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Comparative heterogeneity, soil properties and ecosystem services across different ecotypes in the soon Valley

Aafaq Ali[1]✉, Zafar Iqbal Khan[1], Kafeel Ahmad[1,2], Ahlam Khalofah[3,4] & Muhammad Arif[5]

This study investigated the phytosociological patterns, soil physicochemical properties, and ecosystem services provided by native plants in Soon Valley. The primary objective was to assess variations in plant diversity, soil characteristics, and ecosystem services, specifically carbon sequestration and soil erosion prevention across six sites such as Khabeki (S1), Khoora (S2), Dape Sharif (S3), Anga (S4), Knotti Garden (S5), and Jallar (S6). Quadrat-based sampling and allometric equations were used to evaluate plant diversity and carbon storage potential, whereas soil erodibility was analyzed via the Universal Soil Loss Equation. Significant physicochemical and soil differences were found among the sites. Knotti Garden presented the highest phosphorus (17.2 mg/kg), and potassium (281 mg/kg) levels. The organic matter content ranged from 2.07 to 1.23% and the soil saturation ranged from 75.21 to 51.83%. *Justicia adhatoda* was the dominant species in terms of frequency, density, and cover whereas *Acacia modesta* presented strong ecological performance. *Tecomella undulata* at Dape Sharif stored up to 467,077 kg of biomass derived carbon, whereas *Mangifera indica* at Knotti Garden sequestered 158,789 kg, indicating strong site-species carbon relationships. These findings highlight the ecological significance of site-specific management and native species in supporting sustainable ecosystem services in semiarid regions.

Keywords Soon Valley, Ecosystem services, Carbon sequestration, Potassium, Phosphorus

Ecosystem services are widely understood as advantages that ecosystems offer to humans, i.e., they help make life on Earth both possible and worthwhile[1]. Ecosystem services, on the other hand, are the circumstances and mechanisms that allow ecosystems and the species within them to support and satisfy human life[2]. Several statistics have shown that the current century will face numerous pressing issues, as well as connected ones, such as significant losses in biodiversity or broad changes in ecosystems[3].

The Soon Valley in Punjab, Pakistan, is an environmentally distinctive region with rich native plants and various microclimatic zones. Its major flora include *Justicia adhatoda*, *Acacia modesta*, *Albizia lebbeck*, and *Olea ferruginea*, which provide both provisional and regulating ecological services. These natural plants promote biodiversity, curb erosion, and offer medical and cultural advantages to local communities[4,5]. However, this fragile landscape is increasingly threatened by anthropogenic disturbances, including deforestation, soil erosion, and habitat fragmentation[6,7]. Several surveys reporting on biodiversity and floral composition have been carried out in the salt range[8].

Biological services are critical to humanity's continued existence and socioeconomic activities, ecosystems, particularly terrestrial ecosystems, that enable the coexistence of many plant species and populations under unique ecological conditions[9]. In recent years, the notion that adaptive ecosystem management necessitates the recognition of the complex dynamics of the socioecological system has advanced to a fundamental level[10]. Yang et al.[11] reported that they understood the ability to perceive the positive and negative effects of the socioecological system and that there was a multitiered, nested structure for this purpose. The biomass of shrubs and herbs was studied in the Kumaun Himalaya region by Awasti et al.[12]. to investigate the structure and function of the ecosystem.

[1]Department of Botany, University of Sargodha, Sargodha, Pakistan. [2]Department of Botany, Baba Guru Nanak University, P.O.Box 39100, Nankana Sahib, Lahore, Pakistan. [3]Biology Department, Faculty of Science, King Khalid University, P.O.Box 9004, Abha 61413, Saudi Arabia. [4]Research Centre for Advanced Material Sciences (RCAMS), King Khalid University, P.O.Box 9004, Abha 64413, Saudi Arabia. [5]Department of Animal Sciences, College of Agriculture, University of Sargodha, Sargodha, Pakistan. ✉email: botanistfarooq@gmail.com

Native plants in the Soon Valley provide ecosystem functions that are inextricably related to its high biodiversity. These plants create and maintain habitats that are essential for a range of species, providing ecological resilience and balance. Majeed et al.[13] reported that native plant species such as *Ziziphus mauritiana* and *Acacia nilotica*, for example, are essential for the survival of animals such as insects, birds, and small mammals. A variety of ecological interactions and processes that enhance overall biodiversity are supported by Soon Valley's preservation of a varied range of plant species. Despite its ecological importance, the Soon Valley faces numerous environmental challenges, including soil erosion, deforestation, and habitat fragmentation[14].

The world's ecosystems are facing unprecedented threats, including biodiversity loss, soil degradation, and disruptions to ecosystem services[15]. The conservation and sustainable management of ecosystems are critical for maintaining ecological integrity, supporting human well-being, and promoting sustainable development[16]. Soon Valley, located in the Punjab province of Pakistan, is a unique and ecologically significant region harboring a diverse array of plant species and ecosystems[5].

Indigenous flora are essential for soil preservation. Deep-rooted species mitigate soil erosion and enhance soil fertility by improving nitrogen cycling[17]. Moreover, riparian vegetation, including willows (Salix), enhances water quality by filtering contaminants and stabilizing banks, thereby preserving aquatic ecosystems[18]. Comprehending plant communities is an essential precondition in ecosystem ecology, natural resource management, and conservation. This knowledge is crucial for examining rare or rarely species and for formulating management measures aimed at their protection and/or mitigating habitat fragmentation[19]. The characterization of vegetation has established a solid basis for the advancement of the ecological sciences for numerous decades. Phytosociology (quantitative ecology) facilitates the study of plant species at both the individual and community levels in relation to their environment.

The idea of ecosystem services has demonstrated its utility in conservation and large-scale wetland restoration efforts. This notion offers a crucial framework for environmental management, particularly in terms of illustrating human dependence on natural systems[20]. However, other inquiries concerning ecosystem services persist, including the spatial distribution of these services and the methods for delivering diverse ecosystems. Further research is necessary to assess the valuation of ecosystem services[21].

This study aims to investigate the phytosociological and ethnobotanical data to classify the vegetation of the Soon Valley and assess the impacts of human activity on it. It was hypothesized that variations in these ecosystem services are influenced by species-specific traits, site conditions, and land-use practices. The ultimate goal is to quantify the ecosystem services provided by the natural vegetation. The objectives of this research are to (i) to assess and quantify the floristic diversity and composition of plant species in selected ecotypes (ii) analyze phytosociological parameters, including species richness, abundance, and distribution patterns, (iii) to evaluate the physicochemical properties of the soil, icluding pH, organic matter content, and nutrient availability and (iv) quantify the provisional and regulatory ecosystem services provided by these ecotypes, with a focus on carbon sequestration and soil erosion prevention.

Materials and methods

Study site

Pakistan, covering 796,095 sq km, has diverse geographic areas, ranging from the Himalayan Mountains to the Arabian Sea coast. The country has varying topographical features across its four provinces. The Soon Valley in the Salt Range receives 20 inches of rainfall annually, with temperatures ranging from 1 °C to 36 °C, and experiences hot winds, droughts, frost, and longer winters. The Salt Range, specifically the Soon Valley in Khushab district, is located between 71.30°-73.30°E longitude and 32.23°-33°N latitude. The valley has a semiarid and warm climate, with 250–500 mm annual precipitation, and an altitude of 400–1000 m. The area is divided into forests (38%), cultivated land (22%), and rangelands (40%). The dominant plant species include *Olea ferruginea*, *Acacia modesta*, and *Dodonaea viscosa*. Six sites were studied from 2021 to 2023 to document the plant community structure and vegetation distribution in the semiarid rangelands.

Determination of floristic composition

Systematic field visits were made for plant collection in all seasons from 2021 to 2023 across six plant species in the Soon Valley. Vegetation sampling was conducted at each site via a stratified quadrat approach. Ten regular quadrats were laid (5 m^2 for shrubs and 1 m^2 for herbs and grasses), each separated by a distance of 10 m at all the selected sites. For the ecological attributes 3 replicates were taken for all of the studied parameters. All the plant species were documented inside each quadrat, together with information on their abundance and cover. The plant samples were carefully uprooted or trimmed, then dried, stored, and placed on herbarium sheets for taxonomic identification and reference purposes. The identification technique used conventional floristic keys from the Flora of Pakistan by Ali[22] and Ali and Qaiser[23]. A detailed species list was created, and the plant families are alphabetized. In addition, the species were classified into life-form classes and leaf size groups using Raunkiaer[24] and Hussain's[25] categorization systems.

Vegetation phytosociological sampling and analysis

Shrub height and diameter from ground level were noted. The diameter at breast height (DBH) of each tree was measured. The names and numbers of the trees in each quadrat were recorded. The heights and girths of all branches exceeding 4 cm were measured.

Frequency

The frequency quantifies the proportion of quadrats within plots that include a particular species. The calculation was performed via the formula[26].

$$\text{Frequency} = \frac{\text{Number of quadrats in which a species occurred}}{\text{Total number of quadrats studied}} \times 100$$

Density
Density refers to the number of a plant species per unit area and is computed via the following formula[26].

$$\text{Density} = \frac{\text{Total number of individuals of a species}}{\text{Total area sampled}} \times 100$$

Cover
This indicates the percentage of the ground that is occupied by a particular species of plant.

$$\text{Cover} = \frac{\text{Area covered by species in a quadrat}}{\text{Total area covered by all the species}} \times 100$$

Calculation of plant biomass and carbon sequestration
Plant biomass was estimated using species-specific allometric equations, on the basis of diameter at breast height (DBH), plant height (H), and wood density (ρ). The aboveground biomass (AGB) was calculated using the following general allometric formula, adapted from Brown[27]:

$$\text{AGB (kg)} = 0.0673 \times (\text{r} \times \text{D}^2 \times \text{H})^{0.976}$$

where: ρ = wood density (g/cm^3), D = diameter at breast height (cm), and H = height (m).
The belowground biomass (BGB) was estimated as 20% of the AGB:

$$\text{BGB (kg)} = 0.20 \times \text{AGB}$$

The total biomass (TB) was obtained by summing the AGB and BGB:

$$\text{TB (kg)} = \text{AGB} + \text{BGB}$$

The carbon content was calculated assuming that 50% of the dry biomass is carbon[28]:

$$\text{Carbon (kg)} = 0.50 \times \text{TB}$$

To scale the carbon per hectare, the carbon value per individual plant was multiplied by plant density per hectare which was obtained from quadrat sampling:

$$\text{Carbon per hectare (kg/ha)} = \text{carbon per plant} \times \text{density (plant/ha)}.$$

Collection of soil samples
Soil samples were collected from beneath selected plant species at designated sites in a random manner. Four samples were collected, two from bare soil and two from soil under native plant cover. The samples were labelled, packed in zipper bags, and transported to the laboratory for analysis. Chemical parameters such as pH, EC, P, K, Na, soil organic matter and soil organic carbon were determined following the drying and sieving processes.

Physical parameters
Soil saturation
A saturated paste of soil was prepared and allowed to remain undisturbed for one hour. Additional soil or deionized water was incorporated as necessary to fulfil the requirements for achieving saturation. The soil underwent a filtration process, and the resulting filtrate was subjected to analysis for subsequent evaluation.

Soil texture
A 40 g soil sample was collected, sieved, and air-dried. The homogenized mixture was stirred for 10–15 min. The material was transferred to a one-liter jar, and the volume was adjusted to one liter. Silt and clay measurements were recorded after 40 s, and sand assessment was performed after one hour via a hydrometer. A temperature correction factor of 0.4*T was applied to determine the silt and clay percentages.

$$\text{Silt and clay (\%)} = \frac{\text{R (sc)}}{weight\ of\ soil} \times 100$$

$$\text{Clay (\%)} = \frac{\text{R (c)}}{weight\ of\ soil} \times 100$$

$$\text{Silt (\%)} = (\text{silt and clay (\%)}) - \text{Clay (\%)}$$

$$\text{Sand \%} = 100 - \text{silt (\%)} - \text{clay (\%)}$$

The USDA triangle was employed as a method to ascertain the texture of the soil.

Chemical parameters

pH

The soil pH was determined via an Inno pH meter. Standardization involved buffer solutions with pH values of 4.0 and 7.0. A reading was recorded 30 s after the adjustment electrode was introduced into the suspension.

Electrical conductivity (EC)

The electrical conductivity (EC) of the soil was quantified with a milliemens perimeter (mS/cm) via a conductivity meter (Semso-Direct Con 2000) to analyse the soil extract.

Phosphorus

The phosphorus determination was performed via an 80-D spectrophotometer following Page et al.[29]. A color reagent was added to a 25 ml flask with the solution. A bluish hue indicates that the phosphorus concentration in the soil is proportional to the blue intensity. The absorbance was measured at 880 nm with a spectrophotometer.

Sodium and potassium

The determination of the sodium and potassium contents was conducted via a Jenway flame photometer (AFP 100). This analysis employed a soil: water mixture at a 1:1 ratio, following the calibration of the instrument with a series of standard solutions.

Soil organic matter concentration

The organic matter content was determined via the dry ignition method with a muffle balance. One gram of each soil sample was collected and placed in a crucible in a muffle furnace at 450 degrees Celsius for four hours as per Schulte[30]. After four hours, the subject was weighed to determine the weight of the organic matter.

Soil organic carbon

The determination of soil organic carbon (SOC) was conducted via Walkley's rapid method, as outlined by Walkley[31]. The measurement was conducted via the following formula:

$$\text{Organic Carbon }(\%) = \frac{\text{Organic Matter }(\%)}{1.724}$$

To calculate SOC, in terms of total stock per hectare, the following equation was used:

$$\text{SOC }(\text{t/ha}) = 10,000 \times \text{soil depth }(\text{m}) \times \text{bulk density }\left(\text{g/cm}^3\right) \times \text{SOC}/100$$

Estimation of ecosystem services

Soil erosion prevention

The Universal Soil Loss Equation serves as a critical tool for quantifying soil erosion, as established by the foundational work of Wischmeier and Smith.

A: Amount of erosion or erosion risk; R: Rainfall intensity; K: Soil erodibility; LS: Slope length and steepness; C: Cover; P: Conservation practices.

The soil erodibility factor is influenced by several key components, including the contents of silt, fine soil, and clay, as well as the presence of organic matter and the overall texture of the soil.

$$\text{K} = \text{ton.ha.h/ha.Mj.mm}$$

K: the soil erodibility factor; ton: refers to tons of soil lost due to erosion; ha: stands for hectares, a unit of area; h: This represents hours; Mj (megajoules) refers to the rainfall energy; mm: refers to millimeters typically measuring rainfall depth.

Calculating soil loss

Compared with the community forest site, the forest site experiences significantly lower annual soil loss.

$$\text{A} = \text{R x K x LS x C x P}$$

A: Amount of soil erosion, R: Rainfall erosivity (rainfall intensity), K: Soil erodibility factor, LS: Slope length and steepness, C: Cover factor (vegetation or cropping practices), P: Conservation practices.

Results

Frequency, density and cover

The frequency of each species in proportion to space was measured, and information was gathered from each of six sites. The significantly high frequencies were observed for *Dodonaea viscosa*, at Dape Sharif and Jallar sites. The species *Olea ferruginea* and *Prosopis juliflora* also showed the high frequencies compared to other species at spatial scale. Overall, the highest frequency was shown by *Justicia adhatoda* at Dape Sharif site compared with all other sites and plants (Fig. 1).

In a research area, density is the number of individuals per species. The plants such as *Cymbopogon jwarancusa* and *Dichanthium annulatum* showed the significantly high density compared to other plants at studied sites. *C. jwarancusa* showed the highest density at Khoora site, whereas *D. annulatum* at Knotti Garden. Overall, the

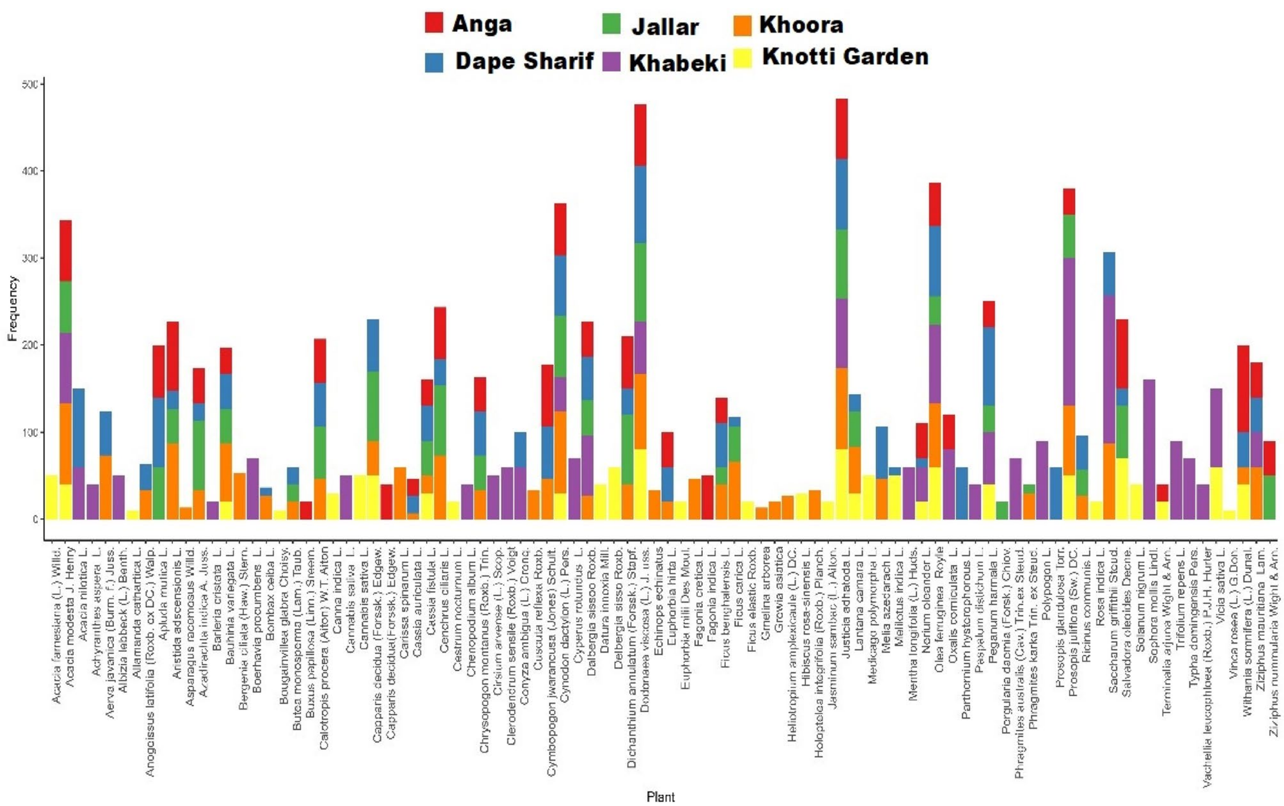

Fig. 1. Frequencies of vegetation at six different sites (Anga, Jallar, Deep Sharif, Khoora, Khabeki and Knotti Garden) across Soon Valley.

maximum density was shown by *J. adhatoda* at Knotti Garden site whereas lowest at Dape sharif by *Ficus elastica* compared with all other sites and plants (Fig. 2).

The graphical data for vegetation cover in Soon Valley presented that significantly high values of *Cynodon dactylon* and *D. viscosa* were present at Anga site compared to other sites and plants. The lowest cover was presented by *F. elastica* at Khoora site. The maximum cover was shown by *J. adhatoda* at Jallar site compared to other sites and plant species (Fig. 3).

Physicochemical properties of the soil in the soon Valley

Loamy soil is widely regarded as the most suitable medium for promoting optimal plant growth, as it is composed of a balanced mixture of salts, clay, and sand. The bar graph distinctly illustrates the spatial variability in the soil parameters observed across various locations.

pH

Bar graph showing the variation in pH values across the different ecotypes in the Soon Valley. The soil at Khoora site 2 presented the highest pH value, whereas that at the Anga site (Site 4) was the lowest. Moderate pH values were observed at Khabeki (Site 1), Dape Sharif (Site 3), Knotti Garden (Site 5) and Jallar site 6. The variation in pH values supports the growth of diverse plant vegetation.

Electrical conductivity

Soil electrical conductivity (EC) is defined as the ability of soil water to carry an electrical current. The soil electrical conductivity indicates the availability of nutrients and salinity levels. Low EC levels indicate low nutrient concentrations, which can cause nutrient deficiencies and slow plant growth. Generally, higher EC levels indicate that more nutrients are available for plants, but very high EC values can cause burn or even kill plants. The soil electrical conductivity varies across different sites, with the maximum value observed at Jallar (Site 6) and the minimum value at Anga (Site 4). Moderate values were recorded at Khabeki (Site 1), Khoora (Site 2), Dape Sharif (Site 3), and Knotti Garden (Site 5).

Soil organic matter

Soil organic matter is the fraction of soil that consists of plant and animal tissues in various stages of decomposition. It plays a significant role in improving the physical, chemical and biological functions of soil. Different levels of soil organic matter were recorded for the selected ecotypes. Knotti Garden (Site 5) presented a relatively high ratio of organic matter, whereas Jallar (Site 6) presented a low organic matter composition. The

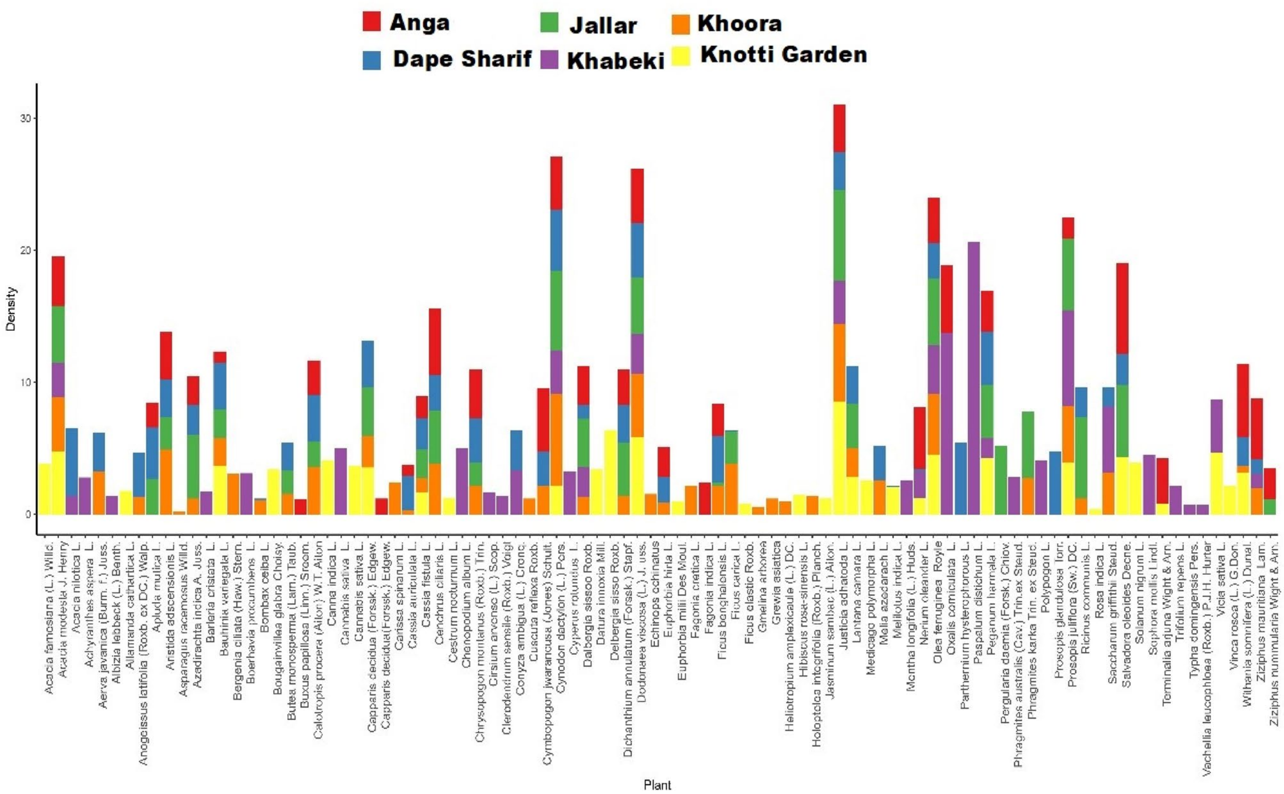

Fig. 2. Densities of vegetation at six different sites (Anga, Jallar, Deep Sharif, Khoora, Khabeki and Knotti Garden) across Soon Valley.

other ecotypes, Khabeki (Site 1), Khoora (Site 2), Dape Sharif (Site 3) and Anga (Site 4), presented moderate concentrations of soil organic matter (Table 1).

Phosphorus (P)
Phosphorus is a major plant nutrient in the soil and is essential for plant cell division and the development of growing tips. It is particularly important for seedlings and young plants. Knotti Garden (Site 5) has a high concentration of phosphorus, whereas Anga (Site 4) has a lower concentration. Khabeki (Site 1), Khoora (Site 2), Dape Sharif (Site 3) and Jallar.

Potassium (K)
Potassium is essential for all processes needed to sustain plant growth and development. Potassium deficiency reduces resistance to drought, insects, and pests. Soil potassium analysis of the selected study sites revealed that Knotti Garden (Site 5) had the highest value, whereas Dape Sharif (Site 3) had the lowest value. Khabeki (Site 1), Khoora (Site 2), Anga (Site 4), and Jallar (Site 6) presented moderate levels of potassium in the soil (Table 1).

Soil saturation
Soil saturation refers to the soil water content when all pore spaces between soil particles are filled with water. Soil saturation is important for agricultural monitoring, flood and drought forecasting, forest fire prediction, water supply management, and natural resource activities. The soil composition analysis revealed maximum saturation at Knotti Garden (Site 5) and minimum saturation at Dape Sharif (Site 3). The soil saturation levels are moderate at Khabeki (Site 1), Khoora (Site 2), Anga (Site 4), and Jallar (Site 6).

Soil texture
The soil texture indicates the relative content of particles of various sizes, such as silt, clay, and sand. Soil texture plays a significant role in nutrient management by affecting nutrient retention. Finer soil textures increase the ability of soil to retain nutrients. The soil textures at Khabeki (Site 1), Dape Sharif (Site 3), Anga (Site 4), Knotti Garden (Site 5), and Jallar (Site 6) are sand-dominated loam, whereas Khoora (Site 2) has a silt-dominated soil texture. These findings underscore the importance of understanding and managing soil quality on the basis of specific characteristics in different locations (Fig. 4).

Carbon sequestration
Carbon sequestration is the process in which plants store atmospheric carbon during photosynthesis and store the carbon in biomass. The sequestration process reduces the amount of carbon dioxide in the atmosphere.

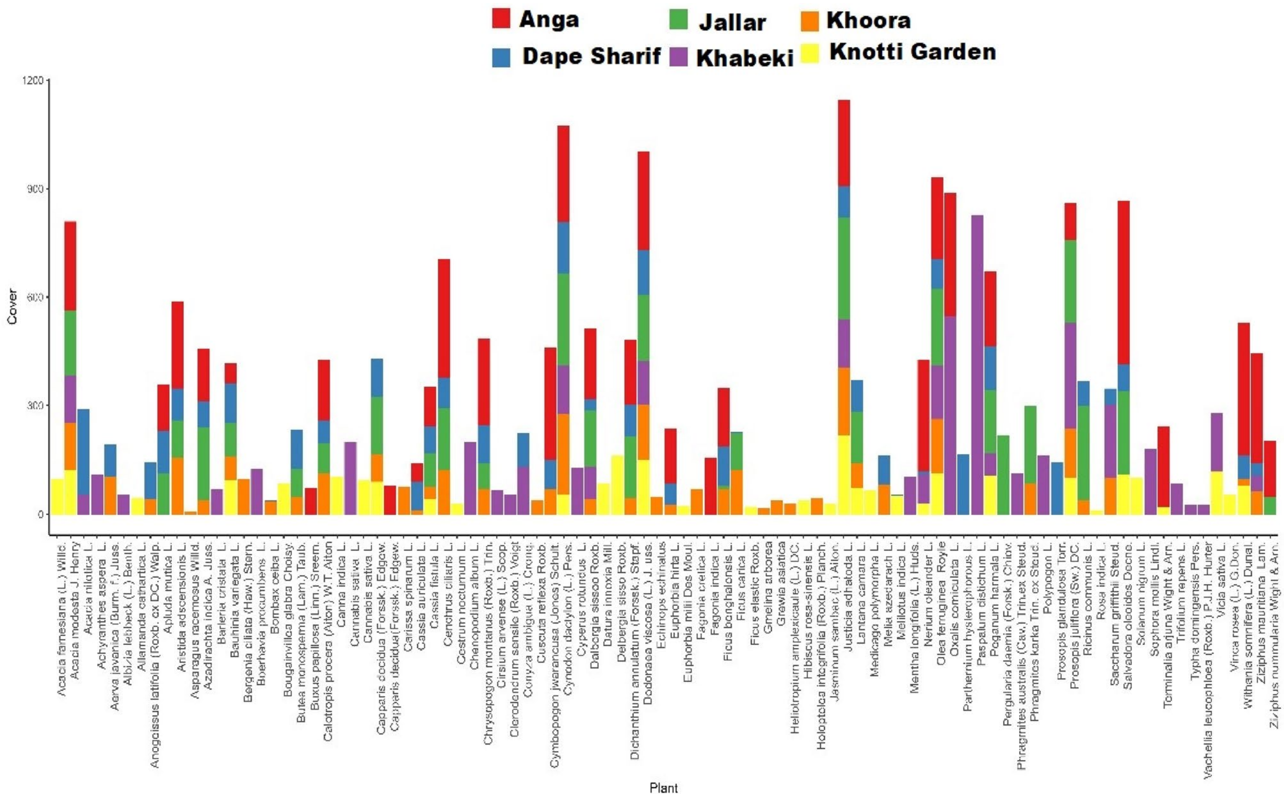

Fig. 3. Cover of vegetation at six different sites (Anga, Jallar, Deep Sharif, Khoora, Khabeki and Knotti Garden) across Soon Valley.

Parameter	Khabeki S1		Khoora S2		Dape Sharif S3		Anga S4		Knotti Gardan S5		Jaller S6	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
pH	7.7	0.00577	7.9967	0.00882	7.53	0.0651	7.2667	0.0882	7.9	0.00577	7.9733	0.012
Ec (ds/m)	0.34	0.0057	0.51667	0.0008	0.4367	0.0186	0.28	0.00577	0.45	0.0057	0.50667	0.0088
Organic matter (%)	1.43	0.011	1.84	0.00577	1.2267	0.0176	1.5867	0.0233	2.0733	0.0145	1.58	0.0057
Phosphrous (mg/kg)	14.6	0.0115	13.8	0.00577	15.213	0.0145	16.517	0.0176	17.2	0.0115	11.83	0.0321
Potasium (mg/kg)	145	0.0057	240.57	0.222	119.03	0.291	103	0.557	281	0.00333	200	0.00577
Saturation (%)	61.227	0.0145	71.5	0.0057	51.833	0.0388	57.433	0.176	75.207	0.0033	64.567	0.291

Table 1. Physiological and phytosociology characteristics of soon Valley at different studied sites.

The carbon sequestration potential of plant species was determined by measuring the aboveground biomass, belowground biomass and total biomass at storage.

At the Khoora site, *Albizzia labbek* sequesters 5752.28 kg, with 3240.36 kg of aboveground biomass and 2511.91 kg of aboveground biomass. *A. nilotica* sequesters 4500.09 kg, with 2000.042 kg above-ground biomass and 2500.05 kg below-ground biomass (Fig. 5A and B). At the Dape sharif site, *T. undulata* sequesters 467,077.32 kg, with 203,191.82 kg of aboveground biomass and 263,885.49 kg of aboveground biomass. *P. cineraria* sequester 92,969.50 kg, split between 50,253.78 kg above-ground biomass and 42,715.71 kg below-ground biomass (Fig. 5C).

At Anga site *P. cineraria* sequesters 16,090.05 kg, comprising 4,245.39 kg of aboveground biomass and 11,844.65 kg of belowground biomass. *Melia azedarach* sequesters 5268.28 kg, with 1170.72 kg of above-ground biomass and 4097.55 kg of below-ground biomass (Fig. 5D). At the Knotti garden site, *M. indica* sequesters 158,789.90 kg, with 42,884.86 kg of aboveground biomass and 115,905 kg of aboveground biomass. *Morus alba* sequesters 35,855.2 kg, with 19,593.04 kg above ground and 16,262.23 kg below ground (Fig. 5E). At the Jallar site, *P. glandulosa* sequesters 3818.29 kg, with 1431.86 kg of above-ground biomass and 2386.43 kg of above-ground biomass. *Z. nummularia* sequesters 2372.93 kg, with 1757.72 kg above ground and 615.20 kg below

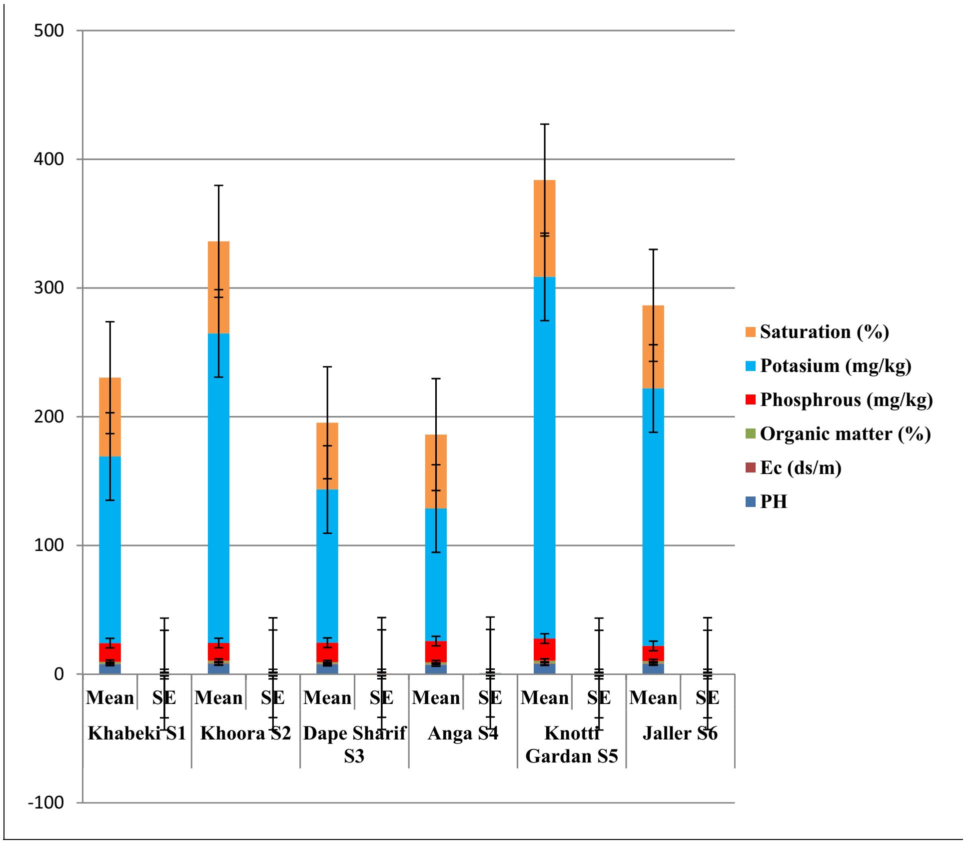

Fig. 4. Multiple variables bar plot graph for soil at six different sites along Soon Valley (S, Site; EC, Electrical Conductivity; P, Phosphorus; K, Potassium).

ground. *D. viscosa* sequesters 233.15 kg, with 155.43 kg above-ground biomass and 77.71 kg below-ground biomass (Fig. 5F).

Soil erosion prevention

The average soil erosion was calculated in t ha^{-1} or kg ha^{-1}, along with the soil loss at the Khabeki site due to several selected plant species, including *A. modesta*, *Z. jujuba*, *O. ferruginea*, and *D. sissoo*. The degree of soil loss in *A. mosdesta* is low because of its deep roots and dense canopy. At the Khoora site, soil erosion is calculated in tons per acre, with data on *A. nilotica*, *F. religiosa*, *A. lebbek*, *B. papillosa*, and *D. sissoo*. *A. nilotica* has low soil loss due to its deep roots and dense canopy. At Dape Sharif, *M. azedarach* has a deep root system and low yield. *P. cineraria* is resilient and effectively prevents soil erosion. *T. undulata* reduces runoff and wind erosion (Fig. 6A and 6C).

Deep and extensive roots systmen in *O. ferruginea* possesses the ability to stabilize soil and prevent erosion, particularly in hilly areas, with a weight of 0.77 kg/acra recorded at the Anga site, Soon Valley. This process maintains soil erosion. At Knotti Garden, *M. indica* effectively prevents soil erosion. *P. guajava* has a moderate root system and a stabilizes topsoil. *T. arjuna* effectively prevents soil erosion. *P. granatum* has moderate soil erosion prevention value. *M. alba* protects against soil and wind erosion (Fig. 7B). At the Jallar site, *Z. nummularia* effectively stabilized the soil. *D. metal* has inadequate soil erosion control. *J. adhatoda* moderates soil erosion values. *D. viscosa* had the highest soil erosion control values. *P. glandulosa* effectively prevents soil erosion (Fig. 7A and 7C).

Discussion

The Soon Valley, situated in the Salt Range of Punjab, is renowned for its rich biodiversity, supporting a diverse array of flora and fauna that thrive in its distinct microclimatic conditions. Examining its floral composition provides a foundation for conservation strategies and sustainable management practices[32]. This study concentrates on the region to enhance the understanding of Pakistan's flora, particularly with respect to ecosystem services. Floodplain ecosystems play crucial roles in regulating water and supporting agriculture while preserving cultural and recreational spaces that are essential to the region's identity[33].

Generally, the physicochemical properties of soils vary in space and time because of variations in topography, climate, weathering processes, vegetation cover[34,35] and microbial activities[36,37] and several other biotic and abiotic factors[38,39]. In the highly dissected landscapes, bioclimatic conditions change rapidly and may vary within short distances resulting in a pronounced heterogeneity in soil types and their chemical and physical properties[40,41].

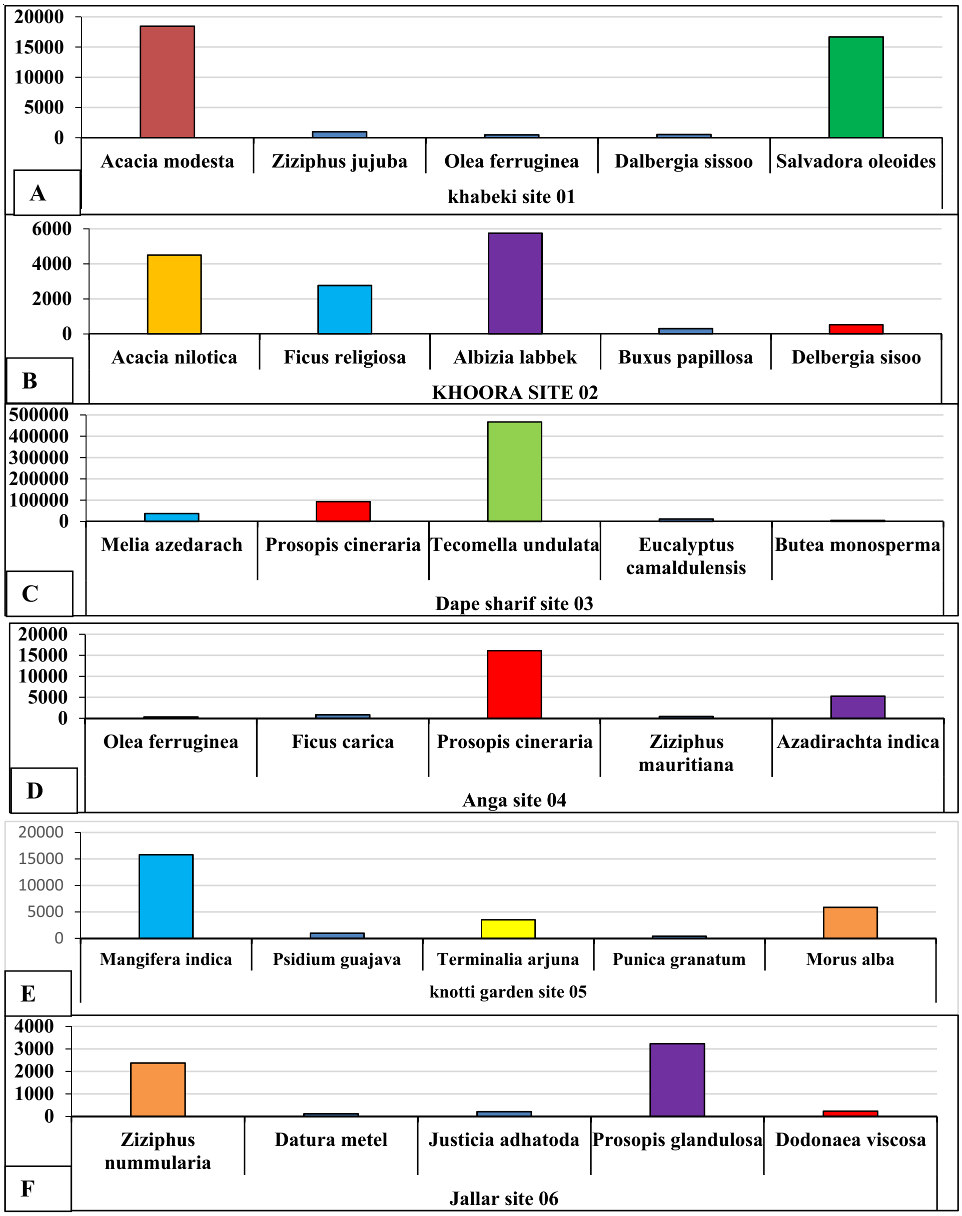

Fig. 5. **(5 A-5 F)** Total carbon sequestration of selected plant species from six different sites of Soon Valley.

Physicochemical properties are frequently used for the estimation of soil quality[42] however certain biological indicators such as microbial biomass, soil respiration, activities of soil macrofauna, and enzymes are reportedly to be related to soil quality and health[43]. Vegetation also influences the nutrient cycling to a great extent and plays an important role in the soil formation[44]. It improves the soil structure, infiltration rate, aeration and water holding capacity[45]. This could directly affect the plant structure and their function[46].

The study carried out in the Soon Valley revealed significant differences in phosphorus levels among the six study sites, with the Knotti garden site exhibiting the highest concentration of phosphorus. This nutrient plays a crucial role in energy transfer within plants and serves as a fundamental component of ATP, which powers numerous metabolic processes[47]. Furthermore, the availability of phosphorus in soil is frequently associated with soil pH and the content of organic matter, which can differ markedly among various ecotypes, as evidenced by the diverse phosphorus concentrations found in the Soon Valley[48]. The variations in phosphorus availability are associated with soil pH levels; given that phosphorus availability in soil is significantly influenced by its pH, a connection that has been extensively recorded in the literature[49].

The growth of vegetation plays a significant role in carbon sequestration, which is an essential ecosystem service amid the challenges posed by global climate change[50]. The high pH concentration at the Khoora site indicates the presence of highly alkaline soil conditions, which are typically associated with arid and semiarid regions. Yahaya et al.[51] reported that the concentration of potassium varied significantly across different sites in the Soon Valley.

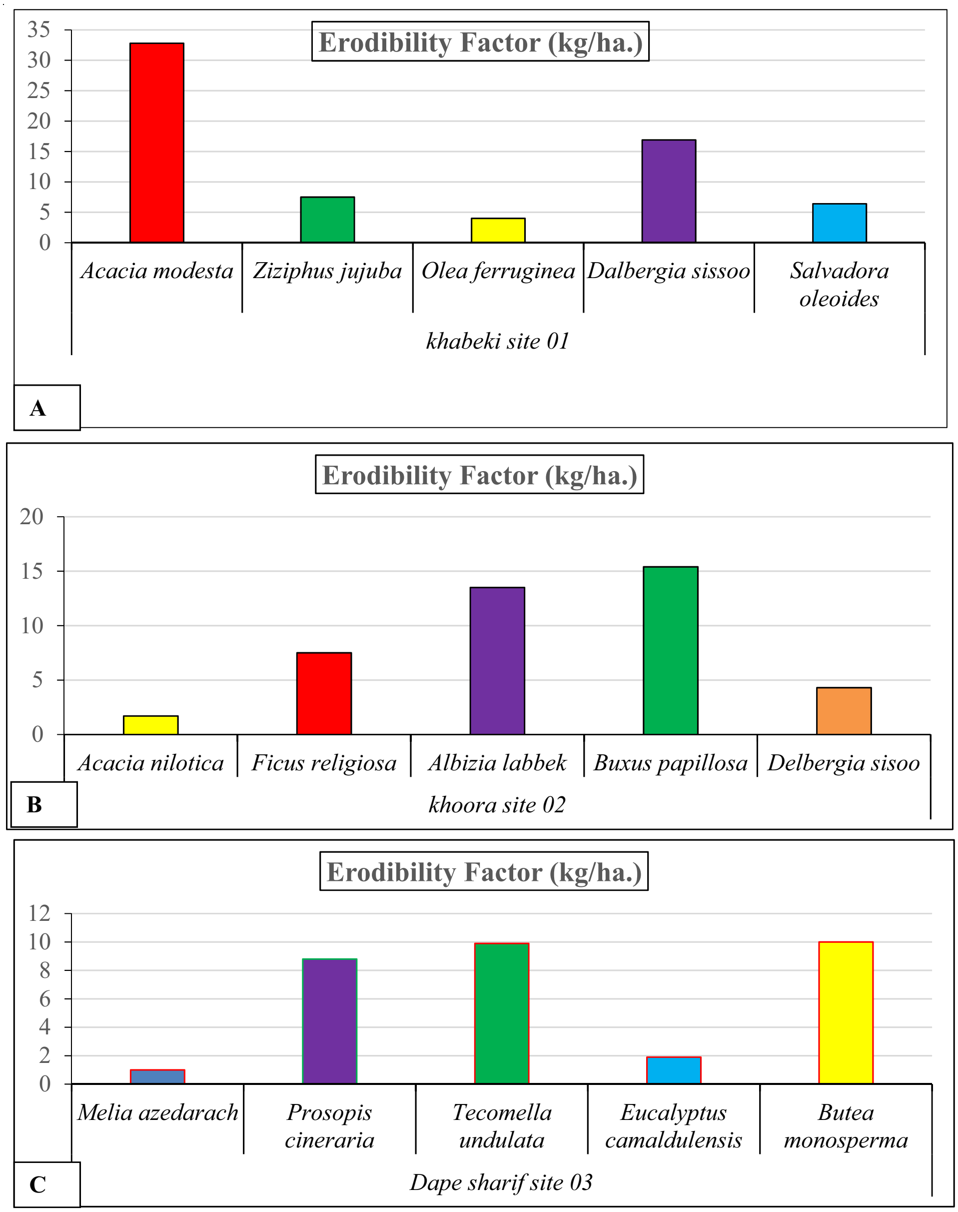

Fig. 6. **(6 A-6 C)** Soil erosion prevention of selected plant species at Khabeki site (A), Khoora site (B) and Dape sharif site (C).

The highest concentrations of potassium were recorded in Knotti garden, which is located in one of the district's fertile ecotypes. This high potassium availability likely contributed to the increased growth and productivity observed in the plants growing in that area. Furthermore, the Anga site, which presented the lowest potassium concentrations, results lower agricultural productivity in that region. These differences underscore the importance of site-specific nutrient management strategies for maximizing agricultural outputs in various ecological contexts[52]. The findings of Yahaya et al.[51] are significant for agricultural practices in the six district ecotypes of the Soon Valley.

A study conducted by Hussain et al.[53] highlighted the importance of organic matter in enhancing soil fertility, notably revealing that the Knotti garden presented the highest concentration of organic matter. The increased level of organic matter in Knotti garden soil reinforces the notion that organic matter plays a significant role in enhancing soil fertility and promoting plant health. The abundance of organic material in the Knotti garden likely fostered a conducive environment for crop growth, leading to healthier plants and increased agricultural yields[54].

Phytosociology is an essential field in plant ecology that involves investigating the structure and composition of plant communities by analysing key parameters such as density, frequency, and cover[55]. By examining density and frequency, one can achieve a thorough understanding of plant community dynamics and the environmental conditions that favour particular species. At Jallar site 6, *J. adhatoda* presented the highest density, indicating

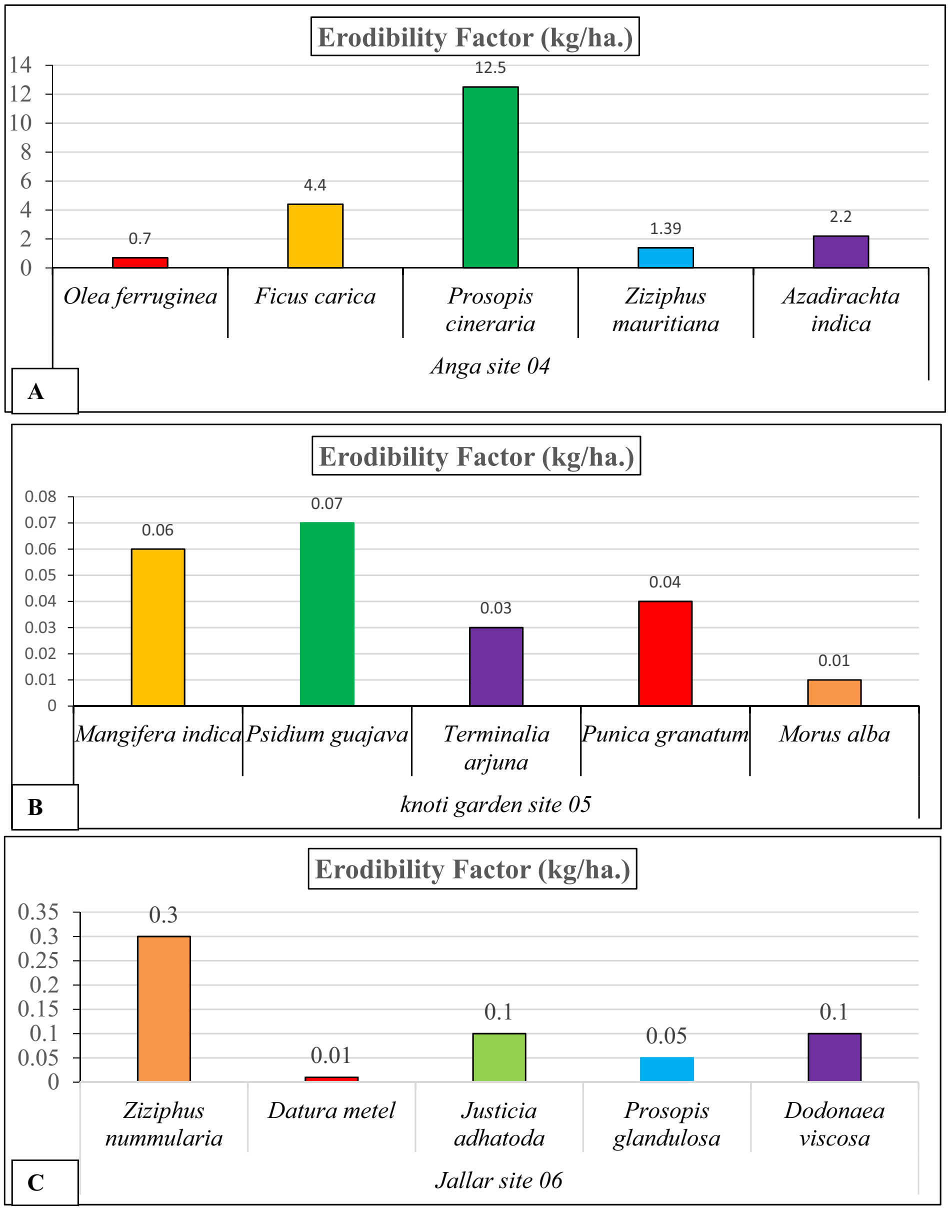

Fig. 7. **(7 A-7 C)** Soil erosion prevention of selected plant species at Anga site (A), Knoti Garden site (B) and Jallar site (C).

that this species is especially well suited to the environmental conditions present at this location. *D. viscosa* had the greatest prevalence at Jallar site 6, indicating its extensive distribution throughout the area. This species demonstrates resilience and drought resistance, rendering it especially appropriate for semiarid and coastal habitats[56].

The greatest densities of *A. modesta* and *C. dactylon* were found at site 4, suggesting that these species are especially suitable for the area and dominate the site's vegetation structure. *C. dactylon* is a resilient grass species typically found in disturbed habitats[57]. The Dape Sharif site presented the highest density of, *A. nilotica* underscoring its prevalence in semiarid environments where it plays crucial ecological roles, including soil stabilization and nitrogen fixation. *A. mutica* and *F. carica* presented the lowest density and cover, likely as a result of adverse conditions such as intense competition or nutrient constraints[58]. *D. viscosa* consistently occurs at a high frequency, reinforcing its extensive distribution and ability to thrive in various environments.

The identified patterns in density and frequency, underscore the ecological prominence of specific species, including *C. dactylon* and *D. viscosa*, which consistently presented elevated values across different sites. The resilience of these species enables them to thrive across diverse ecological conditions, highlighting their significance for ecosystem services, including erosion control, support for biodiversity, and habitat restoration[59]. Moreover, species such as *C. reflexa*, *C. montanus*, and *C. auriculata* consistently presented low values for these parameters, suggesting that they may not be optimally suited to the existing environmental conditions[46,56]. *P.*

distichum ultimately surfaced as a species characterized by significant density, and frequency, underscoring its ecological significance. This species exhibited a remarkable tolerance to waterlogged conditions and has a strong capacity to flourish in disturbed environments[60].

The process of carbon sequestration involves the absorption of atmospheric carbon dioxide by plants, which is then stored in their biomass. This mechanism is vital in the fight against climate change, as it effectively decreases the concentration of CO_2 in the atmosphere. Tariq et al.[61] reported that various plant species have different abilities, for carbon storage, which are influenced by factors such as growth rates, root depth, and biomass accumulation. The findings of this study reveal these differences across multiple sites in the region.

Compared with *A. lebbeck*, *B. papillosa* presented lower carbon concentrations in its biomass *at* the Khoora site. *A. lebbeck* is recognized for its ability to fix nitrogen, grow quickly, and generate substantial biomass, positioning it as a strong candidate for carbon sequestration[62]. *B. papillosa* is characterized by its slower growth rate and limited biomass accumulation, leading to reduced carbon sequestration rates. This underscores the importance of choosing plant species that not only flourish in the local ecosystem but also possess the ability to accumulate substantial biomass[63]. The species *P. cineraria* demonstrated the greatest level of carbon sequestration at both the Dape Sharif and Anga sites.

The highest level of carbon sequestration was demonstrated by *M. indica* in the Knotti Garden location. The Jallar site presented the highest level of carbon sequestration in *P. glandulosa*, which is also part of the Prosopis genus. Like *P. cineraria*, this species possesses a strong root system that enables it to flourish in dry environments and sequester considerable quantities of carbon within its woody biomass[64]. This herbaceous plant has a shorter lifespan and limited biomass accumulation, rendering it less effective at storing carbon[65]. The findings of this study indicate that the potential for carbon sequestration among different plant species varies significantly on the basis of their growth traits, biomass output, and ability to adapt to local environmental factors.

Soil erosion, defined as the removal of the topsoil layer through wind, water, or human activities, presents a significant environmental issue. This process contributes to land degradation and a decline in soil fertility, both of which are critical for supporting plant growth[66]. The most successful plant at lowering soil erosion at Khabeki study site 1 was *A. modesta*. This plant thrives in arid and semiarid regions and is known for its deep and wide root system, which stabilizes soil particles and significantly reduces the effects of wind and water erosion[63].

Khoora study site 2 presented *A. nilotica* which had the most significant capacity to mitigate soil erosion. This tree has significant efficacy in soil stabilization because of its deep taproot and dense canopy, which safeguard the soil against the erosive impacts of wind and water[64]. At Dape Sharif study site 3, *T. undulata* demonstrated the highest efficacy in mitigating soil erosion. *T. undulata* plays a significant role in reforestation initiatives within arid areas, addressing issues of desertification and soil erosion. At Anga study site 4, *P. cineraria* emerged as the leading species in mitigating soil erosion. This species, commonly referred to as the Ghaf tree, remarkably adapts to arid environments, thereby preventing both water and wind erosion[67].

Conclusion

The present investigation delves into the floristic composition, phytosociological attributes, and physicochemical characteristics of soil across six unique ecotypes, namely, Khabeki S1, Khoora S2, Dape Sharif S3, Anga S4, Knotti garden S5, and Jallar S6, which are located in the Soon Valley. The results revealed unique phytosociological patterns and variations in soil properties. This study quantified ecosystem services, including carbon sequestration and soil erosion prevention, highlighting the importance of these ecotypes in maintaining ecological balance and supporting local livelihoods. Research has emphasized the need for conservation and sustainable management of these ecosystems, integrating ecological evaluations with socioeconomic factors to ensure the continued delivery of vital ecological services (MEA, 2005; IPBES, 2019). By adopting a comprehensive approach, this study contributes to a deeper understanding of the complex interconnections within these ecosystems, underscoring the imperative of conservation to preserve biodiversity and ecosystem services for future generations.

Data availability

The data are provided within the manuscript or supplementary information files.

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Author contributions
Aafaq Ali collected and analyzed the samples; Zafar Iqbal Khan and Kafeel Ahmad supervised the study; Ahlam Khalofha revised the original draft and prepared the graphs; Muhammad Arif worked on methodology and reviewed the manuscript. All authors contributed in the manuscript.

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Competing interests
The authors declare no competing interests.

Informed consent
All subjects gave their "informed consent" for the publication of details within the text ("informed consent") to be published in the above Journal and Article. Written "informed consent" was obtained from all authors for the publication of this manuscript.

Ethics approval
The Institutional Ethics and Guideline Committee of the University of Sargodha (Approval No. 128-H33/2019 UOS) has allowed all the protocols used in this experiment. All the experimental methods of this study followed all the appropriate guidance and regulations.

Voucher specimens
The plant samples were identified by Dr. Iftikhar Ahmad, an associate professor at Botany, University of Sargodha, Sargodha, Pakistan, and Dr. Mansoor Hameed, a Professor at the University of Agriculture, Faisalabad. Voucher samples are available from the Department of Botany, University of Sargodha (SB2020/211–223); Muhammad Ali, contact: +923036200205). Prepared slides (number SB2020/45–50) were deposited at the Department of Botany University of Sargodha, Sargodha, Pakistan.

Additional information
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Correspondence and requests for materials should be addressed to A.A.