual rainfall of 250 mm and summer temperature 47°C. Of these two sites, 300 ha was taken near village Sardarpur and 400 ha near village Motigarh, located 50 to 60 km north-west of Bikaner on Bikaner-Anoopgarh road. Both the areas were fenced. Dune crests and windward slopes were covered with 3 x 3 m checker board mulch, which was prepared by burying the *Crotalaria burhia* bushes upside down.

Since the aim was to provide a silvi-pasture system, a mixture of four tree species, viz., *Acacia tortilis*, *Colophospermum mopane*, *Prosopis cineraria*, *Ziziphus rotundifolia*, one shrub, viz., *Dichrostachys nutans*, one creeper, viz., *Citrullus colocynthis* and one palatable grass, viz., *Lasiurus sindicus*, were selected. A seed rate of 14 kg ha^{-1} for the seed mixture of tree, shrub and grass was used. Tree and shrub seeds were treated with dilute sulphuric acid, washed in running water, and soaked in aldrin. *Lasiurus sindicus* seeds were pelletised in mixture of clay, sand and cowdung.

Based on evaluation of the two-year data, it was concluded that afforestation of inaccessible dunes and sandy wastelands is possible with aerial seeding technology, provided seeds of suitable species in appropriate mixture are broadcast in monsoon, adopting all pest control measures (Shankarnarayan and Kumar, 1988). Chances of success will no doubt increase if the aerial seeding happens to coincide with a good rainfall year. Early attempts of aerial seeding at Gadra Road in Barmer district (100 mm rainfall zone) were, however, not successful because of the unfavourable climate, unpelletised seed used, and no treatment for repelling pests or predators (Bhimaya, 1977).

Higher seed germination, better seedling survival and excellent vigour were recorded on bare dune crests which were aerially seeded in July 1987. This indicates that the direct

Activities	Year for advance action												Year I												Year II												Year III											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Survey, layout & demarcation									**	**	**																																					
Purchase of tools and plants										**	**	**	**	**	**																																	
Fencing by angle iron & barbed wire	**	**	**																																													
Mulching on dune																		**																														
Raising nursery seedlings									**	**	**	**																																				
Raising grass slips	**	**																																														
Purchase of fertilizer, insecticides, etc.										**	**	**	**	**	**																																	
Purchase/collection of seeds							Seasonal																																									
Seed sowing along mulch lines																																																
Transport c plants from nursery to site																		**	**	**	**	**									**	**	**	**	**													
Digging of pits, planting and first watering																			**	**	**	**										**	**	**	**													
Planting of grass slips																																																
Casualty replacements																						**	**									**	**	**	**													
Subsequent watering																				**		**	**		**	**		**						**		**	**		**							**		**

Fig. 2. Calendar of activities for planting tree seedlings and grass slips on shifting sand dunes and interdunal plains.

seeding from aircraft is successful on bare dunes which are in fact adding to and accelerating the menace of wind erosion. This is so because bare dunes maintain a favourable water balance even long after the rains are over (Gupta, 1979). Further, there is no competition for moisture from other vegetation.

Economics of Dune Stabilization

Cost

It is difficult to give average figures for the cost of sand dune fixation through afforestation as expenses are likely to vary from region to region.

The per ha cost of sand dune afforestation for a period of three years in Haryana works out to Rs. 7,770 and for Rajasthan, Rs. 6,810. In the case of sand dune fixation in the IGNP Stage II area, the cost per ha for a period of eight years was worked out as Rs. 16,127.

Production

The absolute value of plantations established to protect people, habitations, other structures, roads, fields, or canals from invading sand, is often difficult to asses. However, recent studies by Upadhyaya (1991) have revealed that one and two-year- old plantations reduced sand deposition by 0.513 m^3 and 1.023 m^3 per running metre length of the canal, respectively. In economic terms, these plantations saved cost of desilting by Rs. 6,156 per km in one-year-old plantations and Rs. 12,276 per km in two-year-old plantations. The following information on firewood and fodder yield from treated dunes gives a fair idea of their production potential.

Bhimaya *et al.* (1961) reported that at the end of fifth year of afforestation, shifting dunes produced 15 and 20 t ha^{-1} wood in regions receiving 200 and 360 mm rainfall per annum, respectively. Studies by Kaul and Ganguli (1964) revealed that sand dunes afforested with *Prosopis juliflora*, in areas receiving annual rainfall of 150 to 250 mm, produced 15 t ha^{-1} of firewood at the end of the fifth year. Bhimaya *et al.* (1967) reported wide variations in fuel wood yield with respect to age of the trees and habitat. Differences in fuel wood yield between the habitats generally followed the pattern of rainfall.

The performance of *Acacia tortilis* on sand dunes has been very encouraging. At Barmer (280 mm rainfall), the seven-year-old trees had attained an average height of 7 m and the average expected yield at the end of 10 years was in the order of 25 t ha^{-1}. Muthana (1980) reported a fuel wood yield of 30 t ha^{-1} from *A. tortilis* planted on sand dunes. In Haryana, *A. tortilis* plantations have recorded a mean annual increment of 3.0 to 3.5 m^3 ha^{-1} on stabilized dunes and about 4.5 m^3 ha^{-1} on shifting dunes (Jakati, pers. comm.). Fuel wood yield from stems and branches of *Calligonum polygonoides*, which grows extensively on sand dunes and reaches the size of a small tree in seven years, ranges from 13 to 28 kg $tree^{-1}$, with an average of 19 kg $tree^{-1}$ (Kaul, 1965).

In the case of perennial grasses, the optimum forage yield in well established plots of *Lasiurus sindicus* and *Cenchrus* sp. was recorded up to 3.6 and 4.7 t ha^{-1}, respectively (Ahuja, 1977).

Research Needs

Although the techniques developed to stabilize sand dunes through biological methods have been successful, a few questions still remain to be answered in order to further refine the technology.

Seedling survival and subsequent growth largely depend on the availability of soil moisture. Optimum spacing for different species of trees, shrubs and grasses at the initial and subsequent stages of growth is, therefore, to be determined in relation to optimal utilization of the available soil moisture. In this context, thinning schedule may go a long way for sustainable vegetal growth.

At present, five to nine-month-old seedlings are being planted. Feasibility of planting tall transplants of different tree species need to be explored in relation to seedling survival and subsequent growth, their capability to grow without mulching, operations necessary for survival and subsequent growth of small size seedlings, and the cost effectiveness of planting such tall transplants need to be studied.

Relatively little comparative work has been done in relation to irrigated tree crops. The current practice seems to be based on trial and error or on subjective experience and judgement. Standardization of irrigation schedule for areas where water is available, is an important aspect of study in deciding the optimal irrigation, amount of water at each application, irrigation efficiency and seasonal water use.

Development of suitable silvipasture/silvihorticulture models for shifting sand dunes in different rainfall regions is essential so that information on species compatibility, geometry of planting and management practices can be made available to farmers for application.

Potential productivity in relation to the many-sided protective and productive functions of different dune types, when afforested, need to be worked out for developing economic criteria.

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