Policy Paper 52

Valuation of Ecosystem Services from Sand Dune Stabilization in Indian Thar Desert

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Preface

Arid regions face severe challenges due to wind-induced sand erosion, which accelerates land degradation and disrupts the ecological balance. The mobility of unstabilized sand dunes exacerbates these challenges by encroaching on arable land, damaging infrastructure such as roads and buildings, and threatening the local biodiversity. This dynamic process undermines agricultural productivity and increases its vulnerability to extreme weather events, thereby impacting food security and the livelihoods of communities dependent on these fragile ecosystems. Addressing these challenges requires comprehensive adaptation and mitigation strategies and their associated economic and environmental costs for evidence-based decision-making to prioritize interventions and allocate resources while balancing immediate human needs and long-term sustainability.

In this paper, authors provide a comprehensive assessment of the conditions affecting sand dunes, including the dynamics of sand mobilization, stabilization methods employed, and the economic benefits of sand dune stabilization technologies. Looking forward, this paper proposes pathways for scaling up the deployment of sand dune stabilization technologies, emphasizing their integration into desertification control, afforestation, and water conservation programs. I hope this paper will be a valuable resource for policymakers, researchers, and other stakeholders in understanding the technological gaps in sand dune stabilization efforts and in designing sustainable land management practices for ecologically fragile arid environments.

Pratap Singh Birthal
Director, ICAR-NIAP

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Executive Summary

Arid regions, constituting substantial area of the country, are highly susceptible to wind-induced sand erosion. The high-speed winds further exacerbating desertification, shaping sand dunes of various sizes and forms and creates vicious circle leading to land degradation and consequential socioeconomic and environmental challenges. These sand dunes pose a significant threat to agriculture, infrastructure environment, and human activities, if not stabilized. Over the years, ICAR-Central Arid Zone Research Institute (CAZRI), along with State Government departments, has developed, refined, and disseminated the technologies for stabilizing the dune. Despite, their ecological importance, there is limited research assessing the extent to which these technologies have been adopted and evaluating the ecosystem services generated by stabilized sand dunes. This gap highlights the need for further empirical investigation. Using information collected from Bikaner, Jaisalmer, and Churu districts of Rajasthan through focus group discussions (FGDs), personal interviews, field observations, and secondary sources, this study assesses the adoption and impact of sand dune stabilization technology.

The findings suggest that though sand dune stabilization technology so far has covered around 4.4 lakh hectares, the adoption rate is still very low and the dune stabilization technology has primarily been implemented on government-owned land through state government initiatives. Lack of availability of quality planting material of multipurpose indigenous tree species, insect pests and disease incidences, and labour shortage were the major constraints in adopting dune stabilization technology by farmers on their fields.

The field-level impact assessment showed that sand dune stabilization technology has a significant impact on the production of ecosystem goods and services, manifesting in various tangible and intangible benefits. The economic value of benefits derived from dune stabilization is impressive, estimated to be Rs. 3,44,531 per hectare, with approximately 90% of this value attributed to environmental benefits, particularly carbon sequestration. The direct benefit received by farmers is relatively low, amounting to Rs. 49,101, compared to the indirect benefit of Rs. 2,95,430 per hectare. However, when the total cost of stabilization is spread over 8 years (the time required for stabilization), farmers still receive more direct benefits each year than the investment they made. At the macro level, for Rajasthan state as a whole, the gross economic surplus generated so far from sand dune stabilization through crop production alone was estimated at Rs. 1,57,851 million and the net economic surplus was estimated at Rs. 1,35,978 million. The benefits other than crop yield are atleast 75 times more than that from crop yield improvement. These findings strongly justify and call for strengthening investment in dune stabilization not only in Rajasthan but also in states like Gujarat and Southern Haryana. The important policy implications of the findings are as follows.

- There is a need to establish high-tech nurseries for disease free planting material of multipurpose species, mechanized lopping of trees and eradication of invasive exotic species. Integrating indigenous plant species (*Ziziphus mauritiana, Calligonum polygonoides,* and *Acacia* spp.) having economic significance can revolutionize sand dune stabilization in the region and therefore need to be promoted in a mission mode. Concerted and coordinated efforts involving local communities are needed by all the stakeholders, including State Departments of Forest, Agriculture, and Irrigation, State Agricultural Universities, and Civil Society Organizations for promoting indigenous species to achieve the ambitious target of reclaiming 26 million hectares of degraded lands by 2030.
- Shrubs and grasses prove more viable options than trees for sand stabilization. However, the challenge lies in maintaining grass cover, given issues related to uncontrolled grazing. In regions with relatively inaccessible dunes experiencing minimal grazing pressure, the aerial seeding of palletized grass seeds (*Lasiurus scindicus*) along with shrubs and trees emerges as a suitable option for sand dune stabilization. The pragmatic option is to promote silvi-pastoral models given the role of livestock in the region.
- Fencing and labour are the major components of expenses in sand dune stabilization, a burden that could be alleviated through social fencing facilitated by local community involvement. Moreover, aligning the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) with the sand dune stabilization program could optimize manpower usage. Engaging local communities from the planning to the execution stage is essential to instill a sense of community ownership.
- Benefits are slow to materialize; hence farmers require financial incentives in the early years to ensure continued participation. The high value of carbon sequestration suggests that dune stabilization

projects could qualify for carbon credit programs, generating revenue for local communities besides achieving the targets of the goals of land degradation neutrality and advancing net-zero emission-targets.

- Governments, in partnership with private and civil society organizations, should promote dune stabilization as a climate adaptation strategy, linking it with broader policies on desertification control, afforestation, and water conservation.

1 Introduction

Sand dunes are the characteristic feature of arid regions. In India, the Thar Desert is dominated by aeolian landforms, with about 80% of its area in Rajasthan comprising such features. Among these, sand dunes occupy the largest proportion (49.7%) covering 51801 km^2 area, followed by sand sheets (35%) (Bhadra et al., 2019). These landforms are of significant environmental, ecological, and economic importance which is supporting 27.9 million livestock (GoI, 2019). However, the encroachment of shifting desert dunes poses significant threats, either by directly burying areas beneath migrating dune bodies or by increasing the influx of wind-blown sand from the dunes. Encroachment of desert dunes occurs when strong winds mobilize loose sand, causing dune migration into agricultural lands, settlements, and infrastructure. Human-induced disturbances such as deforestation, overgrazing, and fuelwood collection, and mining exacerbate this process by reducing vegetation cover and destabilizing dune surfaces. These anthropogenic pressures intensify wind erosion, accelerate sand movement, and ultimately aggravate dune encroachment and its associated environmental and socio-economic impacts (Dong et al., 2004; Fadhil, 2013).

The impacts of dune encroachment are extensive and multifaceted. They damage property, industries, settlements, transportation networks, and biodiversity, while also reducing soil fertility and agricultural productivity (Dong et al., 2004; Gad, 2016; Ahmady-Birgani et al., 2017; Bruno et al., 2018; Pradhan et al., 2018; Bass and Delobel, 2022). The average rate of dune movement in the Indian Thar Desert is between 3.51 and 7.11 meters per year (Bhadra et al., 2019). Additionally, migration of dunes also contributes to the dust emissions into the atmosphere. These emissions play a crucial role in the climate-change feedback process, influencing the morphology and dynamics of sand dunes and potentially transforming stable dunes into active ones and vice versa (Muhs and Maat, 1993; Thomas et al., 2005; Yizhaq et al., 2009). Thus, tackling the challenges presented by dune encroachment in arid regions requires formulation of adaptation and mitigation strategies to protect both the environment and local livelihoods.

Land degradation in Rajasthan causes a significant economic burden, largely driven by aeolian (wind) and water erosion. Thanuja et al. (2021) estimated annual losses at Rs. 55.24 billion (2017–18 prices), with wind erosion contributing 55.91% and water erosion 42.26% of the total. At the national scale, India has about 187.77 million hectare of degraded land, leading to an estimated 12% loss in the total value of production (Vasisht et al., 2003). The annual cost of land degradation due to land use and cover change was assessed at approximately 5.35 billion USD in 2009 (Mythili and Goedecke, 2016).

Furthermore, the impacts of climate change are expected to intensify the pace of desertification in the Indian Thar Desert due to rising temperatures, altered rainfall patterns, and increased frequency of extreme events. Projections indicate that arid and semi-arid regions of India will experience higher evapotranspiration, more intense droughts, and declining soil moisture, thereby accelerating wind erosion and land degradation processes (IPCC, 2019). Studies further suggest that under high-emission scenarios (RCP8.5/SSP5), the Thar Desert may undergo enhanced aridification, with expansion of shifting sand dunes, reduced vegetation cover, and higher risks of dust storms (Huang et al., 2016; Panda et al., 2017).

Considerable technological advancements have been achieved in the fixation and stabilization of mobile sand dunes, employing a variety of mechanical, physicochemical, and biological methods. Mechanical measures, or engineering techniques, involve constructing barriers on sand dunes or covering their surface with different materials to decrease wind speed and prevent sand movement. Locally available materials such as plant residues, soil (clay), rocks (pebbles), and waste materials are commonly utilized for this purpose (Ahmed, 1990; Qiu et al., 2004). Chemical measures include the application of petroleum by-products, chemical mulches, or sealants on dune surfaces. Stabilisers, such as bitumen, polyelectrolytes, and latexes, are frequently employed to manage erosion (Zoght, 1978; Rehman, 1995; Amiraslani and Dragorich, 2011). These chemicals function by forming adhesive bonds between sand particles, thereby creating a protective film that stabilizes the surface. Biological methods gained prominence in sand dune stabilization efforts in recent years. Native grasses, shrubs, and trees with deep root systems are selected for their ability to bind sand particles and create a natural barrier against wind erosion.

The integration of these methods has proven to be highly effective. For example, mechanical barriers can be initially installed to offer immediate protection, followed by chemical stabilization to form a temporary crust.

This approach allows time for planted vegetation to establish itself, ultimately resulting in long-term, sustainable dune stabilization. The choice of method or combination of methods depends on various factors, including local climate conditions, available resources, and the specific characteristics of the dune system being addressed.

The establishment of vegetative cover is widely regarded as the most effective, enduring, and sustainable approach to dune stabilization. The selection of plant species for biological sand fixation is based on their adaptability to prevailing climatic and ecological conditions, ensuring optimal performance and resilience in the targeted environment. Vegetative stabilization of sand dunes offers significant economic and ecological benefits. An economic analysis revealed that per rupee investment in the vegetative stabilization method generates returns ranging from Rs. 1.83 to 3.58, depending on the location (Kalla, 1974). This approach not only enhances forage and wood production but also contributes to long-term land restoration and sustainable resource utilization (Kaul, 1996).

Many studies showed that the stabilization of mobile sand dunes significantly improves soil health, biodiversity, crop yield, and ecosystem health (Raji et al., 2004; Rouhipour, 2005; Zuo et al., 2014; Wang et al., 2019). However, the literature remains scarce regarding both the extent of adoption of these technologies and the valuation of ecosystem services derived from stabilized sand dunes. Although dune stabilization technology has evolved during the 1960s but there is limited evidence on their actual adoption in the Indian Thar Desert. Moreover, the ecosystem services generated by stabilized dunes such as improved soil fertility, agricultural productivity, carbon sequestration, economic and livelihood benefits have not been adequately quantified or valued. This lack of systematic assessment constrains policy formulation and the design of scalable interventions for combating land degradation and desertification.

Against this backdrop, this study aims to evaluate the adoption and assess the impact of the sand dune stabilization techniques and technologies developed by the ICAR-Central Arid Zone Research Institute (CAZRI). The specific objectives of the study are: (i) to comprehensively review the existing status of sand dune cover, sand mobilization, and various techniques of sand dune stabilization, (ii) to assess the adoption and impacts of sand dune stabilization in the Thar Desert of Rajasthan, and (iii) to suggest future strategies for upscaling of Sand Dune Stabilization (SDS) technology.

The next chapter gives an overview of sand dunes, a short review of sand dune stabilization technologies available worldwide, and the technologies developed by ICAR-CAZRI. A brief methodology adopted in the present study is given in Chapter 3, while Chapter 4 presents the results of the adoption of technologies, their costs and impact, and the major constraints in the adoption of dune stabilization technologies in the Indian Thar Desert. The conclusions drawn and the policy implications are highlighted in Chapter 5.

♦♦♦

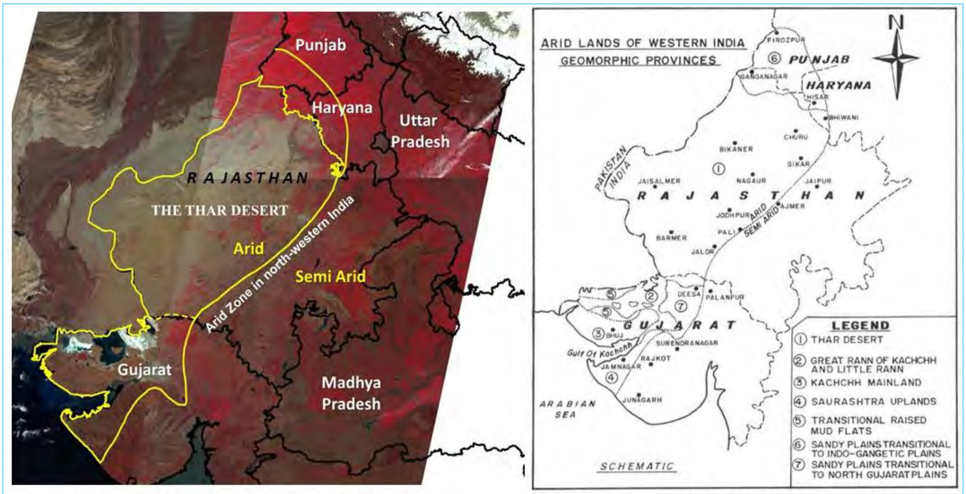
2 Sand Dune of Thar Desert

2.1 The Indian Thar Desert

The Thar Desert, often referred to as the ‘Great Indian Sand Desert,’ is situated along the Eastern edge of the Indo-Saharan hot arid belt in the North-Western part of the Indian subcontinent. In India, it spans approximately 32 million hectares, predominantly in the Western and North-Western regions of Rajasthan (over 60%), followed by Gujarat (20%), and the South-Western areas of Punjab and Western Haryana (Figure 1). The desert stretches from the Eastern foothills of the Aravalli ranges to the international border with Pakistan in the West. Extending further into Pakistan, it includes the fertile alluvial plains of the Indus.

The Thar Desert is characterized by low and erratic rainfall (<200 mm to 450 mm/year), very high evaporation (1600 – 2000 mm/year), sparse vegetation, and deep aquifers. The harsh environmental conditions present significant challenges for agriculture and sustainability. The frequent occurrence of droughts, with an average of frequency of once in every 2.5 years, further compounds these difficulties. Notable droughts in 1918, 1987, and 2002 saw rainfall deficits of up to 81% (Rathore, 2005). Droughts have had devastating consequences in Western Rajasthan. The

Figure 1. Indian Thar Desert



Geographical location of Thar Desert in India on Satellite image
Graphics credit : Pratap Chandra Moharana, CAZRI, Jodhpur

Kar, A. 1995. Geomorphology of arid western India. Memoirs, Geological Society of India 32: 168-190

2002 drought, in particular, caused a severe decline in agricultural output, with the area under kharif crops shrinking by about 56% and production falling by nearly 87%, most notably in pearl millet and pulses (Tewari and Arya, 2005). Fodder availability also declined sharply, dropping by 40–50% in the worst-affected districts during 2002–03 (Narain and Kar, 2005). The region's coarse-textured soils deficient in organic matter and nitrogen (N), and exhibiting poor moisture retention capacities (Gupta et al., 2000) exacerbate the condition further. The arid region supports livestock population of 27.9 million. Intense biotic pressure is evident from the fact that human population increased by more than 25% between 1960 and 2011 and livestock population by 72% between 1966 and 2019, which has led to the overexploitation of resources (GoI, 2019; GoI, 2011). This poses a significant and imminent threat to the sustainability of the natural resources. As per a study by Chand et al. (2024), agriculture in Rajasthan is the least sustainable among the major states of India. The situation is particularly critical for agriculture, which struggles to maintain productivity under these harsh environmental conditions. This finding highlights the urgent need for innovative and sustainable strategies for ensuring the long-term viability of agriculture in such challenging environments requires integrated and responsible approaches to natural resource management.

The dominance of light-textured soils with inherently low fertility and limited water-holding capacity imposes significant constraints on land productivity and undermines the sustainability of the regional life-support system. To address these challenges, rural communities in the region have developed intricately interdependent production systems that integrate crops, perennial woody plants, and livestock. These systems have evolved through continuous practice and refinement over centuries, aligning with the prevailing climatic conditions and available natural resources. The cropping pattern in the region is also highly diversified. Evidence indicates that livestock in the region is relatively less affected by droughts than crops (Chand and Sirohi, 2015). The cultivation of perennial grasses such as Lasiurus sindicus *Cenchrus ciliaris, Cenchrus setigerus*, and *Panicum antidotale* contributes to fodder production for livestock also serves as a dune stabilizer in the region.

Agriculture in this region is rainfed, and major rainfed crops of the state are pearl millet (*Pennisetum glaucum*), cluster bean (*Cyamopsis tetragonoloba*), moth bean (*Vigna aconitifolia*), green gram (*Vigna radiata*), and sesame (*Sesamum indicum*). These crops are cultivated both as sole and mixed crops. In irrigated areas, crops such as groundnut (*Arachis hypogaea*), cotton (*Gossypium* spp.), wheat (*Triticum aestivum*), mustard (*Brassica juncea*), chickpea (*Cicer arietinum*), isabgol (*Plantago ovata*), and cumin (*Cuminum cyminum*) are cultivated. Fruit crops like ber *(Ziziphus mauritiana*), pomegranate (*Punica granatum*), citrus fruits (*Citrus* spp.), date palm (*Phoenix dactylifera*), and Indian gooseberry (*Phyllanthus emblica*) are grown mainly where irrigation is available.

2.1.1 Landforms and dune types

The Thar Desert is characterized by a notable diversity of landforms, including both structural and denudational features such as pediments, dykes, ridges, hills, valleys, and hamada formations. These landforms are primarily aeolian, resulting from wind-related processes, which account for 79% of the desert in Western Rajasthan. This is followed by fluvial processes associated with water-related activities, comprising 13%, and to a lesser extent, they are also influenced by denudational and structural processes (Moharana et al., 2013). Aeolian features include sand sheets, dunes, interdune plains, desert pavements, and playas The fluvial landforms comprise alluvial plains, abandoned/paleochannels, gullied land, and river beds. These are mainly found in Pali, Jalore, Nagaur, and Sirohi districts, which fall within the Luni basin, and Ganganagar and Hanumangarh districts that are part of Ghaggar basin. Apart from these, flavor-marine formations like the Playas or saline depressions (also called the "inland Ranns") occur in Sambhar, Didwana, Tal Chhapar, Pachpadra, Thob, Bap and Lunkaransar, Lawan, Pokaran, Mitha Rann, Kanodwala Rann and Kharariwala Rann (Moharana et al., 2013). Within the aeolian landforms, sand dunes constitute the largest share, accounting for almost half of the total, followed by sand sheets at 35% (Bhadra et al., 2019).

Sand dunes of the Thar Desert exhibit significant variation in forms, sizes, and dynamics influenced by factors such as the strength and duration of the wind, sediment supply, rainfall, vegetation cover, and land surface conditions, and are accordingly categorized into several classes (Kar, 1993; Kar et al., 2004). Based on morphological characteristics, dunes can be classified into various types, but the most commonly found are parabolic (accounting for 49.66% of the total dunes), transverse (25.60%), longitudinal (linear) (21.74%), and barchans (2.99%) (Bhadra et al., 2019). Characteristics of different types of dunes and their distribution are given in Table 1. In addition, other dune types such as barchanoids and megabarchanoids, star dunes, network dunes, obstacle dunes (formed along hill slopes), and sand streaks are also present.

Linear, parabolic, transverse, star, network, and major obstacle dunes are classified as ancient dunes, having been formed as a consequence of historical climatic changes. These dunes are also known as "dormant" dunes, as sand transport is minimal or only periodically reactivated. Old dunes, typically measuring between 10 and 40 meters in height, demonstrate natural stabilization through the presence of calcified roots from vegetation and the incorporation of soft carbonate nodules within their structure. Many of these dunes may have a reactivated crest and flanks. With a silt and clay content ranging from 10-15%, these dunes possess high water-holding capacity, enabling them to sustain substantial natural vegetation. Dunes formed under the current arid conditions in the Western part of the desert, such as crescentic barchans, barchanoids, megabarchanoids, and smaller dunes like nebkhas, source-bordering dunes, sand streaks, and zibars, are categorized as dunes of the new system (Kar, 1995; Kar, 1999). These are considered as active dunes. Most high sand dunes in the Thar are the old dunes and including the presently stabilized and vegetated linear, parabolic, transverse, star, network, and obstacle dunes.

Table 1. Major types of sand dunes, their characteristics, and distribution in the Indian Thar Desert

Type	Characteristics	Distribution
Parabolic	Possess two arms in the upwind direction and a curved nose downwind; occurs in isolation or chains of 4 – 8 or more and 3 – 4 tier arrangements; having arms of 5 – 8 km long in the West, which gradually shorten Eastward to about ≤1 km; average windward, flank and leeward slopes are 2° – 4°, 8° – 12° and 22° – 24°, respectively. In Barmer-Jodhpur-IGNP command of Jaisalmer region, most of these dunes are 20 – 30m high, while in some cases, the height can be as high as 50 m. In the farmer's lands, slopes of parabolic dunes are utilised for cultivation. Average mobility is 3 – 6 m per year.	Barmer, Jaisalmer, Jodhpur and Bikaner Districts
Longitudinal	Aligned in the direction of dominant sand transport, having broad convex summit with similar slopes on both flanks. Length varies from ~10 km in the extreme West of the field to 1 – 2 km in the East. Orientation of dune gradually changes from West-South-West in the Western part to South-West in the Eastern part. Dunes of 30 – 50 m are more frequent. Shape dunes have been reported to change from West to East in the Indian part of Thar.	Western part of the Thar (West and South-West of Jaisalmer, Bikaner, Didwana, and Laxmangarh)
Transverse	Oriented across the path of sand-moving wind (NW-SE), occur in 1– 5 km long chains with narrow interdune plains in between, average spacing between transverse dune chains is 300 – 800 m. The slopes of the leeward, flank and windward sides of the dunes are 22°, 10° to 12° and 3° to 4°, respectively. Height: 20 – 40 m in Western part of Thar 8 – 15 m in the East.	Along the North-Western part of the Thar (Western Bikaner, North-Western Jaisalmer, and parts of Ganganagar and Hanumangarh)
Barchans/ Barchanoids	Have a crescent form (two horns protruding downwind). Smaller (2 – 4 m height) and single dunes are called barchans. Dunes of 9 – 12 m in height are called barchanoids and of 15 to 40 m high in the coalesced pattern are called mega-barchanoids. The later two occur in long chains within the longitudinal dune field. Barchans are the fastest-moving dunes.	West and South-West of Jaisalmer (between Shahgarh and Dhanana)

Source: Kar, 1996 and 1999.

The dissected obstacles dunes, located along the hill slopes and low sand streaks in sandy plains adjacent to the fence lines of agricultural fields, as well as shrub coppice dunes "nebkhas, surrounding small bushes", represent another category of dunes. The classification, morphology, mobility, patterns of air and sand flow, and environmental context, including vegetation and land use practices, are crucial for implementing sand control measures in dune-covered regions (Kar, 1996). Newly formed dunes, particularly barchans and barchanoids, exhibit the highest mobility. In contrast, older dunes have largely stabilized; however, they have been subdivided into private land holdings and are utilized for agricultural purposes, predominantly rainfed farming, which has led to their reactivation.

2.1.2 Land degradation in Thar Desert

The arid Western part of Rajasthan, containing the Indian segment of the Thar Desert, account for over 62% of the hot arid area. The region faces a major challenge of desertification, which is physically manifested mainly as wind erosion/deposition, water erosion, water logging, and salinity. Studies show that >60% area of the region is affected by desertification (Moharana et al., 2013; Kar et al., 2009). Wind erosion is the major source of land degradation, with more than two-thirds of the area affected by various erosion and deposition activities (Kar et al., 2009; Moharana et al., 2013), affecting crop yield directly by damaging the crops through abrasion, burial, and dust deposition, etc. and indirectly by reducing soil fertility. The severity of erosion is also very high as almost half of the total area of the region falls either under the very severe (aeolian mass transport ≥7kg per meter per day) or severe (≥4kg per meter per day) category of erosion (Santra et al., 2017). Yield loss in crops like pearl millet, mustard, wheat, ground nut, moth bean and cluster bean due to wind erosion varies across categories, with moderate cases experiencing a loss of 14–48 kg per hectare severe cases losing between 56–198 kg per hectare, and very severe cases suffering a loss ranging from 93–331 kg per hectare (Santra et al., 2017). Aeolian-caused shifting sand bodies in the desert pose a threat beyond affecting crop yield. They adversely affects human activities and man-made structures, including burial of settlements, railway tracks, roads, siltation of groundwater recharge and irrigation infrastructures, particularly the canal networks, disruption of communication networks, etc. (Kar, 1996).

The economic impact is substantial, with annual losses estimated at around Rs. 25.6 billion for major crops alone (Santra et al., 2017). Additionally, the region faces challenges related to water erosion, waterlogging, and salinity, further complicating land management and conservation efforts. The impact of desertification in this region goes beyond mere crop losses.

Shifting sand formations present significant threats to human activities and infrastructure. These multifaceted issues underscore the urgent need for comprehensive strategies to combat desertification and mitigate its wide-ranging impacts on the environment, agriculture, and human activities in Western Rajasthan.

2.2 Sand dune stabilization

2.2.1 Basic principles and techniques of sand dune stabilization

Globally, an array of sand dune stabilization technologies has been developed with the basic principle of preventing sand movement for a sufficient duration through natural or planted vegetation. Effective control of sand encroachment involves the reduction of saltation, achieved either by stabilizing the soil or mitigating the wind speed gradient near the ground surface. High-speed winds contribute to sand removal, clearing previously sanded-over areas, while slower winds lead to sand deposition. Therefore, manipulating wind speed plays a crucial role in managing sand dunes. Based on these principles, dunes fixation can be classified as primary and definitive (also known as biological) fixation.

Primary fixation involves the use of mechanical and chemical methods. The main aim of this approach is to slow down the speed and movement of sand masses through mechanical stabilization and to prevent the formation of such masses by implementing strategies that reduce sand mobilization, shield the ground, and reduce transport capacity. The commonly used mechanical methods include deploying technologies to construct barriers on sand dunes and covering their surfaces with various materials like stone fencing, mulching, and fencing with plant residues such as wheat straw, sorghum stalks, rice straw, reeds, twigs, and branches of trees or shrubs, plastic sheets, nets, and geotextiles.

The design of mechanical approaches varies with their efficacy contingent upon the specific characteristics of the area in which they are implemented. The most common approach is using protective fences, typically 1 to 1.5 meters in height, in the form of a chessboard pattern or strategically placed to hinder the advancement of sand. These fences exhibit a degree of permeability to the wind. The dimensions of the rectangular patterns within the checkerboard design are adapted to the specific land characteristics of the area. For example, while Shehata and Al-Rehaili (2013) recommended a checkerboard for Egypt with a typical height of 50-70 cm, forming 3 x 3 m rectangles, whereas Qiu et al. (2004) suggested that 10-15 cm in height, forming 1 x 1 m rectangles for Shapotou in the Tengger Desert of China, where the annual rainfall is <200 mm and vegetation is very sparse (1-2%). Other methods like applying chemicals, wetting with water, mixing clay particles, and adding organic carbon, coupled with iron and other trace elements, are also used to stabilize sand dunes (Pandey and Rokad, 1992).

Definitive fixation, also known as biological fixation, is accomplished by establishing and safeguarding a lasting natural vegetation cover or shelterbelts with plants composed of trees, shrubs, and grasses suitable for local environmental conditions and resilience in harsh climates, including droughts, heat, and strong winds. Their lower water requirements, especially critical in semi-arid and arid areas, also contribute to their suitability. The effectiveness of sand fixation also depends on tree density and the combination of plant species (Di et al., 2018). Some studies recommend species exhibiting rapid growth and a robust capacity for proliferation propagated through aerial seeding to stabilize sand dunes (Deng et al., 2020). However, such strategies may have adverse effects on indigenous species. The introduction of *Neltuma juliflora (earlier known as Prosopis juliflora)* for this purpose is often quoted as an example of such a fast-growing species. Ample evidence on the negative impacts of *Neltuma juliflora* on ecosystems, floral and faunal diversity, availability of water resources, and loss and degradation of grasslands, farmlands, and rangelands are available in the literature (Gorgens and Wilgen, 2004; Maundu et al., 2009; Kaur et al., 2012; Schachtschneider and February, 2013; Chandrasekaran et al., 2014; Kumar and Mathur, 2014). Therefore, the selection of species should be based on multi-criteria including suitability to the local climate, requirement of local communities, impact on indigenous vegetation and other socio-economic factors.

Furthermore, biological soil crusts, composed of intricate organic amalgamations involving cyanobacteria, microalgae, mosses, lichens, fungi, and other organisms embedded in a polysaccharide matrix, are also applied to bind the loose sand and improve soil quality. However, these crusts are delicate and susceptible to damage from disturbances such as animal trampling, and recovery from damage is a time-consuming process (Zhao et al., 2016).

The choice of the measure, or a combination of different measures, depends on several factors, including the severity of sand storms and the availability of materials. For stabilizing dunes that border sandy desert encroachment and extremely arid regions prone to intense wind and sand movement where plant survival and growth are challenging, mechanical measures become essential to prevent the encroachment of dunes. When the objective is to plant trees, shrubs, or grasses on sand dunes, mechanical measures should precede the planting process. This precaution is necessary to shield the seeds or seedlings of the chosen plants from the wind and from being buried by blown sands. Even if the soil moisture content is sufficient and other natural factors favour plant growth, implementing mechanical measures under these conditions is crucial. The mechanical methods not only halt the movement of sand dunes but also ensure the survival of seedlings belonging to sand-binding plant species. Various methods used for sand dune stabilization are listed in Table 2.

The primary fixation, which is typically conducted before planting, is relatively less stable, and should ideally be followed by definitive fixation. These measures are particularly applied for dunes with an unstable surface prone to severe wind-blown damage so that the necessary micro-environmental conditions conducive to the survival and growth of introduced plants are developed. The use of chemicals should be judicious as these may have adverse effects on the health of soil, humans, and plants. For example, relying solely on asphalt emulsion can reduce permeability, forming a thin consolidation layer that inhibits water penetration and is less conducive to plant growth (Pei et al., 1981). This thin layer also lacks strength and stability. Chemical sand fixation methods also costly and require specialized equipment (Zang et al., 2015).

Biological measures are costlier than mechanical and chemical measures; however, they demonstrate significantly superior sand fixation performance and greater longevity (Gong et al., 2001). Nevertheless, biological measures have two limitations. Firstly, these methods may not achieve the anticipated sand-fixation effectiveness promptly, especially during the initial stages, as the restoration of vegetation and the assembly of the plant community require time. Secondly, a thorough preliminary investigation of site conditions and field testing of selected plants are imperative before implementing any biological measures in the target areas. Therefore, mechanical measures are often complemented with additional strategies, with a notable emphasis on biological measures. This integrated approach ensures a more comprehensive and sustainable method for dune stabilization, as has also been highlighted by Pye et al. (2017).

Table 2. Methods used for sand dune stabilization in different countries

Country/ Location	Primary fixation	Definitive fixation and plant species used	Source
China	Surface mulches of clay, straw, or Kang-Mein stones	Green belts using *Salix mongolica* and *Tamarix juniperia*.	Ahmed, 1990

Country/ Location	Primary fixation	Definitive fixation and plant species used	Source
China, Tengger Desert	Straw checkerboards (1 × 1 m); Sand fence (1.2 m tall and 30% porosity)	Vegetation belt: *Caragana korshinskii, Hedysarum scoparium, Elaegnus angustifolia, Calligonum arborescens*.	Zhang et al., 2011
China Taklamakan Desert	Reed checkerboards; Nylon sand fences with narrow tripped nets; Sand-fixing materials: LVA (a polyvinyl alcohol emulsion), LVP (a polyvinyl acetate emulsion), WBS (a mixture of water glass and calcium chloride), and STB (a mixture of water glass and urea).	Drip irrigation system; saline water irrigation; vegetation: *Tamarix ramosissima, Haloxylon ammodendron, Calligonum aborescens*	Han et al., 2003, 2007 He et al., 2014; Zhang et al., 2016.
Iran	Mechanical stabilization using dead plants of *Panicum antidotale, Aristida pennata, Erulagal vamifera* erected in (5 - 10 in) checkerboard systems; oil extracts spraying on dunes before	Vegetation: *Haloxylon persicum* , *Atriplex canescens*	Sankary, 1987
Iran, Khuzistan & Khorasan	Petroleum mulch	Windbreak establishment; vegetation: *Haloxylon persicum, Calligonum comosum, Smirnovia iranica*	Amiraslani and Dragovich, 2011;
Tunisia	Afforestation and exclosure; Fencing and grids (corrugated iron and asbestos cement sheets on artificial sandy bunds)	Vegetation: *Eucalyptus, Calligonum* comosum, *Retama* raetam, *Tamarix*, etc.	Mainguet and Dumay, 2011
Pakistan	Chemical stabilization: clay, mud, petroleum products.	Vegetation : *Tamarix gallica, Calligonum polygonoides.*	Rehman, 1995
Libya	Fencing of dry and dead plants (*Imperata cylindrical, Aristida pungens, Artemisia herba alba*); burying Asphaltic material (depth of 50 - 60 cm); oil extracts and chemical		Zoght, 1978
Saudi Arabia	Fence (0.7 – 1.0 m height) of date palm fronds; chemicals (asphalt, synthetic latex, polyvinyl polymers, sodium silicate, and gelatine).	Vegetation: *Tamrixs* Sp., *Eucalyptus* Sp., *Prosopis juliflora*, *Parkinsoni aaculata*.	Watson, 1985

2.2.2 Sand dune stabilization in India

Since 1952, India has made significant efforts in sand dune stabilization and afforestation, beginning with the establishment of the Desert Afforestation Station in Jodhpur, Rajasthan. In 1957, this station was reorganized into the Desert Afforestation and Soil Conservation Station, which was further upgraded as ICAR-Central Arid Zone Research Institute (CAZRI) in 1959. The institute has conducted comprehensive studies on the natural conditions of the Thar Desert and has been instrumental in developing technologies for stabilizing sand dunes through mechanical, chemical, and biological methods. While the institute advocates for integrating all approaches, it places a greater emphasis on developing vegetative methods and establishing shelterbelt plantations as long-term sustainable solutions.

The technologies developed by ICAR-CAZRI can be broadly categorized into three groups: (i) protection from biotic interferences, (ii) construction or development of physical barriers to reduce surface sand drift, and (iii) re-vegetation or afforestation of the treated dunes (Bhimaya et al., 1961; Kaul, 1985a; Kaul, 1985b). The sequence of these interventions is crucial, as the success of one category significantly influences the success of the subsequent ones (Bhimaya and Kaul, 1960; Muthana, 1982; Kaul, 1985a; Harsh and Tewari, 1993). In essence, these technologies are most effective when implemented as a comprehensive package, which the institute has developed. The details of this package, along with the specific purpose of each component, are described below.

(i) Protecting against biotic interferences: If left undisturbed, the natural vegetation anchors the sand, allowing the dunes to stabilize and increase in size. To protect dunes from biotic interferences, such as encroachments by humans and livestock, fencing is employed. This fencing typically consists of barbed wire attached to angle iron posts, which are aligned in rows with spacing of 6 meters (Figure 2(b)). Bio-fencing with shrubs like *Zizyphus nummularia* is also done.

(ii) Erection or development of physical barriers: The second component of the technology package involves installing barriers in parallel strips or a checkerboard pattern using locally sourced brushwood or grass materials, as illustrated in Figure 2(c). These materials typically extend from the crest to the downslope of the dunes, functioning as micro-wind breaks. The selection of species and their arrangement is influenced by wind directions and human activities on the dune slopes. Plant species like *Crotolaria burhia, Leptadenia pyrotechnica, Zizyphus nummularia, Aerva*

pseudotomentosa, Calligonum polygonoides, and *Panicum turgidum* are used as barriers. Shrubs are gathered on site and buried vertically into the ground with their crowns facing downward, arranged in rows with spacing between 2 to 5 meters. This method aims to reduce wind velocity near the surface of sand dunes and stabilize them.

Figure 2. Sand dune stabilization technologies developed by CAZRI, Jodhpur

(a) Unstabilised dune

(b) Protection against biotic interferences

(c) Erection (checkerboard)

(d) Afforestation

(iii) Re-vegetation or afforestation: The third component of the technology involves the vegetation on the stabilized dunes, which includes a combination of grasses, trees, and shrubs, featuring both indigenous and exotic species to maintain stabilization (Figure 2(d)). The selection of species is influenced by several factors, with the region's rainfall pattern being a crucial consideration. The recommended species are listed in Table 3. Tree seedlings are cultivated in sun-dried earthen bricks or polythene bags filled with an equal mix of sand, clay, and manure. Grasses or leguminous creepers are planted on the leeward side of micro-wind breaks at the onset of the monsoon. To protect them from gerbils, grass slips or seeds are treated with sodium arsenate. Continuous and effective management is maintained until the dune is fully covered with vegetation, and the cost of input is typically recovered within 10-15 years.

Table 3. Species recommended for vegetation to stabilize sand dunes for different rainfall ranges

Mean rainfall (mm per year)	Species		
	Tree	Shrub	Herb
150-300	*Acacia tortilis, A. senegal, Neltuma juliflora*	*Calligonum polygonoides, Zizyphus spp.*	*Lasiurus sindicus*
300-400	*Acacia tortilis, A. senegal, Prosopis cineraria, N. juliflora, Tecomella undulata.*	*Zizyphus spp., Calligonun polygonoides, Ricinus communis.*	*Cenchrus ciliaris, C. setigerus, Lasiurus sindicus, Saccharum munja*
>400	*Prosopis cineraria, N. juliflora, Acacia nilotica, A senegal, A. tortilis, Tecomella undulata, Parkinsonia aculeata, Ailanthus excelsa, Albizia lebbeck.*	*Cassia auriculata Ricinus communis, Zizyphus spp.*	*C. ciiaris, C. setigerus, Panicum antidotale, S. munja*

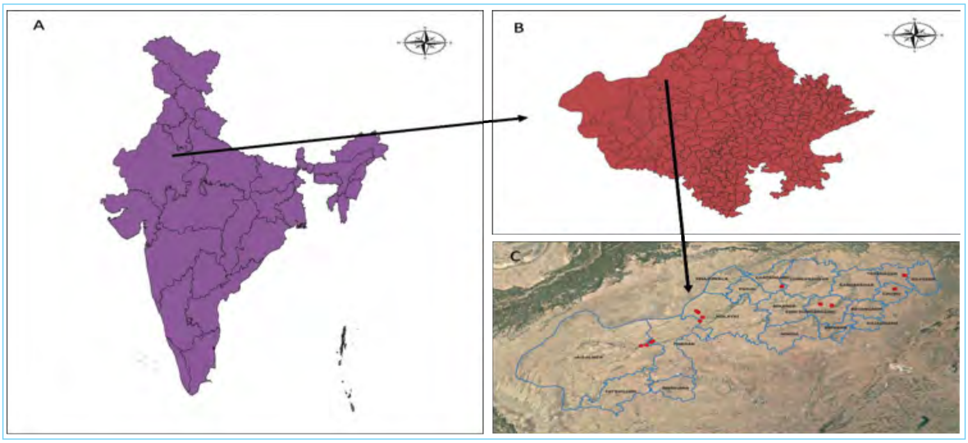
Source: Modified from Venkatswarlu, 1993.

3 Data and Methodology

3.1 Data

The study used both primary and secondary data to evaluate the adoption and impact of Sand Dune Stabilization (SDS) technology. Secondary data were sourced from official publications, such as the Statistical Abstract published by the Directorate of Economics and Statistics (GoR), as well as reports from the Forest Department, to assess the adoption rate of the SDS. The primary data were collected to evaluate the changes in economic and environmental benefits derived from the stabilized sand dunes, using a set of direct and proxy indicators such as crop yield, fodder availability, fuelwood sourcing, reduction in drudgery, and decreased de-silting costs for irrigation channels. This data was gathered through focus group discussions (FGDs) conducted at nine locations across the Bikaner, Jaisalmer, and Churu districts, which together encompass the major areas of sand dunes (Figure 3). From each village, two sites were selected: one with stabilized dune and another with unstabilized sand dune. Additionally, soil and plant samples were collected from these sites to assess the impact of SDS on soil properties and on both above and below-ground carbon sequestration.

Figure 3. Location map of the study area
(A) National scale, (B) Rajasthan state of India, and (C) sampling sites.



3.2 Analytical tools

3.2.1 Impact of sand dune stabilization

Various indicators were used as a proxy to assess the economic and environmental effects of sand dune stabilization, including increased crop yield, fuelwood production, fodder, and related supporting services. In our case, supporting services include reducing labour intensity and minimizing the costs associated with desilting canals and water channels. Data on these indicartors were collected through FGDs, systematic literature reviews, and the application of scientifically grounded assumptions, as detailed below.

Crop yield enhancement: Farmers gain direct advantages from dune stabilization, with the extent of these benefits depending on the severity of wind erosion and the resulting losses. Through focus group discussions (FGDs), we assessed the yield of various crops in both rainfed and irrigated regions across different locations and translated these yield differences into moth bean equivalent yield.

Fuel wood: To estimate fuel wood production, primarily from *Acacia tortilis*, only trees planted over five years ago were considered as a minimum of five years are necessary for tree establishment. The current market price of fuel wood in the region stands at Rs. 2700 per ton.

Fodder: The stabilized dunes help establish a variety of grasses, such as *Cenchrus ciliaris*, *Cenchrus biflourus, Lasiurus sindicus*, and shrub species like *Calligonum polygonoides* and *Haloxylon spp*, which have significant fodder potential. The prevailing price of dry grass fodder is Rs. 3500 per ton.

Drudgery: As discussed in the FGDs, it was assumed that one hectare of stabilized dunes would suffice to meet the fuelwood and fodder needs of a household with an average family size of five members and one standard animal unit (SAU). Based on the relationship between the area of stabilized dunes and the labour required for fuelwood and fodder needs, the daily labour savings per hectare in tasks related to grazing and fuelwood collection were estimated for further calculations.

Water channel desilting: The desilting of sediment accumulated in canals and water channels due to the movement of sand dunes incurs significant costs, particularly in terms of labour. Stabilizing dunes helps reduce sedimentation, thereby decreasing the expenses related to desilting. The cost savings were estimated based on the labour required, measured in man-days, to desilt channels for irrigating one hectare of land. This estimation was derived from information gathered during the FGDs. The average labour cost is Rs. 400 per man-day.

Soil physico-chemical properties: To analyze the soil physico-chemical properties such as electrical conductivity (EC), pH, soil organic carbon (SOC), and available N, P, and K, both stabilized and unstabilized sand dunes were examined. For this analysis, samples were taken from the topsoil layer (0–30 cm). The soil analysis followed standard methods as suggested by Singh et al. (2005), which included measuring pH and EC (soil/H_2O, 1:2.5; Richards, 1954), determining soil organic carbon (Walkley–Black method, 1934), assessing available nitrogen (Alkaline Potassium permanganate method; Subbiah and Asija, 1956), determining available phosphorus (0.5 N $NaHCO_3$; Olsen, 1954), and evaluating available potassium (1 N NH_4 acetate; Metson, 1956).

Carbon sequestration: To estimate carbon sequestration from sand dune stabilization, both soil and plant carbon storage were considered. In plants, analyses were conducted on both above-ground and below-ground biomass. For soil carbon sequestration assessment, 54 samples were collected from six layers of top soil (0–15, 15–30, 30–45, 45–60, 60–75, and 75–100 cm). This process involved determining the amount of carbon stored in the soil over a specific period. Dried soil samples were analyzed for soil organic carbon (SOC) using the Walkley–Black $K_2Cr_2O_7$–H_2SO_4 oxidation method, while inorganic carbon was assessed using the Hutchinson rapid titration method. Total soil carbon, comprising both organic and inorganic forms, was converted into tonnes per hectare. Soil carbon stocks were computed using Equation 1 (Stringer et al., 2015).

$$\text{Carbon Stocks (tons per hectare)} = Bd \times d \times C \quad (1)$$

Where, Bd is the soil bulk density (g cm^{-3}), d is the depth of sampling (in cm), and C is the soil organic carbon content (%).

To calculate carbon sequestration from various plant species, including trees, shrubs, and grasses, samples were collected from all eighteen sites. A total of fifty-four plots, each measuring 10 m × 10 m, were strategically placed across nine locations of stabilized dunes and nine locations of unstabilized dunes in three districts, randomly selected based on sand dune distribution. In each plot, a systematic approach was employed, with a 1 m × 1 m plot randomly chosen for grass biomass sampling. Within each 1 m × 1 m grass quadrat, the aboveground biomass was meticulously harvested and categorized into living biomass and litter biomass. For belowground grass biomass, an 8 cm inner-diameter soil auger was used in each quadrat.

In each plot, meticulous records were kept for the shrubs, detailing vegetation coverage, shrub species diversity, and the dimensions of individual shrubs, including height and crown breadth. For shrubs less than 50 cm in height, the entire aboveground biomass was harvested, while for taller shrubs, half of the aboveground biomass was collected. Clippers were used to gather the aboveground biomass, and roots were excavated to determine the root/shoot biomass (R/S) ratio for each shrub species, following the measurement of height and crown diameter. Allometric equations of different species were used to estimate carbon sequestration (FSI, 1996). After harvesting, the aboveground biomass was divided into distinct components: leaves, branches, and plant litter. The roots of each common species were combined and mixed to determine the carbon content in the root biomass component using the loss-on-ignition method (Dean, 1974). Plant carbon content was calculated by multiplying the plant's dry weight by the factor of 0.475, as suggested by Nelson and Sommers (1996).

The carbon stock in each biomass pool was calculated using Equation 2, based on the pool's oven-dry biomass and carbon fraction.

$$CS_i = TDW_i \times CF_i \tag{2}$$

Where, CS_i is carbon stock in i^{th} component (kg); TDW_i is total oven dry weight of i^{th} component (kg); and CF_i is carbon content in biomass of i^{th} component (%).

3.2.2 Economic value of benefits

The monetary value of the benefits arising from sand dune stabilization was assessed through a range of direct and indirect valuation methods. Table 4 presents the methods and indicators employed to quantify these benefits.

Table 4. Methods and indicators used for valuation of ecosystem services from sand dune stabilization

Parameter	Estimation formula	Method used	Price	Source
Crop yield	Moth bean equivalent yield (kg/ha) × market price (Rs./kg)	Production method	Moth bean price = Rs. 57.75/kg	Local market price, 2022-23
Fuelwood	Yield (ton/ha) × market price (Rs./ton)	Market price method	Rs. 2700/ton	Local market price, 2022-23

Parameter	Estimating formula	Method used	Price	Source
Fodder	Yield (ton/ha) × market price (Rs./ton)	Market price method	Rs. 3500/ton	Local market price, 2022-23
Drudgery	Man-days = (Number of hours saved per day × active days) /8.	Opportunity cost method	Wage rate = Rs. 400/man-days	Local wage rate, 2022-23
Water channel desilting	No. of times desilting in area of unstabilized – No. of times desilting in area of stabilized	Avoided cost method	Wage rate = Rs. 400/man-days	Local market price, 2022-23
Soil fertility	Net nutrient (NPK) availability in stabilized sand dunes compared to unstabilized sand dunes	Replacement cost method	Rs. 110.9/kg of N Rs. 132.2/kg of P Rs. 86.6/kg of K	Sandhu et al., (2008)
Carbon sequestration	Amount of total (soil and plant) carbon sequestrated (ton/ha) × Social cost of Carbon (Rs./ton CO_2e)	Social cost method	US$80/ton of CO_2 e	World Bank and Ecofys, 2015

3.2.3 Economic surplus model

To evaluate the economic impact of sand dune stabilization technology on crop productivity at the field level, the economic surplus model (ESM) was employed. This model analyzes the potential market responses that may arise from the introduction of such technology. ESM accomplishes this by examining the establishment of new equilibria through a demand-supply framework. It operates on the fundamental assumption that adopting new technologies enhances crop productivity, thereby shifting the supply curve to the right, which benefits both producers and consumers. Consequently, the net surplus can typically be divided into the producer's surplus and the consumer's surplus. In this particular analysis, any observed increase in surplus is attributed solely to the producer, excluding consideration of the consumer's surplus.

Moreover, factors such as innovator's rent and technology fees are pivotal in determining the overall economic impact of adopting new technology. Essentially, the intricacy of these elements adds depth to the evaluation of the scale and distribution of the economic benefits linked to the technology. The economic surplus model focuses solely on the effects of technological changes within the market where they occur, intentionally ignoring the consequences in other markets, including input markets. This targeted approach allows for a concentrated analysis of the direct effects of technological advancements on the specific market, simplifying the assessment of economic surplus by excluding external market influences.

The estimation of economic surplus involved a series of following procedures.

Step-I: Estimating production increases due to the technology (j parameter): The j is the total increase in production due to sand dune stabilization, assuming no change in the cost of production of agricultural crops. It is estimated as follows.

$$j = \frac{(\Delta Y \times n)}{Y} \tag{3}$$

where ΔY is the change in yield of the crop due to stabilized sand dune compared to that in un-stabilized dunes (kg per hectare); Y is the average yield of the crop; n is the adoption rate, i.e., area under sand dune stabilization divided by the total area of sand dune.

Step-II: Estimating supply shifts (k parameter): Here k is the net reduction in production costs as a proportion of product price induced by the sand dune stabilization, combining the effects of increased productivity and adoption costs. It corresponds to a vertical shift in the supply curve, given j (increase in productivity) and c (adoption costs of the sand dune stabilization technology), and could be computed using the elasticity of supply (e_s) as follows.

$$k = \left[\frac{j}{e_s}\right] - c \tag{4}$$

Step-III: Estimating equilibrium quantity change (ΔQ): The change in quantity actually caused by dune stabilization (ΔQ) depends on the shift in supply and the responsiveness of supply and demand. The ΔQ can be computed as:

$$\Delta Q = \frac{[Q \times e_s \times e_d \times k]}{[e_s + e_d]} \tag{5}$$

where ΔQ is the total (aggregate) production of all crops (kg), and e_d is the elasticity of demand (assumed 0.5).

Step-IV: Computing social gains and net gains: The economic benefits from the adoption of SDS technologies were calculated as:

$$\text{Social gains (SG)} = [k \times P \times Q] \pm \frac{1}{2}[k \times P \times \Delta Q] \tag{6}$$

where, P is the crop price in real term (Rs. per kg). The second term of RHS of Equation (5) is subtracted for ex-post impact assessment while it is added for ex-ante impact assessment. The base price (P_0) denotes the deflated current price expressed at constant 2022-23 levels, while the base quantity (Q_0) refers to the total production in arid Rajasthan during 1984, standardized in terms of moth bean equivalents. In this case we subtracted the term since the study is ex-post impact assessment of the sand dune stabilization. Net surplus was estimated after subtracting the costs of research (R) which includes cost of implementation i.e. cost of sand dune stabilization as:

$$\text{Net surplus} = SG - (R + E) \tag{7}$$

Net surplus was calculated at constant price with base year 2022-23.

3.2.4 Cost of sand dune stabilization

Farmers have been hesitant to adopt sand dune stabilization technology on their fields due to its limited direct benefits and labour-intensive nature. Consequently, the Department of Forest, Government of Rajasthan, has primarily undertaken its implementation. Therefore, we have sourced the costs associated with sand dune stabilization from the Indira Gandhi Nahar Pariyojana (IGNP), Stage-II, Bikaner. In this project, the current average cost of sand dune stabilization is Rs. 1,36,419 per hectare spread over an eight-year period (IGNP Stage-II, Bikaner).

3.2.5 Adoption of sand dune stabilization technology

The diffusion of new technology is closely linked to the adoption process. Numerous models have been developed to understand and measure this phenomenon, but the most recognized is the theory proposed by Roger (2003). This theory illustrates the gradual expansion of technology over time and serves as crucial data for understanding trends, forecasting the prospects of sand dune stabilization technology, and offering valuable insights into its future adoption progress. The logistic adoption curve provides a clearer representation of the rate at which technology is adopted over the years. Typically, the logistic adoption curve exhibits S shape. In this study, we chose a straightforward interpretation by employing a simple logistic S-curve, as suggested by CIMMYT (1993).

$$N(t) = \frac{K}{1 + e^{-\alpha t - \beta}} \tag{8}$$

where, N(t) is the cumulative adoption rate (area under sand dune stabilization) in time ‘t’; K is maximum adoption rate or ceiling point; ‘α’

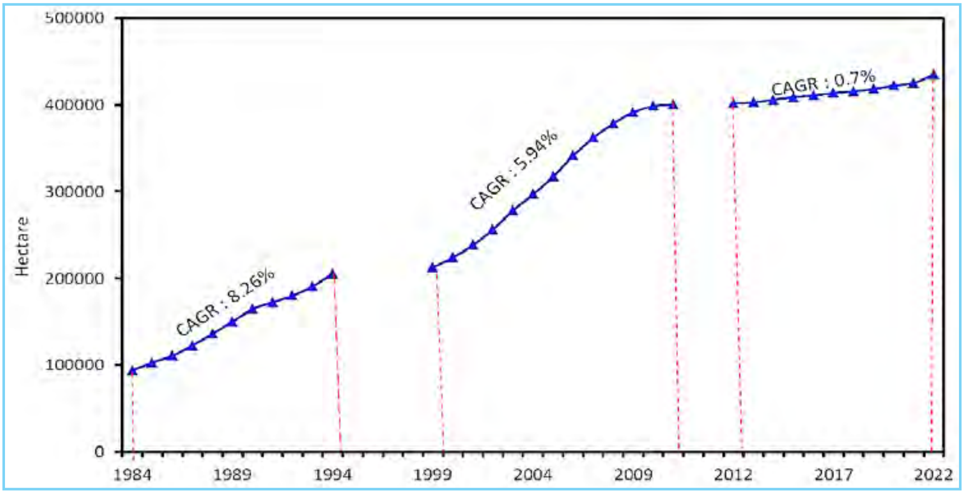
is steepness of the curve, frequently replaced with a variable that qualifies the time required for the "trajectory" to grow from 10% to 90% of limit K; t is time in year; 'β' is the time (t_m) when the curve reaches 0.5K (t_m implies symmetry of a single logistic S-curve); and 'e' is the base of the natural system of logarithms having a numerical value of approximately 2.72.

4 Adoption and Impact of Sand Dune Stabilization

4.1 Adoption of sand dune stabilization technology

The sand dunes stabilization technology developed by CAZRI has been widely adopted across India, particularly in Rajasthan and its neighbouring states. The domain area of sand dune stabilization in the Indian Thar desert is 51,80,108 hectares spread in Western hot arid region of Rajasthan (Bhadra et al., 2019). In Rajasthan alone, the area utilizing this technology expanded from 0.94 lakh hectares in 1984 to 1.65 lakh hectares in 1990, and further to 4.4 lakh hectares by 2022, reflecting an annual growth rate of 4.58% (Figure 4). The annual increase in stabilized areas continued to rise until 2006-07, after which the growth rate began to decline and remained steady. The Government of Rajasthan has played a key role in promoting sand dune stabilization, primarily through the state Forest Department by implementing various programs and schemes. Notable among these are the Maru Vikas Pariyojana (1986-87 to 1994-95), the Combating Desertification Programme (1999-2000 to 2011-12), and the Climate Change and Combating Desertification Programme (2012-13 to 2022-23).

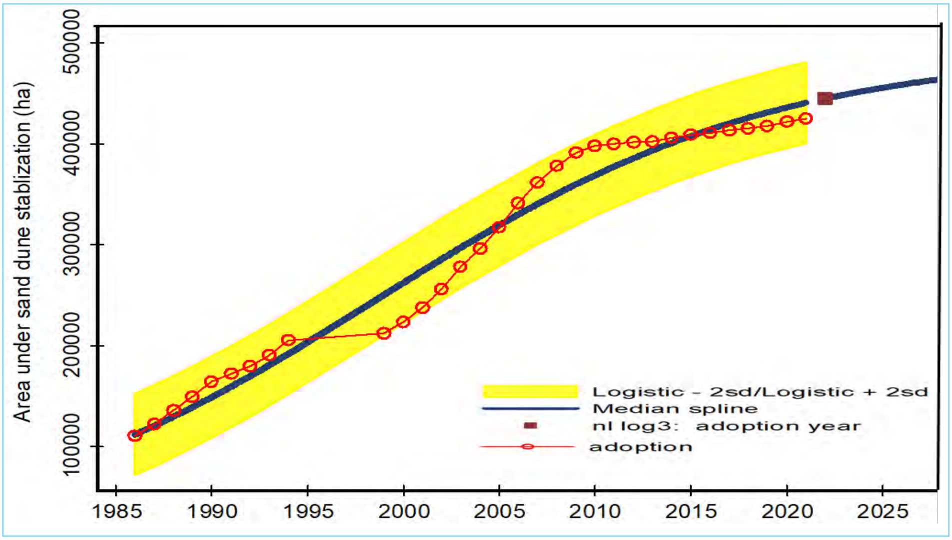
Figure 4. Growth rate of sand dune stabilization in Indian Thar Desert



Source: Authors' estimation based on data from Government of Rajasthan.

The Logistic adoption model was utilized to estimate the uptake of sand dune stabilization technology. This model provides a clear illustration of the technology's adoption rate over time (Figure 5). The findings revealed that the maximum adoption of sand dune stabilization (K parameter) is projected at 491,026 hectares, assuming the current adoption rate remains constant, *ceteris paribus* (Table 5). The steepness of the adoption curve (α), which reflects the technology's speed of adoption, is 0.097 at a specific time fraction. The parameter β indicates that the technology's adoption reached the midpoint of its maximum potential in 1998.

Figure 5. Adoption curve of sand dune stabilization technology in Indian Thar Desert



Source: Authors' estimation based on data from Government of Rajasthan.

Table 5. Parameter estimation of logistic adoption model

Parameters	Coefficient	Std. Err.	T
K	491026.4***	22470.45	21.85
α	0.097***	0.008	11.84
β	1998***	1.23	1622.32

Source: Authors' estimation; Note: *** indicates at 1% level of significance

4.2 Cost of sand dune stabilization

Estimating the cost of sand dune stabilization through afforestation is often complex and challenging due to potential regional variations (Kaul, 1996). For example, in the mid-1990s, the cost of afforesting sand dunes over three years was estimated at Rs. 7,770 per hectare in Haryana and Rs. 6,810 per hectare in Rajasthan. In the IGNP Stage-II area, encompassing the Bikaner, Jaisalmer, Churu, and Jodhpur districts of the Indian Thar Desert, the cost over eight years was estimated at Rs. 16,127 per hectare. These variations indicate regional differences in stabilization costs, which arise from disparities in material usage, wage rates, and plant costs.

In this analysis, cost estimates were derived from data provided by the Divisional Forest Office of Indira Gandhi Nahar Pariyojana, Stage-II, Bikaner, Rajasthan. As shown in Table 6, the average cost for sand dune stabilization over eight years was estimated at Rs. 1,36,419 per hectare. The primary cost components include fencing the plantation area (~Rs. 13,600 per hectare), creating micro-windbreaks (~Rs. 10,120 per hectare), constructing water storage tanks or water harvesting structures (~Rs. 8,160 per hectare), and raising plants (~Rs. 3,883 per hectare), with the highest expenses occurring in the first year. It is noteworthy that sand dune stabilization is a labour-intensive process, with labour costs comprising 83% of the total expenses for this activity.

Table 6. Cost of sand dune stabilization (Rs. per hectare)

Year	Labour cost	Material cost	Total cost	Major item of works
Year 0 – Advance action	27701	13515	41216	• Fencing • Raising of plants • Construction of water storage structure/water harvesting • Creation of micro-windbreak
Year 1 –Planting year	37510	4711	42221	• Maintenance of plants • Plantation • Sowing of pellets/balls • Watering, weeding/hoeing • Watch and ward
Year 2 – Maintenance I	29615	4028	33642	• Gap filling • Watering, weeding/hoeing • Watch and ward
Year 3 – Maintenance II	6670	441	7110	• Watering, weeding/ hoeing Watch and ward
Year 4 – Maintenance III	3463	42	3505	• Watch and ward
Year 5 – Maintenance IV	3463	42	3505	• Watch and ward
Year 6 – Maintenance V	3463	42	3505	• Watch and ward
Year 7 – Maintenance VI	1668	47	1715	• Watch and ward
Total	**113553**	**22868**	**136419**	

Source: Authors' estimation based on data from DFO, Indira Gandhi Nahar Pariyojana, Stage-II, Bikaner, Rajasthan. Note: Costs are at 2021-22 prices.

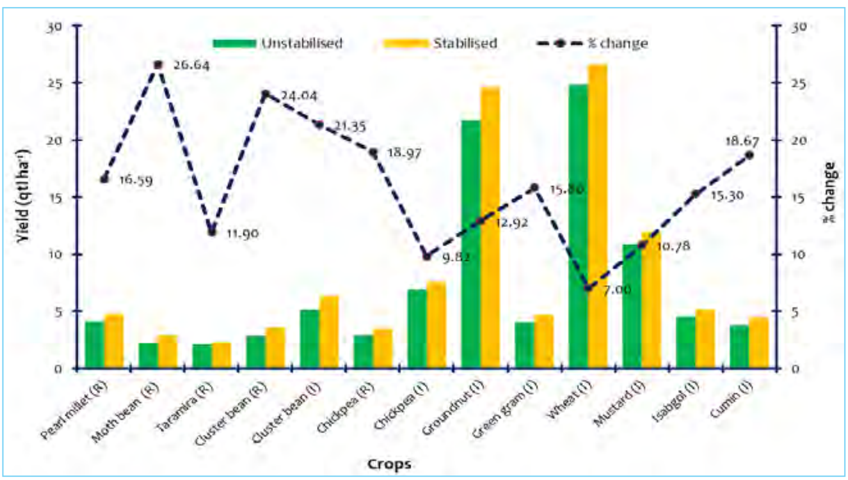
4.3 Impact of sand dune stabilization

The impact of dune stabilization technology was evaluated at both on-farm and off-farm levels, as well as at the macroeconomic level. Various indicators were employed to capture the economic and environmental effects of sand dune stabilization. The assessment focused on improvements in crop yield, fodder, and fuelwood, along with associated services such as reducing drudgery, minimizing the cost of desilting canals and field water channels, conserving soil nutrients, and enhancing carbon sequestration, both above and below ground.

4.3.1 Crop yield

Crop yield improvement is the direct benefit received by the farmers when the dunes are stabilized and varied depending on the wind erosion severity as the losses. The yield in farm areas near stabilized sand dunes is higher compared to those near unstabilized dunes, due to the reduction in wind erosion and the scorching effect of moving sand particles. The dune stabilization technology minimizes these losses by 78.97 kg per hectare of moth bean equivalent yield, an improvement of 14.5% over unstabilized dunes (Table 7). However, this enhancement in yield varies significantly among different crops with the highest in moth bean (27%) followed by cluster bean (24%), rainfed chickpea (19%), cumin (19%), pearl millet (17%), and green gram (16%) and lowest in wheat (7%), irrigated chickpea (10%), Indian mustard (11%), taramira (12%), groundnut (13%), and isabgol (15%) (Figure 6). The yield enhancement was more pronounced in rainfed and *kharif* crops (Figure 6). Estimates show that wind erosion reduces the yield of pearl millet by 195 kg per hectare under the very severe category, 117 kg per hectare under the severe category, and 29 kg per hectare under the moderate category of wind erosion (Santra et al., 2017).

Figure 6. Impact of dune stabilization on crop yield in Indian Thar Desert



Source: Author's estimations based on FGDs
Note: R&I refers to rainfed and irrigated farming system, respectively

Table 7. Impact of sand dune stabilization in the Indian Thar Desert

Parameters	Unstabilized dunes	Stabilized dunes	Change
Crop yield (kg/ha Moth bean equivalent)	544.14	623.11	78.97
Fodder (tons/ha)	-	0.27	0.27
Fuelwood (tons/ha)	-	9	9
Drudgery (man-days/ha)	223	186.76	36.24
Water channel desilting (No. of times)	5	2	3

Source: Author's estimations based on FGDs.

4.3.2 Fodder

Stabilization often involves methods like planting drought-resistant grasses or shrubs that help prevent sand movement and reduce erosion. These plants not only improve soil quality but can also serve as valuable fodder for animals, particularly in arid regions where such vegetation may be scarce. The presence of stabilized dunes creates a more hospitable environment for sustainable grazing. The dune stabilization improves the fodder production by 0.27 ton per hectare. (Table 7).

4.3.3 Fuelwood

The findings revealed that the fuel wood yield in the stabilized sand dunes varies depending on the age of the trees, ranging from 13 kg per tree at 4 years to 50 kg per tree at 9 years, typically following the pattern of rainfall in various habitats. The stabilized sand dunes planted with *Acacia tortilis* achieve an average fuelwood yield of 13 tons per hectare by the age of 5 years, an increase of 9 tons per hectare over un-stabilized dunes (Table 7). Previous studies have underscored the relatively higher production potential of wood production from stabilized sand dunes ranging from 15 to 25 tons per hectare depending on the rainfall and the age of the plantation (Bhimaya et al.,1961) and in some cases even up to 30 tons hectare of plantation aged 10 years (Muthana, 1982).

4.3.4 Drudgery

Similarly, to assess the reduction in physical labour, two primary tasks, *i.e.*, collecting fuelwood and fodder were considered. On average, dune stabilization saves approximately 1.3 hours per household per day in performing grazing and fuelwood collection tasks because now rural households can get fuelwood and fodder in their close vicinity due to stabilized sand dunes. Households reported conducting these activities daily, except during May, June, July, and a few days in winter. This adds to approximately 223 active collection days of fuelwood and fodder collection per year, enabling rural households to save about 36.24 man-days per hectare per year (Table 7).

4.3.5 Water channel desilting

Sand dunes cause silting issues in the farm's irrigation channel, necessitating continuous desilting. During focus group discussions (FGDs), farmers noted that in areas where dunes were stabilized, irrigation channels required desilting twice a year (before the Kharif season and mid-Kharif season), compared to five times a year in areas with unstabilized dunes. The silting problem has decreased near stabilized dunes due to the reduced mobility of sand particles. Cost savings were calculated based on the requirement of four man-days per hectare to desilt water channels for irrigating one hectare of land which is approximately 100 m in length.

4.3.6 Soil fertility

Stabilizing sand dunes has a significant impact on soil health by improving its physical properties and nutrient content. The topsoil layer (0-30 cm) of stabilized dunes exhibited higher levels of organic carbon, nitrogen, phosphorus, and potassium compared to unstabilized dunes (Table 8). Dune stabilization led to a slight reduction in soil pH (4.7%) and electrical conductivity (EC) (7.4%). The most notable improvement was in nutrient content, with organic carbon increasing by 0.08 percent point, phosphorus by 107%, nitrogen by 76%, and potassium by 40%. Per hectare, dune stabilization resulted in an increase of 34.22 kg of nitrogen, 7.40 kg of phosphorus, and 61.22 kg of potassium.

Table 8. Changes in soil parameters due to sand dune stabilization

Parameters	Unstabilized dunes	Stabilized dunes	% Change
pH	8.75 (8.53-8.99)	8.34 (7.80-8.72)	-4.7
EC (ds/m)	0.094 (0.05-0.14)	0.087 (0.05-0.18)	-7.4
Organic Carbon (%)	0.06 (0.04-0.08)	0.14 (0.10 -0.22)	0.08*
Nitrogen (kg/ha)	44.9 (33.1-63.0)	79.1 (53.1 – 121.0)	76.2
Phosphorus (kg/ha)	6.9 (3.3-9.4)	14.3 (10.9-17.6)	107.2
Potassium (kg/ha)	150.7 (130.1-267.0)	211.9 (138.2-281.0)	40.6

Source: Author's estimations.
Note: Figure in parenthesis indicate the range. *Expressed in percentage point change.

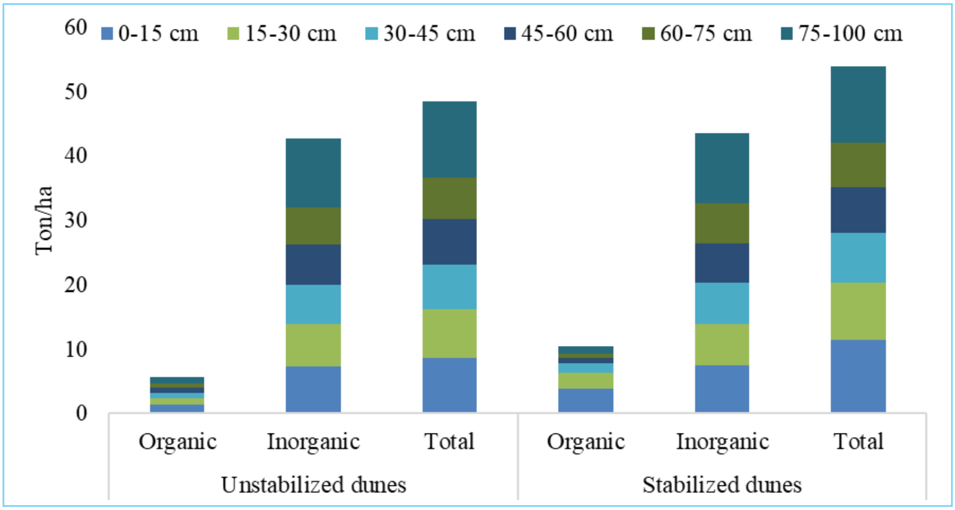
4.3.7 Carbon sequestration

The analysis of the soil carbon stocks up to the depth of one meter showed that the dune stabilization helps in improving the carbon stock by 11%

from around 49 to 54 tons per hectare. The improvement was much higher in the case of organic carbon sequestration compared to inorganic carbon (Figure 7). The increase was more pronounced in top soil (0 – 30 cm). The average increase in soil carbon at the different depths of soil is depicted in Figure 7. The organic carbon stock in the soil of sand dunes tends to follow a rainfall gradient with variation in organic carbon content being higher than that of inorganic carbon.

The vegetation found on sand dunes plays a significant role in the accumulation of carbon. These sand dunes host a variety of vegetation, including trees (e.g. *Acacia tortilis*), shrubs (e.g. *Calligonum polygonoides, Leptadenia pyrotechnica, Acacia jacquemontii, Capparis decidua, Zizhiphus nummularia,* and *Areva javanica*), and grass (*Lasiurus sindicus, Cenchrus setigerus,* and *Cenchrus ciliaris*) species. The total carbon stored in plant biomass on the stabilized sand dunes was 6.54 tons per hectare, and the additional accumulation was 6.19 tons per hectare, the majority of which (5.44 tons per hectare) was on account of the plantation of tree species (Table 9). This indicates that sand dune stabilization helps in increasing the carbon stock by approximately 19 times compared to unstabilized sand dunes. This highlights the importance of vegetation composition in influencing carbon accumulation in plant biomass in sand dune ecosystems.

Figure 7. Soil carbon stock at different soil depths in the Indian Thar Desert (ton per hectare)



Source: Author's estimations.

Table 9. Carbon stock in plant biomass in sand dunes of the Indian Thar Desert (ton per hectare)

Type of plantation	Carbon stock		Change
	Unstabilized dunes	Stabilized dunes	
Below ground	48.58	54.10	5.52
Above ground	0.35	6.54	6.19
Trees	0.22	5.66	5.44
Shrubs	0.09	0.76	0.67
Grasses	0.04	0.12	0.08
Total	**48.92**	**60.63**	**11.71**

Source: Author's estimations.

4.4 Monetary value of benefits

The enhancement in crop yield resulting from sand dune stabilization, quantified as moth bean equivalent yield (78.97 kg per hectare), equates to a monetary value of Rs. 4,561 per hectare. Among the primary provisioning services offered by sand dune stabilization is animal fodder, which boosts fodder production by 0.27 tons per hectare, valued at Rs. 945 per hectare (Table 10). The local market price for fuelwood is Rs. 2,700 per ton, leading to an estimated value of Rs. 24,300 per hectare from fuelwood production. Additionally, a notable advantage is the reduction in labour, or drudgery, with savings amounting to Rs. 14,495 in terms of saved man-days.

Supporting services encompass a reduction in the cost of desilting field water channels, which amounts to Rs. 4,800 per hectare. The value of soil nutrients, including NPK (Nitrogen, Phosphorus, and Potassium), is estimated at Rs. 10,071 per hectare, indicating improvements in soil fertility and nutrient levels in the topsoil of sand dunes. For carbon sequestration, using a global average carbon price of US$ 80 per ton of CO_2e (as recommended by the World Bank and Ecofys, 2015), the per hectare value of sequestered carbon is approximately Rs. 2,85,359 per hectare. Across the total area of 440,311 hectares of stabilized sand dunes, the total value of additional carbon sequestration is estimated at Rs. 1,25,647 million. The contribution of additional carbon sequestration in soil and plants is nearly equal. The total economic value of the additional benefits from sand dune stabilization is estimated at Rs. 3.44 lakh per hectare, with about 90% of this value attributed to environmental benefits, particularly carbon sequestration. The direct benefit received by farmers is relatively low, amounting to Rs. 49,101, compared to the indirect benefit of

Rs. 2,95,430. However, when the total cost of stabilization is spread over 8 years (the time required for stabilization), farmers still receive more direct benefits each year than the investment they made.

Table 10. Valuation of ecosystem services of sand dune stabilization in the Indian Thar Desert

Parameters	Change	Value (Rs. per hectare)
Crop yield (kg/ha)	78.97	4561
Fodder (ton/ha)	0.27	945
Fuelwood (ton/ha)	9	24300
Drudgery (man-days/ha)	36.24	14495
Water channel desilting (No. of times)	3	4800
Soil fertility		
Total available NPK (kg/ha)	216	10071
Carbon sequestration (ton/ha)	11.71	285359
Total		**344531**

Source: Author's estimations.

4.5 Macroeconomic impact: An economic surplus approach

The macro-economic impact of sand dune stabilization was estimated using the economic surplus approach. The estimation of economic surplus requires data on parameters, including the cost of development and adoption of technology, changes in yield parameters, prices, elasticities of demand and supply, rate of adoption, *etc*. The sand dune stabilization (SDS) technology developed by CAZRI and embraced mainly by the Rajasthan Forest Department, entails substantial costs, both on development and adoption. For the purpose of this analysis, the focus is specifically on the expenses incurred during the adoption or stabilization of dunes, amounting to Rs. 1.36 lakh per hectare. The data on sand dune stabilization was collected from 1984 onwards. The cost incurred in sand dune stabilization has been adjusted for inflation using the wholesale price index (WPI) with the base year 2022-23. On an average, the productivity gains (in terms of moth bean equivalent yield) for various crops in the current year stand at 78.97 kg per hectare over un-stabilized sand dune situations. We have assumed a price elasticity of supply and demand to be 0.5. We used farm harvest prices for pearl millet, moth bean, mung bean, chickpea, Indian mustard, wheat, and Taramira (*Eruca Sativa*). Additionally, for cluster bean, isabgol (*Psyllium*), and cumin, we used the average market prices in our analysis. The parameters used in the economic surplus model are given in Table 11.

Table 11. Parameters of economic surplus model for dune stabilization in the Indian Thar Desert

Parameter	Value	Source
Price (P_0) (Rs./quintal)	688	Deflated at 2022-23 base price FGDs
Increase in yield (%)	14.5%	FGDs
Maximum adoption level	10%	Assumed on the basis of experts' opinion
Supply elasticity	0.5	Author's assumption
Demand elasticity	0.5	Author's assumption
Cost of stabilisation (Rs./ha)	1,36,419	DFO, Indira Gandhi Nahar Pariyojana-Stage-II, Bikaner

Source: Author's estimations.

The gross economic surplus generated from sand dune stabilization through crop production alone was estimated at Rs. 157,851 million for the period 1984 to 2022 (Table 12). After deducting the cost of stabilization, the net economic surplus was Rs. 135,978 million. This figure exclusively represents farm-level economic gains attributable to crops. Additional benefits arising from other impacts or spillover effects associated with the technology have been discussed above. If these additional impacts were accounted for, the total economic surplus would likely be significantly higher. The straightforward calculation suggests that the benefits from other than crop yield would be atleast 75 times more. Furthermore, the analysis emphasizes the economic impact generated per hectare of land, highlighting the efficiency and localized benefits of the intervention.

Table 12. Estimates of economic surplus from sand dune stabilization in the Indian Thar Desert (Rs. in million)

Particular	1984 to 2022
Total economic surplus	157851
Total cost	21873
Net economic surplus	135978
Economic surplus per annum	3578
Net present value (NPV)	30638.1
Internal rate of return (IRR)	30.3%
Benefit cost (BC) ratio	4.5

Source: Author's estimations.

5 Conclusions and Policy Implications

Drawing on data gathered through focus group discussions (FGDs), personal interviews, field observations, and secondary sources, this study meticulously evaluates the adoption and impact of the sand dune stabilization technology innovated by the Central Arid Zone Research Institute (CAZRI) in the Indian Thar Desert. The findings suggest that sand dune stabilization technology has covered around 4.4 lakh hectares from 1984 to 2022. However, the speed of adoption of 0.097 at time fraction of the area under sand dunes is still very low. Moreover, the sand dune stabilization technology has primarily been implemented on government-owned land through state government initiatives, lacking active involvement from local communities. A greater focus on the promotion of fast-growing exotic tree species, like *Neltuma juliflora*, the non-availability of disease-free quality planting material of multi-purpose tree species, and labour shortage are possible reasons why adoption by farmers has not been very encouraging. Therefore, there is a need to ensure disease free adequate availability of planting material of indigenous tree species (*Ziziphus mauritiana, Calligonum polygonoides*, and Acacia Spp.), adoption of suitable grass (*Lasiurus scindicus*, and *Cenchrus ciliaris*) and multi-purpose woody perennial adapted to sand dunes of Thar Desert, and eradication of invasive exotic species.

To achieve the ambitious goal of reclaiming 26 million hectares of degraded lands by 2030, concerted and coordinated efforts are required from all stakeholders, including local communities, State Departments of Forest, Agriculture, and Irrigation, State Agricultural Universities, and Civil Society Organizations, to promote indigenous multipurpose species. It was observed that shrubs and grasses are more viable than trees for sand stabilization. However, maintaining grass cover poses a challenge due to issues related to uncontrolled grazing. In areas with relatively inaccessible dunes and minimal grazing pressure, aerial seeding of palletized grass seeds (*Lasiuruss scindicus*) along with shrubs and trees emerges as a suitable option for sand dune stabilization. Given the role of livestock in the region, promoting silvi-pastoral models emerges as a pragmatic solution.

Fencing and labour are the major components of expense in sand dune stabilization, a burden that could be alleviated through social fencing facilitated by local community involvement. Moreover, aligning the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) with the sand dune stabilization program could optimize manpower usage. Engaging local communities from the planning to the execution stage is essential to instil a sense of community ownership.

The field-level impact assessment showed that the dune stabilization technology has a significant impact on the production of ecosystem goods and services, manifesting in various tangible and intangible benefits. The crop yield increased by 14.5%, the highest being in moth bean and cluster bean. The yield increase was more pronounced in *kharif* crops compared to *rabi* crops. Additionally, the stabilization efforts act as a protective barrier, preventing sand encroachment in irrigation channels, while also providing economic products such as fuelwood and fodder. Every hectare of stabilized dune added ~9 tons of fuelwood and 0.27 tons of fodder, besides effectively helping to reduce human drudgery by 36 man-days in a year because of the on-farm availability of fodder and fuelwood.

There are discernible improvements in soil properties and an increase in carbon sequestration. The available potassium, nitrogen, phosphorus, and organic carbon content in the soil improved by 1.4, 1.8, 2.1, and 2.2 times, respectively, while soil pH and EC decreased by 4.7% and 7.4%, respectively. The increase in biomass, identified as a crucial component of decarbonization strategies to mitigate climate change, was reported to be very significant in dune stabilization, with a remarkable 24% increase (equivalent to 11.71 tons per hectare). Much of this addition was contributed by plant biomass (53%), mostly by trees (46.5%). While below-ground carbon sequestration is considered more stable (Forfora et al., 2024), the increase in above-ground biomass, particularly from trees, will help in bridging the timber supply gaps in the country, as more than half of the country's wood demand is met through imports.

The economic value of benefits derived from dune stabilization are impressive, estimated to be Rs. 3,44,531 per hectare, with approximately 90% of this value attributed to environmental benefits, particularly carbon sequestration. The direct benefit received by farmers is relatively low, amounting to Rs. 49,101 per hectare, compared to the indirect benefit of Rs. 2,95,430 per hectare. However, when the total cost of stabilization is spread over 8 years (the time required for stabilization), farmers still receive more direct benefits each year than the investment they made. Since the benefits are slow to materialize, farmers require financial incentives in the early years to ensure continued participation. The high value of carbon sequestration suggests that dune stabilization projects could qualify for carbon credit programs, generating revenue for local communities besides achieving the targets of goals of land degradation neutrality and advancing net-zero emissions targets.

At the macro level for Rajasthan state as a whole, the gross economic surplus generated so far from sand dune stabilization through crop production alone was estimated at Rs. 157,851 million and the net economic surplus was estimated at Rs. 135,978 million. If these additional impacts were accounted for, the total economic surplus would likely be significantly higher. The straightforward calculation suggests that the benefits other than crop yield would be atleast 75 times more than that from crop yield improvement. These findings strongly justify and call for strengthening the investment in dune stabilization not only in Rajasthan but also in states like Gujarat and Southern Haryana. Governments, in partnership with private and civil society organizations, should promote dune stabilization as a climate adaptation strategy, linking it with broader policies on desertification control, afforestation, and water conservation.

Enhancing and adoption of sand dune stabilization in the Indian Thar Desert requires and integrated approach across technical, institutional, and policy fronts. Technically, establishing advanced nurseries of indigenous species, promoting grass-shrub-tree models and using mechanized tools can improve efficiency and effectiveness. Institutional measures such as community led models and multi-stakeholder coordination platforms can strengthen ownership and implementation. Policy support through integration with MGNREGA, targeted financial incentives particularly early stage incentives, and across the carbon credit markets can make adoption more economically attractive. Complementing these with robust research, extension, and training, along with incorporating ecosystem service valuation into planning, will help secure long term investment and scale up sustainable stabilization efforts.

References

Ahmady-Birgani, H., K. G. McQueen, M. Moeindaddini, and H. Naseri. 2017. Sand dune encroachment and desertification processes of the Rigboland Sand Sea, Central Iran. *Scientific Reports* 7(1): 1–10.

Ahmed, N. B. 1990. The stabilization of Aeolian sand dunes. Durham theses, Durham University, Durham, The UK. http://etheses.dur.ac.uk/1099/

Amiraslani, F., and D. Dragovich. 2011. Combating desertification in Iran over the last 50 years: An overview of changing approaches. *Journal of Environmental Management* 92: 1–13.

Baas, A., and L. Delobel. 2022. Desert dunes transformed by end-of-century changes in wind climate. *Nature Climate Change* 12: 1–8. doi:10.1038/s41558-022-01507-1

Bhadra, B. K., S. K. B. Rehpade, H. Meena, and S. S. Rao. 2019. Analysis of parabolic dune morphometry and its migration in Thar Desert area, India using high-resolution satellite data and temporal DEM. *Journal of the Indian Society of Remote Sensing* 47: 2097–2111. doi:10.1007/s12524-019-01050-1

Bhimaya, C. P. and R. N. Kaul. 1960. Some afforestation problems and research needs in relation to erosion control in arid and semi-arid parts of Rajasthan. *Indian Forester* 87:354-367.

Bhimaya, C. P., R. N. Kaul, and D. N. Ganguli. 1961. Sand dune rehabilitation in Western Rajasthan. *Proceedings of the 5th World Forestry Congress* 1:58-363.

Bruno, L., M. Horvat, and L. Raffaele. 2018. Windblown sand along railway infrastructure: a review of challenges and mitigation measures. *Journal of Wind Engineering and Industrial Aerodynamics* 177:340-365.

Chand, P. and S. Sirohi. 2015. Sectoral priorities for sustainable livestock development in Rajasthan: lessons from total factor productivity growth. *Agricultural Economics Research Review* 28:81-92. https://doi.org/10.5958/0974-0279.2015.00024.5

Chand, P., T. M. Kiran Kumara, S. Pal, and K. Naik. 2024. *A spatial assessment of sustainability in Indian agriculture*. Policy Paper 42, ICAR-National Institute of Agricultural Economics and Policy Research, New Delhi.

Chandrasekaran, S., K. Saraswathy, N. S. Saravanan, N. Kamaladhasan, and N. A. Arunnagendran. 2014. Impact of *Prosopis juliflora* on nesting success of breeding wetland birds at Vettangudi bird sanctuary, South India. *Current Science* 106:676-678.

CIMMYT. 1993. The adoption of agricultural technology: a guide to survey design. *Economics Program*, International maize et wheat improvement center, Mexico.

Dean, W. E. Jr. 1974. Determination of carbonate and organic matter in calcarcous sediments sedimentary rocks by loss on ignition. *Journal of Sedimentary Petrology* 44:242-248.

Deng, S., D. Zhang, G. Wang, X. Zhou, C. Ye, T. Fu, T. Ke, Y. Zhang, Y. Liu, and L. Chen. 2020. Biological soil crust succession in deserts through a 59-year-long case study in China: how induced biological soil crust strategy accelerates desertification reversal from decades to years. *Soil Biology and Biochemistry* 141:107665. https://doi.org/10.1016/j.soilbio.2019.107665.

Di, W. J, Y. C. Zhang, and L. He. 2018. Selection principles of plant species for wind break and sand fixation. *Agriculture and Technology* 38:216.

Dong, Z., Chen, G., He, X., Han, Z., and Wang, X. 2004. Controlling blown sand along the highway crossing the Taklimakan Desert. *Journal of Arid Environments* 57(3), 329–344. https://doi.org/10.1016/j.jaridenv.2002.02.001

Fadhil, A. M. 2013. Sand dunes monitoring using remote sensing and GIS techniques for some sites in Iraq Proc. SPIE 8762, PIAGENG 2013: Intelligent Information, Control, and Communication Technology for Agricultural Engineering, 876206. https://doi.org/10.1117/12.2019735

Forfora, N., I. Azuaje, K. A. Vivas, R. E. Vera, A. Brito, R. Venditti, S. Kelley, Tu Qingshi, W. Alex, and G. Ronalds . 2024. Evaluating biomass sustainability: Why below-ground carbon sequestration matters. *Journal of Cleaner Production* 439:140677. https://doi.org/10.1016/j.jclepro.2024.140677.

FSI. 1996. Volume Equations for Forests of India, Nepal and Bhutan. Forest Survey of India, Ministry of Environment and Forests, Dehradun.

GoI. 2011. *Census of India 2011*. Office of Registrar General & Census Commissioner, Ministry of Home Affairs, New Delhi.

GoI. 2019. *20th Livestock census, 2019: all India report*. Department of Animal Husbandry and Dairying, Ministry of Fisheries, Animal Husbandry and Dairying, New Delhi.

GoR. 2022. *Divisional Forest Office*. Indira Gandhi Nahar Pariyojana, Stage-II, Bikaner

GoR. Various years. *Annual reports*. Department of forest, Ministry of Forest, Government of Rajasthan, Jaipur.

Gad, A. 2016. Sand dune distribution and related impacts on agricultural resources of Sinai Peninsula, Egypt, using integrated remote sensing-GIS techniques. *Global Advanced Research Journal of Agricultural Science* 5:42-50.

Gong, F. H., X. D. He, and X. Y. Peng. 2001. Comparison of properties and cost of different sand-fixing system along Tarim Desert Highway. *Journal of Desert Research* 21:45-49.

Gorgens, A. H. M. and B. W. Van Wilgen. 2004. Invasive alien plants and water resources in South Africa: current understanding, predictive ability and research challenges: working for Water. *South African Journal of Science* 100:27-33.

Gupta, J. P., D. C. Joshi, and G. B. Singh. 2000. Management of arid agro ecosystems. In: Yadav, J. S. P. and G. B. Singh (eds.), *Natural Resource Management for Agricultural Production in India*. Indian Society of Soil Science, New Delhi, pp. 551-568.

Han, Z., T. Wang, Q. Sun, Z. Dong, and X. Wang. 2003. Sand harm in Taklimakan Desert highway and sand control. *Acta Geographica Sinica* 58:201-208. https://doi.org/10.11821/xb200302006

Han, Z., T. Wang, Z. Dong, Y. Hu, and Z. Yao. 2007. Chemical stabilization of mobile dune fields along a highway in the Taklimakan Desert of China. *Journal of Arid Environments* 68:260-270. https://doi.org/10.1016/j.jaridenv.2006.05.007.

Harsh, L. N, and J. C. Tewari. 1993. Sand dune stabilization, shelterbelts and silvipastoral plantation in dry zones. In: Sen, A. K. and A. Kar (eds.), *Desertification and its control in the Thar, Sahara and Sahel,* Regions Scientific Publishers, Jodhpur, pp. 269-279.

He, Z. H., S. Y. Li, and H. F. Wang. 2014. Comparison of wind prevention and sand blocking effects of 4 types of sand blocking nylon nets in the Central Taklimakan Desert. *Arid Zone Research* 31:369-374.

Huang, J., X. Guan, G. Wang, and R. Guo. 2016. Accelerated dryland expansion under climate change. *Nature Climate Change* 6:166–171. https://doi.org/10.1038/nclimate2837

IPCC. 2019. Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Intergovernmental Panel on Climate Change, Geneva.

Kalla, J. C. 1974. Economic evaluation of arid land management technology. In: Mann, H.S. (ed.), *Desert ecosystem and its environment*. CAZRI, Jodhpur. pp. 285-295.

Kar, A. 1993. Aeolian processes and bedforms in the Thar Desert. *Journal of Arid Environments* 25:83-96.

Kar, A. 1995. Geomorphology of arid Western India. *Memoirs of Geological Society of India* 32:168-190.

Kar, A. 1996. Morphology and evolution of sand dunes in the Thar Desert as ley to sand control measures. *Indian Journal of Geomorphology* 1:177-206.

Kar, A. 1999. Neotectonic and climatic controls on drainage evolution in the Thar Desert. In: Paliwal B.S. (ed.), *Geological evolution of North-Western India*, Scientific Publishers, Jodhpur. pp. 246-259.

Kar, A., A. K. Singhvi, N. Juyal, and S. N. Rajaguru. 2004. Late Quaternary aeolian sedimentation history of the Thar Desert. In: Sharma H. S, S. Singh, and S. De (eds.), *Geomorphology and Environment*, ACB Publications, Kolkata, pp. 105-122.

Kar, A., P. C. Moharana, P. Raina, M. Kumar, M. L. Soni, P. Santra, Ajai, A. S. Arya, and P. S. Dhinwa. 2009. *Desertification and its control measures*. In: Kar, A, B. K. Garg, M. P. Singh, and S. Kathju (eds.), *Trends in arid zone research in India*, Central Arid Zone Research Institute, Jodhpur, pp. 1-47.

Kaul, R. N. 1985a. Afforestation of dune areas. In: *Sand dune stabilization, shelterbelts and afforestation in dry zones*, Conservation Guide 10, FAO, Rome, pp. 75-85.

Kaul, R. N. 1985b. Sand dune fixation and afforestation traditional procedures for dune fixation: the hedge system. In: *Sand dune stabilization, shelterbelts and afforestation in dry zones*, Conservation Guide 10, FAO, Rome, pp. 65-74.

Kaul, R. N. 1996. Sand dune stabilization in the Thar Desert of India: a synthesis. *Annals of Arid Zone* 35:225-240.

Kaur, R., W. L. Gonzáles, L. D. Llambi, P. J. Soriano, R. M. Callaway, M. E. Rout, Gallaher, and T. J. Inderjit. 2012. Community impacts of *Prosopis juliflora* invasion: biogeographic and congeneric comparisons. *PLOS ONE* 7:e44966. https://doi.org/10.1371/journal.pone.0044966.

Kumar, S. and M. Mathur. 2014. Impact of invasion by *Prosopis juliflora* on plant communities in arid grazing lands. *Tropical Ecology* 55:33-46.

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

Maundu, P., S. Kibet, Y. Morimoto, M. Imbumi, and R. Adeka. 2009. Impact of *Prosopis juliflora* on Kenya's semi-arid and arid ecosystems and local livelihoods. *Biodiversity* 10:33-50. https://doi.org/10.1080/14888386.2009.9712842.

Metson, A. J. 1956. Methods of chemical analysis for soil survey samples. Bulletin 12, New Zealand Department of Scientific and Industrial Research, Soil Bureau, p. 08.

Moharana, P. C., M. K. Gaur, C. Choudhary, J. S. Chauhan, and R. S. Rajpurohit. 2013. A system of geomorphological mapping for Western Rajasthan with relevance for agricultural use. *Annals of Arid Zone* 52:163-180.

Muhs, D. R. and P. B. Maat. 1993. The potential response of aeolian sands to greenhouse warming and precipitation reduction on the Great Plains of the U.S.A. *Journal of Arid Environment* 25:351-361.

Muthana, K. D. 1982. A review of sand dune stabilization and afforestation. *Proceedings of the workshop on the problems of the Deserts in India*. Miscellaneous Publication 49, Geological Survey of India, Kolkata, pp. 363-368.

Mythili, G., and J. Goedecke. 2016. Economics of land degradation in India. In: Nkonya, E., Mirzabaev, A., von Braun, J. (eds) Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development. Springer, Cham, pp. 471–498. https://doi.org/10.1007/978-3-319-19168-3_15

Narain, P. and A. Kar. 2005. *Drought in Western Rajasthan: Impact, Coping Mechanism and Management Strategies*. Central Arid Zone Research Institute (CAZRI), Jodhpur.

Nelson, D. W. and L. E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In A.L. Page (ed.) *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*, 2nd Edition, Agronomy Series *No. 9*, ASA SSSA, Madison, pp. 961-1010.

Olsen, S. R., C. V. Cole, F. S. Watanabe, and L. A. Dean. 1954. *Estimation of available phosphorus in soils by extraction with* $NaHCO_3$. USDA 3 Cir. 939. U.S. Washington.

Panda, D. K., A. Aghakouchak, and S. K. Ambast. 2017. Increasing heat waves and warm spells in India, observed from a multiscale climate change perspective. *J. Geophys. Res. Atmos., 122, 3837–3858*. https://doi.org/10.1002/2016JD026292

Pandey, A. N. and M. V. Rokad. 1992. Sand dune stabilisation: an investigation in the Thar Desert of India. *Journal of Arid Environments* 22:287-292. https://doi.org/10.1016/S0140-1963(18)30647-5.

Pei Z. Q., G. P. Guoping, F. Z. Yang, and L. Weitung. 1981. The test of sand stabilization by asphalt emulsions. *Journal of Desert Research* 3:23-29. (in Chinese).

Pradhan, B., A. A. A. Moneir, and R. Jena. 2018. Sand dune risk assessment in Sabha region, Libyausing Landsat 8, MODIS, and Google Earth Engine Images. *Geomatics, Natural hazard and Risk* 9:1280-1305.

Pye, K., S. J. Blott, and G. Guthrie. 2017. *Advice on options for sand dune management for flood and coastal defence*. Volume 1: Main Report, NRW Evidence Report, Report No: 207, Natural Resources Wales, Bangor, pp. 118.

Qiu, G. Y., In-Bok Lee, H. Shimizu, Y. Gao, and G. Ding. 2004. Principles of sand dune fixation with straw checkerboard technology and its effects on the environment. *Journal of Arid Environments* 56:449-464.

Raji, B. A., E. O. Uyovbisere, and A. B. Momodu. 2004. Impact of sand dune stabilization structures on soil and yield of millet in the semi-arid region of NW Nigeria. *Environmental Monitoring and Assessment* 99:181-196. https://doi.org/10.1007/s10661-004-4018-2.

Rathore, M.S. 2005. *State level analysis of drought policies and impacts in Rajasthan, India*. International Water Management Institute, Colombo, Sri Lanka.

Rehman, S. 1995. *Sand dune stabilization in Mastung Valley: Secheresse*. 6:347-354.

Richards, L. A. 1954. *Diagnosis and improvement of saline alkali soils*. Agriculture Handbook 60. US Department of Agriculture, Washington DC.

Rogers, E. M. 2003. *Diffusion of innovations*. 5th Edition, Free Press, New York.

Rouhipour, H. 2005. Investigation of crop production in stabilized sand dune using AMB layer associate with drip irrigation system. *Sociedade & Natureza* 1:615-627.

Sandhu, H. S., S. D. Wratten, R. Cullen, S. Chaturvedi, and B. Case. 2008. The future of farming: the value of ecosystem services in conventional and organic arable land. An experimental approach. *Ecological Economics* 64(4), 835-848.

Sankary, M. N. 1987. *Plant patterns in plant reproduction mechanism in the sandy environments in North Africa, and its importance in the desertification monitoring and control*. Al-ZiraahWal-Miyaah, *ACSAD*, Damascus, Syria, pp. 8-22. (in Arabic).

Santra, P., P. C. Moharana, M. Kumar, M. L. Soni, C. B. Pandey, S. K. Chaudhari, and A. K. Sikka. 2017. Crop production and economic loss due to wind erosion in hot arid ecosystem of India. *Aeolian Research* 28:71–82

Schachtschneider, K. and E. C. February, 2013. Impact of Prosopis invasion on a keystone tree species in the Kalahari Desert. *Plant Ecology* 214:597-605.

Shehata, W. M. and M. H. Al-Rehaili. 2013. *A review on sand dune stabilization*. Saudi Geological Survey, Saudi Arabia.

Singh, D., P. K. Chhonkar, and B. S. Dwivedi. 2005. *Manual on soil, plant and water analysis*. Westville Publishing House, New Delhi.

Stringer, C. E., C. C. Trettin, S. J. Zarnoch, and W. Tang. 2015. Carbon stocks of mangroves within the Zambezi River Delta, Mozambique. *Forest Ecology and Management* 354:139-148. http://dx.doi.org/10.1016/j.foreco.2015.06.027.

Subbiah, B. V. and G.L. Asija. 1956. A rapid procedure for the estimation of available nitrogen in soils. *Current Science* 25, 259.

Tewari, V. P. and R. Arya. 2005. Degradation of arid rangelands in Thar Desert, India: A review. *Arid Land Research and Management* 19(1), 1–12

Thanuja, P., G. L. Meena, H. Singh, and L. Sharma. 2021. Economic implications of land degradation in Rajasthan: An assessment. *Economic Affairs* 66, 601–608. https://doi.org/10.46852/0424-2513.3.2021.11.

Thomas, D. S., M. Knight, and G. F. Wiggs. 2005. Remobilization of Southern African desert dune systems by twenty-first century global warming. *Nature* 435:1218-1221.

Vasisht, A. K., R. P. Singh, and V. C. Mathur. 2003. Economic implications of land degradation on sustainability and food security in India. *Agropedology* 13(2), 19–27.

Venkateswarlu, J. 1993. Problems and prospects in desertification control - Role of Central Arid Zone Research Institute. In *Desertification and Its Control in the Thar, Sahara and Sahel Regions* (Eds., A.K. Sen and Amal Kar). Scientific Publishers, Jodhpur, pp. 249-267.

Walkley, A. and J. A. Black. 1934. Estimation of soil organic carbon by chromic acid titration method. *Soil Science* 17:29-38.

Wang Y., L. Chu, S. Daryanto, L. Lü, M. Ala, and L. Wang. 2019. Sand dune stabilization changes the vegetation characteristics and soil seed bank and their correlations with environmental factors. *Science of The Total Environment* 648:500-507. https://doi.org/10.1016/j.scitotenv.2018.08.093.

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

World Bank and Ecofys. 2015. *State and trends of carbon pricing*. World Bank Group, Washington.https://www.worldbank.org/content/dam/Worldbank/document/Climate/State-and-Trend-Report-2015.pdf

Yizhaq, H., Y. Ashkenazy, and H. Tsoar. 2009. Sand dune dynamics and climate change: a modeling approach. *Journal of Geophysical Research* 11:1-11. https://doi.org/10.1029/2008JF001138.

Zang, Y. X., W. Gong, H. Xie, B. L. Liu, and H. L. Chen. 2015. Chemical sand stabilization: a review of material, mechanism, and problems. *Journal of Environmental Technology Review* 4(1):119-132. https://doi.org/10.1080/21622515.2015.1105307

Zhang, J., C. Zhang, N. Zhou, and X. Ma. 2011. Spatial pattern of grain-size distribution in surface sediments as a result of variations in the aeolian environment in China's Shapotou railway protective system. *Aeolian Research* 3:295–302. https://doi.org/10.1016/j.aeolia.2011.07.005.

Zhang, J., X. Xu, S. Li, Y. Zhao, A. Zhang, T. Zhang, and R. Jiang. 2016. Is the

Taklimakan Desert Highway Shelterbelt sustainable to long-term drip irrigation with high saline groundwater? *PLoS ONE* 11(10):e0164106. https://doi.org/10.1371/journal. pone.0164106

Zhao, Y., M. A. Bowker, Y. Zhang, and E. Zaady. 2016. Enhanced recovery of biological soil crusts after disturbance. In: Weber, B., B. Büdel, and J. Belnap (eds), *Biological soil crusts: An organizing principle in drylands*. Ecological Studies, 226. Springer, Cham. https://doi.org/10.1007/978-3-319-30214-0_24

Zoght, M. F. 1978. *Sand dunes (fixation - afforestation - exploitation)*. The Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD), Syria, Damascus.

Zuo, X., S. Wang, X. Zhao, and J. Lian. 2014. Scale dependence of plant species richness and vegetation-environment relationship along a gradient of dune stabilization in Horqin Sandy Land, Northern China. *Journal Arid Land* 6:334-342. https://doi.org/10.1007/s40333-013-0221-8.

Publications

Policy Papers

38. Birthal, P.S., J. Hazrana, and R. Saxena. 2023. *Livestock Farmers' Information Needs, Search Behaviours, and Their Impact: Lessons for Extension Policy*.

39. Saxena, R., S.K. Srivastava, S.J. Balaji, A. Jhajhria, and M. A. Khan. 2023. *Changes in Indian Agriculture: Household-level Evidence*.

40. Nikam, V., H. Veesam, T.M. Kiran Kumara, and P. Chand. 2023. *Farmer Producer Organizations in India: Challenges and Prospects*.

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50. Birthal, P.S., S.K. Srivastava, R. Saxena, S. Godara, P. Chand, P. Kishore, J. Jumrani, A. Kandpal, P. Sharma and D.K. Pant. 2025. *Indian Agriculture to 2047: Reshaping Policies for Sustainable Development*

51. Balaji, S.J., Birthal, P.S., Pal, B.D., Thurlow, J., Gotor, E., Sharma, P., Srivastava, S.K., Kingsly, I.T., and Naresha, N. 2025. *The Future of Food in India: A 2050 Perspective*.

Policy Brief

53. Sharma, P., B.D. Pal, and P.S. Birthal. 2023. *Technology and Policy Options for Sustaining Pulses Revolution*.

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