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Research Article

Conserving the threatened woody vegetation on dune slopes: Monitoring the decline and designing adaptive strategies for restoration

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Abstract

The southern tip of the Thal desert in Pakistan harbors the remnants of the original tropical thorn forest, amounting to two percent, which covered the province of Punjab a hundred years ago. In the past three decades, there has been a progressive decline in woody species cover on dunes, which is directly related to the increase in population in the surrounding area. Stabilized and destabilized dunes were subjectively selected followed by quantification of cover and diversity of woody species on the top and lower slopes. Dunes closely resembling the overall cover were grouped to suggest corresponding restoration measures. The results suggest that trends of decrease in cover and diversity of woody species were evident in the upper slopes of some stabilized dunes having less than 50% cover. The destabilized dunes with less than 20% cover are highly vulnerable to erosion. A general trend observed among dunes was that with a decrease in the cover of upper slopes, there is a decrease in the cover on lower slopes. The number of destabilized dunes is increasing without effective restoration measures against the prevailing trends of disturbances. Ranking dunes on the basis of cover could help in proposing simple restoration measures as a first step towards developing an understanding of designing adaptive strategies to restore the woody cover.

Key words: Anthropogenic factors, conservation, desertification, restoration, threatened tropical thorn forest

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Introduction

Although pervasive economic incentives to support human settlement are regarded as underlying causes of destruction and vulnerability in fragile arid lands, they are still being unabatedly pursued in developing countries (GOP 1992; Basso et al. 2000; Bakr et al. 2012). Aerodynamics models of interaction between wind, vegetation, and topography indicated that warmer temperatures can amplify the impacts of drought, making dunes more susceptible to mobilization (Wasson and Nanninga 1986; Lancaster 1988; Shumack et al. 2021; Kamel-Eddine 2022). Research in technology transfer, knowledge of local people, and governmental behavior are increasingly used at both spatial and temporal dimensions for characterizing the driving factors to control land use management (Ash and Wasson 1983; Lancaster and Baas 1998; Wolfe et al. 2010; D'Odorico et al. 2013; Siegal et al. 2013; Thomas and Redsteer 2016). Effective knowledge of vegetation dynamics has also played an important role in the identification of disturbance factors and developing protocols in categorizing biological features of dunes in terms of plant growth, stabilization process, and vegetation improvement (Aguiar and Sala 1999; Xiaodong et al. 2013; Yang et al. 2013; Zhang et al. 2013). Engineering and technological measures for combating desertification like chemical mulching and hydraulic solutions and many kinds of cementing materials have been used in improving sand dune stabilization (Fryrear 1985; Glen et al. 1998; Rezaie 2009; Gao et al. 2010; Khalili Moghadam et al. 2016) for prioritizing restoration in arid sandy land under the looming threats of climate change.

The bi-species association of *Salvadora oleoides* and *Prosopis cineraria* is considered to be the ultimate climax of the tropical thorn forests of the Indus Plain; stretching from the foothills of the Himalayas to the Arabian Sea (Khan 1994). These forests provided fodder and shelter to wildlife, medication, recreation, and most importantly, it was used as famine food in drought (Khan 1996). In Pakistan, 80% of land comes under arid and semi-arid climate, and at the turn of the twentieth century after the advent of the canal irrigation system, most of the native tropical thorn forest was gradually replaced by agriculture, and its remnants now survive in the deserts of Thal, Cholistan, and Thar. In these deserts uncontrolled extraction of colonizer species, and the use of *Leptadenia pyrotechnica* and *Calligonum polygonoides* as fuel wood, further eliminated the possibilities of natural succession and these trends of mismanagement of native woody vegetation are now threatening the last remnants of dry woodlands (GOP 1992; Khan 2003; Book Hut 2014; Gratzfeld and Khan 2015).

In addition, piloting restoration of four woody species on a sand ridge by enrichment planting showed 40% survival of *S. oleoides*, of the four woody species planted (Khan 2022). Simple amendments like the addition of loamy soils, which are freely available to local farmers after annual dredging of the irrigation canal, have augmented the growth of *S. oleoides* after the cessation of irrigation. It indicates that such an amendment might also help in stabilizing stressed plants on sandy dune slopes. This project also demonstrates that active restoration on a ridge over a period of six years costs nearly 100$ per plant, making it an expensive and time-consuming proposal and further strengthening the argument that the conservation of woody vegetation on dunes should be prioritized.

Most of the work conducted in the deserts of this region is based on investigating the characteristics of soil and vegetation parameters, and socio-economic and developmental factors (Hassan and Hassan 1998; Singh 2004; Arshad et al. 2008; Qureshi and Bhatti 2008; Sivaperuman et al. 2008). Little information is available on designing strategies to combat loss of diversity and assessment of intangible protective values of indigenous vegetation to the landscape stability. This paper copes with the knowledge gap between the vulnerability and sustainability of threatened vegetation on the fragile landscape by categorizing them into groups and suggesting choices of restoration strategies for their long-term sustainability on the dunes. In short, this is a last-ditch effort to propose the conservation of fast-declining climatic climax species on the dune tops. The paper also captures the historical ecology of the study area, and prevailing practices, and gives some policy insights to identify, categorize and rank relevant measures for practical implications for large-scale restoration.

Historical ecology of the study area

The Thal desert (Fig. 1) presented a complex geological and geomorphological pattern of alluvial deposition by a westerly drifting Indus river progressively, followed by wind resorting of the sediments into various forms of sand ridges or dunes (GOP 1968). Summer winds are from the south and winter winds from the north and they seldom increase in force to three in strength (12–19 km/h) on the Beaufort scale (GOP 1968). The desert originally extended over 25,809 km but most of it was claimed by agriculture after the advent of the canal irrigation system. Rakh Khairewala (RK), a state-controlled land (160 km^2) jointly looked after by the Rangeland and Livestock Departments, is located in the arid southern tip of Thal desert (mean annual temperature 26 °C; with a mean summer 32 °C, mean winter 19 °C, and average annual rainfall of less than 125 mm). The plant cover of RK comprises a two-phased mosaic; sandy loam flats and fine sand dunes (Fig. 2). Flats and ridges are dominated by bi-species groves of *S. oleoides* and *P. cineraria*, climatic climax of the region, colonizer shrub, *Calligonum polygonoides* and less common sub-climax species *Capparis decidua*. Ground cover is dominated by grasses; *Cenchrus ciliaris*, *Cymbopogon jawarancusa* and *Eleusine flagillefera*. The dunes have cover of woody patches, forming either single or clumpy plant communities composed of *S. oleoides*, *P. cineraria* and *C. polygonoides* with scanty cover of *Aristida mutabalis*, *C. jawarancusa* and *Aera javanica*.

Research (Khan 2010) on structural and functional status of bi-species groves of *P. cineraria* and *S. oleoides*, provided information on the coexistence

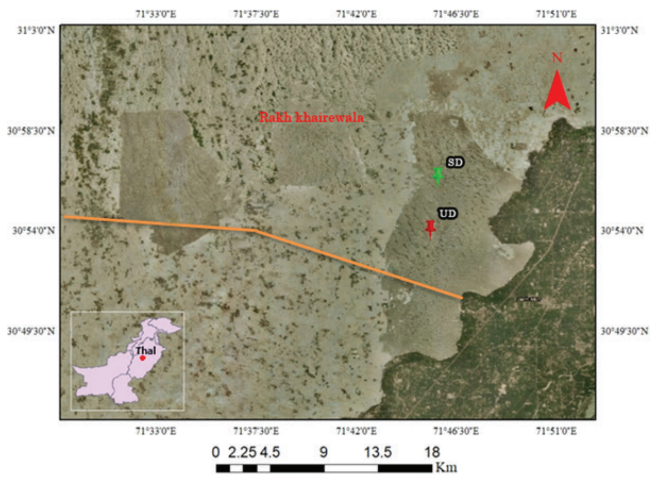

Figure 1. General view of RK and the surrounding landscape: dark grey color represent natural forest cover in which stabilized (SD) and destabilized dunes (DS) are located, and intervening light grey color shows the cultivated area with seasonal cropping. Dark grey patch on the left is the rangeland area in which the restoration site is located near the town of Chaubara. Green color shows the private arable canal irrigated zones. The road (orange) across the desert between two main towns. Map powered by google imagery 2023 CNES / Airbus, Maxar Technologies, Map data 2023.

Figure 2. General view of the KP with grove of *P. cineraria*, *S. oleoides* and *C. polygonoides* with grass cover on the flats and ridges, where sheep can be spotted, and a dune in the background showing slopes occupied by woody patches.

between species in the form of biomass allocation and root architecture. It also highlighted the impact of anthropogenic activities which have altered this association between species making them vulnerable on destabilized slopes. The livestock rearing and gram cultivation (*Cicer arientinum*) are the main sources of livelihood in this area; the latter is being extended on fragile sandy soils by leveling dunes and extraction of natural vegetation. These practices have made landscape more vulnerable to desertification and threatened the survival of the relict species of tropical thorn forest (Khan et al. 2016).

Studies (Khan 2010) on the contribution of litter by *S. oleoides*, *P. cineraria*, *C. polygonoides* and *C. decidua* indicated that these woody species are, in fact, acting as fertile islands (Chen et al. 2003) on the sandy substratum. Canopy cover and litter (composed mainly of twigs, barks, leaves, fruits and seeds) decreased on the upper slopes due to stressed status of species as compared to lower slopes. Among the four species, *S. oleoides* produced twice as much litter on both slopes and this higher litter accumulation of *S. oleoides* was attributed to its drought evading habit of growth; evergreen with surface feeder roots, and multi-stemmed drooping branches that protect and trap the litter from being dispersed. The low litter accumulation of *P. cineraria* was attributed to its arboreal and deciduous habit, whereas *C. polygonoides* and *C. decidua* are both leafless.

A survey (Khan et al. 2016) showed that woody patches on slopes are larger on stabilized dunes as compared to the destabilized dunes and their formation and spread seems to be related to the maintenance of balance between disturbance and availability of resources. Woody patches on slopes of stabilized dunes seem to be contributing to the build-up phases of natural processes, as they are more suited for extending the vegetative spread of woody species by basal branching forming above ground canopy size with lateral root spread beneath. Bottom slopes, on the other hand, (where they merge with flats), provide favorable microenvironment for the recruitment of grasses and herbs. Comparative analysis of surveys (Khan 1990; Khan et al. 2016) showed that the cultivated fields, which were about 10 km away from the southwestern boundary of RK, are now adjacent to its boundary; this is also evident from the satellite images taken during the period 1991–2021 (Google Earth Pro 2021). There has been a noticeable increase in the number of mud tracks and encounters with donkey load of extracted wood, even in remote areas, several kilometers away from the road. Moreover, RK is a state-controlled rangeland, therefore more land is cleared and reseeded, and rented for grazing on an annual basis.

Over the past two decades pumping of ground water by turbines has made agriculture more reliable in non-irrigated areas, resulting in an increase in the cultivated areas and a corresponding increase in population in the adjacent villages. In addition, this is because sugar cane is the most popular crop grown in irrigated areas and bagasse an agricultural by-product (Dotaniya et al. 2016) derived from the sugarcane milling process has become a popular source of organic fertilizer in crop production on the sandy soil in this region. When applied as a soil amendment it improved soil pH, BD, WHC, OM, macro- and micronutrients, tiller count, and, ultimately, yield (Bhadha et al. 2017; Chacha et al. 2019). It was available to the local farmer at 10 cents per 40 kg bag in 2021.

Studies conducted at RK (Khan 1990, 1994, 1996, 2010; Abbas 2015) revealed that the decline in groves of *P. cineraria* and *S. oleoides* is also linked with the general discriminatory perception about the two species among public and planners. The former species is officially protected because of its superior quality fuel and fodder over the latter, which is discarded as inferior quality fuel wood and home for vermin and its complete extraction is recommended prior to any agriculture or afforestation program. On the contrary, patterns of interaction of *S. oleoides* with environment showed that despite its low market value, it is ideal for stabilization of dunes. Similarly, there is no restriction on extraction of *C. polygonoides* and its scarcity in the vicinity of metaled roads is linked to its transportation to nearby towns where it is sold (by the trolley load), as a popular fuel wood. Research work being carried out at RK, covering a period of nearly three decades, also revealed that there are strong links between an increase in land under cultivation and a corresponding increase in unrestricted extraction of woody species, and an increase in the number of de-stabilized dunes. It is obvious that weak law enforcement on controlling the extraction of woody plants, which provided a protective cover to the sandy substratum for many centuries, has resulted in accelerating the pace of degradation.

Methodology

Study design for grouping dunes

Obtaining true replication was difficult at the landscape-scale level for this management-based study, therefore it was hoped that comparisons based on pseudoreplicates would effectively help in interpreting the trends of the decline of woody vegetation on the dune slopes. Priori categorization of dunes was made by selecting assemblages of one square kilometer area in stabilized and destabilized dunes located in less exploited and over-exploited areas, respectively. The assemblage of stabilized dunes was located about 3 km away from the metaled road connecting the two main towns whereas assemblage of destabilized dunes was located adjacent to the metaled road. The stabilized dunes generally have a greater height (>4 m) and dimension as compared to destabilized dunes (<3 m).

The criteria of selection of dunes were slightly different in the two assemblages. In the assemblages of stabilized dunes adjacent ten dunes having approximately 50 m^2 cover of woody species on both slopes were demarcated for study. In the assemblages of destabilized dunes where most upper slopes are devoid of woody species, dunes having at least 5 m^2 cover of woody species on upper slopes were selected. GPS coordinates of the selected dunes were noted. The cover value of the following woody species was made: *P. cineraria*, *S. oleoides*, *C. polygonoides*, and *C. decidua*. Grasses and herbs were not included in the cover estimates as they have poor representation on the slopes.

Upper and lower slopes were visually bifurcated; as the upper slope is the top of the dune and the steep slopes whereas lower slopes are gentle slopes before it merges with flats dominated by grasses and herbs. It varies from dune to dune; they are more defined in the stabilized dunes as compared to destabilized dunes.

A rope was used to demarcate a circle in order to estimate the cover of woody species. Since the cover of woody species was very scattered, ranging from a single plant to patches of various sizes, therefore measurements were based on the proportion of the ground cover occupied by the perpendicular projection of the aerial crown (Kershaw and Looney 1985).

Statistical analysis

Hierarchal cluster analyses (HCA) using Ward method was applied to provide classification of upper and lower slopes of both stabilized and destabilized dunes. Two-way ANOVA was applied to find out the statistical mean difference of vegetation cover between the upper and lower slope of both stabilized and destabilized dunes. Shannon Diversity Index was used to determine the vegetation diversity trends with cover among the groups. Linear regression analysis was applied for grouping dunes on the basis of cover. In this research, the dependent variable represented by average coverage of plant species and independent factor is the condition of the dune in terms of stabilized and destabilized dunes. And dunes having close resemblance of overall cover were grouped to suggest corresponding restoration measures. All statistical methods were applied using software SPSS (SPSS 21). Species nomenclature followed the taxonomic criteria of Stewart (1972).

Results

The results are analyzed on the basis of the cover of upper and lower slopes separately and also dunes as a unit by combining cover on upper and lower slopes and then grouping them in order to suggest appropriate techniques for restoration and conservation of the woody plant cover.

The result of vegetation hierarchical clustering (Fig. 3) on the horizontal axis shows the squared Euclidean Distance between units. At the cluster distance of 25, vegetation units (slopes) are separated into 2 clusters A (destabilized) and B (stabilized) consisting of 21 and 19 units respectively. Cluster A includes slopes having average cover of less than 20 m^2, B having greater than 48 m^2 cover. The cluster B at lower distance (5), further splits on the basis of cover into C (7) and D (14) units. Units in cluster C have average cover of 40 m^2, referring to upper slopes of some stabilized dunes, with the exception of one

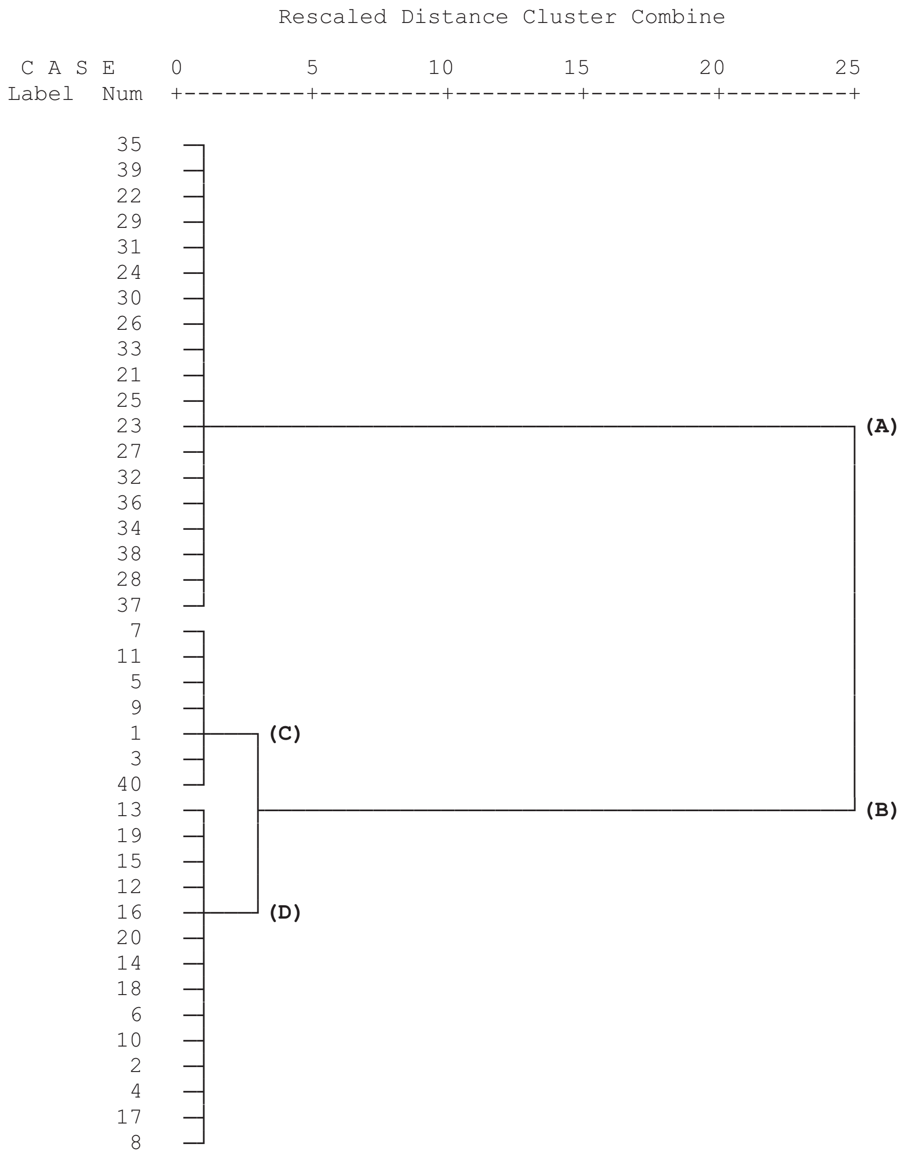

Figure 3. Hierarchial cluster analyses (HCA) showing classification of upper and lower slopes of both stabilized and destabilized dunes into distinct communities' groups. Slopes of destabized dunes were placed in group **A** where as slopes of stabilized slopes were placed in group **B** the group **B** at a lower distance splits into **C** representing upper slopes of stabilze dunes and **D** representing their lower slopes.

unit (40) from lower slope of destabilized dune with lower than average cover (28 m^2). Units in cluster D have average cover of 57 m^2, referring to lower slopes of all the stabilized dunes. The division of cluster groups showed that the cover is the most influenced factor in detecting the trends of decline of woody species and corresponding erosion which seems to be highest in lower slopes of stabilized dunes followed by upper slopes of stabilized dunes and finally destabilized dunes.

These units formed by cluster analysis also indicate a kind of interconnection among the upper and lower slopes of a dune as a decrease in the cover of upper slopes is reflected by trends of decrease on lower slopes. Therefore it was considered that by ranking dunes on the basis of overall cover and then suggesting restoration measures for the two slopes would be more practical in restoration of the woody plant cover. Results of two-way ANOVA show that the difference in woody cover (m^2) between upper and lower slopes is more significant in the stabilized dunes compared to the destabilized dunes. This trend is also obvious in the difference between mean cover of upper and lower slopes which is significantly higher in stabilized dunes compared to destabilized dunes (Fig. 4).

Similarly, linear regression showed that expected cumulative cover (Fig. 5) of stabilized dunes is higher than five, whereas it is less than three for the destabilized dunes. The dune 40 appeared to be an anomaly in the cluster analysis; its upper and lower slopes are located in two different clusters and its expected cumulative prob is less than 4, which indicates that it is a transition dune between the two clusters. It can be regarded as tipping point; where the decrease in cover of the upper slope is beginning to show its impact on the cover of lower slopes. The expected cumulative prob also indicates grouping within the stabilized dunes. Three dunes on the top have expected cumulative prob above nine corresponds to cluster D, followed by two groups having above seven and five

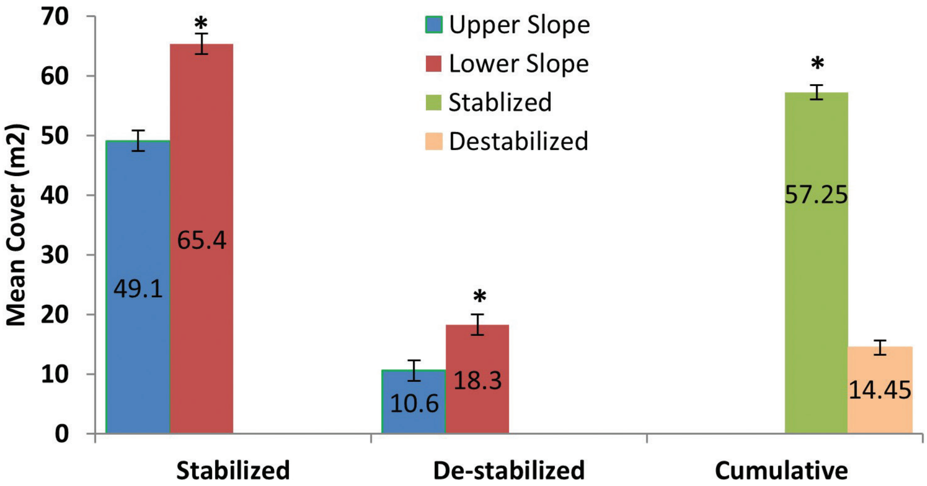

Figure 4. Mean cover (m^2) of woody vegetation on upper and lower slopes of stabilized and de-stabilized sand dunes. Upper bars show ± *S.E.* *Significant difference between means ($P < 0.01$), Two-way ANOVA.

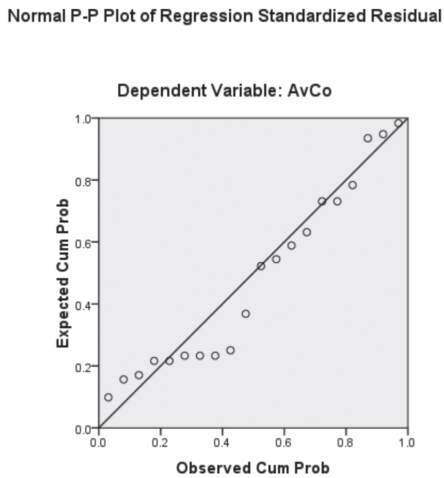

Figure 5. Linear regression analysis showed grouping of dunes on the basis of cover, destabilized groups have lower expected cum prob as compared to stabilize groups.

respectively. The latter two groups of dunes reflect the gradual decline of cover on upper slopes, which corresponds to the cluster C. These three groups clearly show that the difference in cover of upper and lower slopes is more significant in group 1 and 2 as compared to 3, showing how decrease in cover of upper slopes has gradually impacted on lower slopes. In addition, the Shannon diversity index applied to the five groups ranked on the basis of cover indicated trends of increase in diversity with increase in expected cumulative prob (Table 1).

Ranking dunes on the basis of cover

The following dune groups were segregated after ranking them on the basis of overall cover for both stabilized and destabilized dunes and corresponding restoration measures were suggested for the two slopes.

Stabilized dunes

Ranking of stabilized dunes on the basis of overall vegetation cover (Table 2) shows linear trends of steepness in the cover among the dunes (Fig. 5). The dunes were ranked and categorized into the following three groups and corresponding restoration measures were suggested for the two slopes of the dune (Fig. 6).

The group I includes dunes 1, 2 and 3, the overall cover is less than 55 m^2 although they have 60 m^2 cover on lower slopes but the upper slopes have less than 45 m^2. In addition, upper slopes have low diversity as compared to lower slopes. The presence of lone *P. cineraria* on dune 2 seems to be a vestige from the original cover. This group of dunes could naturally restore their cover on protection from further exploitation but at the same time active restoration based on enrichment planting of saplings *P. cineraria* and *C. polygonoides* on upper slopes by soil amendments could assist in increasing stability of the patch.

The group II with dunes 4, 5 and 10, have overall cover of less than 60 m^2 although lower slopes have 60 m^2 cover but the upper slopes have less than 50 m^2 (Fig. 7). Diversity of woody species on both slopes is similar. The presence of *P. cineraria* and *C. polygonoides* indicates that it is less exploited and retain the capacity to expand its cover by simple protection from exploitation. The presence of associate species indicates that simple soil amendments on upper slopes might help in stabilizing the cover.

The group III with dunes 6, 7, 8, and 9, have more than 60 m^2 overall cover; their upper slopes have slightly less than 60 m^2 cover. The presence of *C. decidua*, indicates that the woody patches are stabilized as they are harbouring species preferring more stable sandy loam soils. This group represents a low level of

Table 1. Shannon Diversity Index applied to the groups indicating trends of increase in diversity with increase in cover among the groups.

	Dune no.	Group	Upper	Lower
Stabilized	1,2,3	1	0	0.175
Stabilized	4,5,6	2	0.92	0.93
Stabilized	7,8,9,10	3	1.06	1.06
Destabilized	1,3,4,5,9	4	0	0.11
Destabilized	2,6,7,8,10	5	0.42	0.48

Table 2. Arranging stabilized dunes (SD) on the basis of cover.

Dune Rank and no ( )	Slope	Area (m²)	Plant species (m²)				Total cover (m²)	Mean cover (m²)
			S. oleoides	*P. cineraria*	*C. polygonoides*	*C. decidua*		
1 (SD 1)	US*	120.5	41	0	0	0	41	51.5
	LS**	156.7	62	0	0	0	62	
2 (SD 2)	US	125.6	44	0	0	0	44	53
	LS	206.2	54	8	0	0	62	
3 (SD 3)	US	121.1	43	0	0	0	43	54
	LS	288.5	65	0	0	0	65	
4 (SD 4)	US	130.5	35	5	8	0	48	54
	LS	250.7	49	1	10	0	60	
5 (SD 5)	US	140.9	25	11	6	0	42	54
	LS	192.7	40	14	12	0	66	
6 (SD 10)	US	109.4	24	9	13	0	46	57.5
	LS	201.9	36	12	19	2	69	
7 (SD 6)	US	108.9	29	12	14	0	55	60
	LS	192.8	38	19	8	0	65	
8 (SD 9)	US	131.5	28	11	13	0	52	60
	LS	226.6	37	16	15	0	68	
9 (SD 7)	US	162.2	30	10	21	2	63	64
	LS	289.1	34	10	18	3	65	
10 (SD 8)	US	185.1	26	8	23	0	57	64.5
	LS	311.7	35	11	26	0	72	
Total ± S.E.			775 ± 2.85	157 ± 1.32	206 ± 1.90	7 ± 0.19		
Frequency (%)	US		100	70	70	10		
	LS		100	80	70	20		

*Lower Slope ** Upper slope.

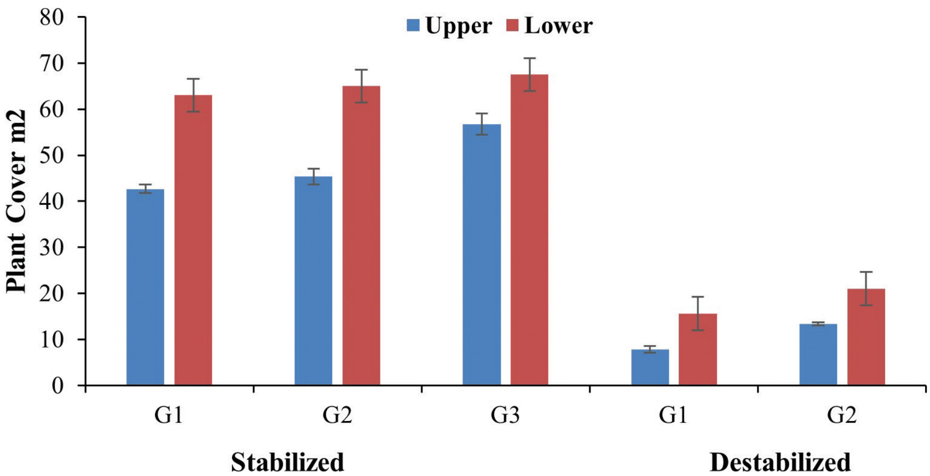

Figure 6. Mean overall cover of woody patches in the three groups on the upper and lower slopes of stabilized and destabilized dunes.

exploitation and are therefore less susceptible to natural disturbance. These dunes are recommended to be officially designated as model dunes, barring them from any form of extraction.

Figure 7. Close view of stabilized dune showing decrease in the cover of upper slopes while still retaining the diversity of species.

Destabilized dune

Ranking of destabilized dunes on the basis of overall vegetation cover (Table 3) shows a decrease in linear trends of steepness (Fig. 5) as compared to stabilized dunes. In addition, the absence of *C. polygonoides*, the scanty presence of *P. cineraria* and signs of stress on *S. oleoides*, indicates that the surviving woody species are susceptible to wind erosion. The dunes were ranked and categorized into the following two groups and corresponding restoration measures were suggested for the two slopes of the dune (Fig. 6).

The group I with dunes 1, 3, 4, 5, 9, have low cover (< 10 m^2) and surviving *S. oleoides* on upper slopes have either exposed root system (Fig. 8) or are partially buried. The dune 5 with lone *P. cineraria*, seems to be a relic from its original cover. It appears that with time this scanty cover would succumb to wind erosion, which has manifested on both slopes. In this group proposed adaptive management includes enhancing the growth of the stressed species by adding bagasse and even mulching to evade the impacts of wind erosion. Absence of colonizers on the destabilized dunes are warning signs of decline of woody cover therefore designing restoration should also be based on planting of strips of perennial colonizers, *Calligonum polygonoides* and *Cymbopogon jawarancusa*, after soil amendments. Both species were occasionally present on top slopes of sand dunes, and could help in soil binding around the stressed woody plants as they compete less with them and will prevent erosion around the plants.

The group II with dunes 2, 6, 7, 8 and 10 have higher cover (>18 m^2) and *S. oleoides* appears less stressed and presence of occasional *P. cineraria*, showed increase in diversity as compared to group I. Proposed amendments for upper slopes should be similar to those suggested for group I; at the same time enrichment planting of woody sampling on lower slopes with bagasse amendments could help to expand the woody patches.

Table 3. Arranging destabilized dunes (DD) on the basis of cover.

Dune Rank and no ( )	Slope	Area (m^2)	Plant species (m^2)		Total cover (m^2)	Mean cover (m^2)
			S. oleoides	***P. cineraria***		
1 (DD 1)	US*	91.9	8	0	8	10
	LS**	143.5	12	0	12	
2 (DD 5)	US	86.3	7	0	7	11
	LS	95.8	13	2	15	
3 (DD 9)	US	79.9	8	0	8	11
	LS	153.1	14	0	14	
4 (DD 3)	US	58.3	5	0	5	11.5
	LS	95.8	18	0	18	
5 (DD 10)	US	51.9	11	0	11	13
	LS	95.8	15	0	15	
6 (DD 4)	US	90.9	11	0	11	15
	LS	163.5	19	0	19	
7 (DD 6)	US	86.6	9	5	14	16
	LS	95.0	13	5	18	
8 (DD 7)	US	49.4	12	0	12	15.5
	LS	155.6	19	0	19	
9 (DD 8)	US	114.7	13	5	18	18
	LS	237.3	11	7	18	
10 (DD 2)	US	76.9	12	0	12	24
	LS	239.4	27	8	35	
Total ± *S.E.*			257 ± 1.12	32 ± 0.60		
Frequency (%)	US		100	20		
	LS		100	40		

*Lower Slope ** Upper Slope.

Figure 8. Exposed root system of *S. oleoides* on the upper slopes of destabilized dunes.

Discussion

Trends of decline of cover exhibited in the stabilized and destabilized dunes indicated that the woody patches on top of the slope are more vulnerable to destabilization and once its cover decreases below a minimum on the top slopes

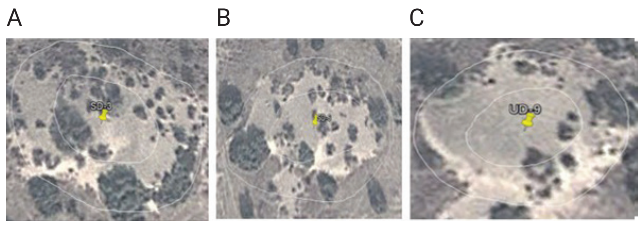

Figure 9. A stabilized dune, showing both slopes having more than 50% cover **B** stabilized dune showing decrease in the cover of upper slopes **C** destabilized dune showing decrease in cover on both slopes. Map powered by google imagery 2023 CNES / Airbus, Maxar Technologies, Map data 2023.

it could destabilize woody patches on the lower slopes. Signs of initiation of the process of destabilization are evident in the low ranked stabilized dunes in the form of decrease in cover and diversity on the upper as compared to lower slopes (Fig. 9A–C). But, in destabilized dunes the loss of cover on upper slopes has been effectively transferred down slope. It seems that the prevailing regime of anthropogenic extraction is further jeopardizing the basic processes of plant succession essential for the development of woody patches in this harsh environment. Higher cover and frequency of *S. oleoides* on dunes highlights its drought-evading attributes (Khan 2010) which has allowed it to adapt to burial and abrasion under increasing sand movement as compared to associate species, thus making it an ideal species for restoration of dunes. The restoration experiment on a sand ridge (Khan 2022), showed enhanced growth response of *S. oleoides* to addition of sandy loam soils, and therefore one can expect similar amendments on in situ stressed species on dunes would be a far better option cost- wise compared to active restoration. Similarly, if sandy loam with (5%) organic matter supplemented the growth and survival of species on sandy soil, naturally bagasse amendments (95% organic matter) with numerous other agronomic benefits, would further augment the growth of stressed species on the destabilized dunes.

This study shows that large woody patches on the slopes retain the ability to naturally expand their cover on sandy slopes but once they are destabilized they are increasingly impacted by sand mobilization and therefore cover seems the most influential factor in suggesting control measures. At the moment there is virtually no data available on the economic cost of wind erosion, including, site damage, loss of biodiversity and soil productivity in terms of organic matter removal. Neither have any measures ever been adopted to monitor and restore the woody patches. The simple restoration measures proposed here could be considered as a first step in developing an understanding towards designing adaptive strategies on conservation of the woody cover.

The decline of woody species on dune slopes reflects the lack of recognition and understanding of values and attributes of species in influencing physical, chemical and biological characteristics of fragile soils at societal and official levels. Effective knowledge of vegetation dynamics has played an important role in identification of disturbance factors and developing protocols in categorizing biological features of dunes in terms of plant growth, stabilization process and vegetation improvement, (Su et al. 2004; Thomas and Redsteer 2016). Furthermore, good governance in sandy deserts demands maximizing total benefits from natural vegetation irrespective of their market value and the only way forward for the planner is to implement a conservation and restoration program based on consumptive and productive use of natural vegetation (McNeely 1988; Akbari et al. 2020; You et al. 2021). Large areas on the verge of desertification due to human pressure were stabilized by community participation and ratification of anti-desertification movement (Levin and Ben-Dor 2004; Amiraslani and Dragovich 2011; Rubinstein et al. 2013; Xiaodong et al. 2013). Similarly, China has accumulated rich experiences in combating desertification by using various control measures which were innovated and developed with experience over the years (Down to Earth 2021). Unfortunately, developing countries are confronted by serious economic deficits and their policies are therefore geared to the interest of the present at the expense of future generations. These results in the enactment of policies indirectly accelerating the pace of extraction of woody species, leading to serious environmental problems in inherently fragile desert areas. In this era of global recession constructing a pilot project can help in further refining the proposals and its scaled implementation.

Conclusion

The significance of study findings in combating loss of threatened woody species on sand dunes emphasizes that management strategies in a spatially heterogeneous edaphic system, where the stability of dunes is of great significance to the basic ecology of this region, needs to be adapted to an understanding of the factors and processes. Suggesting high-ranked stabilized dunes as protected representative benchmarks is compatible with the objectives of the range land. This would discourage leveling of dunes as it would affect the productivity of grasses on flats and therefore can be adopted on a large-scale restoration plan. Whereas conserving stressed plants on destabilized dunes can be proposed to be implemented at a small scale to develop a protocol for large-scale restoration. In addition, the indigenous threatened species can be popularized as a productively chosen species by proposing it as a multiple-species shelter belt for sustainable agriculture, which will effectively control erosion and provide food and fodder, and pest control, and as a seed production area for recruitment. But in the absence of laws encompassing the conservation of natural vegetation on sandy land, these proposals seem to be ahead of their time.

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Conflict of interest

The authors have declared that no competing interests exist.

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Author contributions

Amin Khan conceived, designed the research and wrote the manuscript; Asad Abbas contributed in data collection and performing experiment; Asma Mansoor applied the all statistical analysis and edited the manuscript; Faiza Sharif and Zafar Siddiq reviewed the manuscript

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Data availability

All of the data that support the findings of this study are available in the main text.

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