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Role of Traditional Agroforestry Systems in Climate Change Mitigation through Carbon Sequestration: An Investigation from the Semi-Arid Region of Pakistan

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Abstract: Several agroforestry systems prevail in different agro-ecological zones of Pakistan, and cover a remarkable area of 19.3 million hectares. They not only play an important role in slowing down CO_2 emissions, but also contribute to mitigating climate change. However, in many regions, the relevant effect of agroforestry systems on overall carbon (C) stock and their reliance on various factors are quite unidentified. This study was planned to assess the biomass accumulation and C stocks of different commonly practiced agroforestry systems (boundary, bund, scattered, agri-horticulture) and their constituent land use types (tree + cropland) through a non-destructive approach (allometric equations) in a semi-arid region of Punjab, Pakistan. The results showed that the highest plant biomass (87.12 t ha^{-1}) increased by 46%, 17%, 78%, and 339%, and C stock (42.77 t ha^{-1}) increased by 49.51%, 20%, 82%, and 361% in the boundary planting system compared to the bund, scattered, agri-horti and sole cropland, respectively. The soil organic carbon (SOC) stock at all three depths, 0–15 cm, 15–30 cm & 30–45 cm, was found in the following order: boundary planting system > bund planting system > agri-horti system > scattered planting system > agricultural system, with a maximum in the boundary planting system and minimum in the sole cropping system at all three depths. Overall, the total C stock of the ecosystem's vegetation + soil C (0–30 cm) in the forested area was 275 t ha^{-1}, equating to 37 t ha^{-1} in the agricultural system alone. Our results highlighted that agroforestry systems have the highest potential for C sequestration. We suggest that research and investment in agroforestry systems can be a successful way for Pakistan to achieve some of its climate change mitigation goals.

Keywords: agroforestry; boundary planting; carbon stock; climate change; plant biomass

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1. Introduction

Climate change mitigation and food security are major issues worldwide and are the major concerns of the United Nations' goals regarding sustainable development [1]. To overcome the demands of providing food with efforts to achieve climate change mitigation, the world requires promising carbon (C) sequestration strategies, especially land-based ones, that can be achieved without compromising food security [2–4]. Agroforestry is a viable option to tackle the above challenges, as it is a combined land use system in which perennial woody trees and crops are cultivated in the same land area [5]. Agroforestry acts as a viable land use system, enhancing land fertility and productivity, protecting biodiversity, increasing income, and sequestering C [6–8].

Agroforestry systems (AFS) can be used on a larger scale to restore soil productivity and improve farmers' ability to adapt to climate change, considering that soils around the world are being depleted by various factors such as industrialization, deforestation, intensive farming, soil erosion, and the increase in unsustainable agricultural practices [9,10]. Comparing AFS research worldwide has shown that AFS can boost C storage in both above and below-ground portions and soil [7,11]. Uncertainty still exists regarding the proportional contributions of distinct C pools, including the diverse above-ground plant strata, litter surface, and below-ground portions, such as root biomass and soil, to the total ecosystem C stocks of agroforestry systems. The above-ground biomass of vegetation can be divided into several strata such as trees (overstory and midstory), shrubs, and ground vegetation, whereas the below-ground vegetation biomass includes both fine and coarse roots [5,12]. However, the origin, species, land use system type, age, density, and diversity of the tree species can all affect the overall quantity of C captured in each biological constituent of the agroforestry system [7,13]. Nevertheless, our knowledge of how all these factors affect overall C stocks, comprising various forms of AFS, is currently inadequate. Generally, the biomass carbon stock in agroforestry systems is predicted to increase with tree age; however, this biomass and C accumulation rate is greater initially, but subsequently drops as trees attain their maximum potential growth [9].

Change in soil carbon after establishing an agroforestry system is also strongly time-dependent [14], and the equilibrium among various carbon inputs eventually estimates it through litter and losses from its microbial decomposition and organic matter of soil [7]. For instance, greater carbon breakdown and erosion brought on by soil disturbance in the early years after agroforestry methods may decrease soil carbon [15]. Tree density and biomass production play an important role in determining the carbon-capturing capacity of agroforestry systems. Higher tree species density and diversity within agroforestry systems make them capable of using resources such as soil water, light, and nutrients more efficiently than those with low tree species diversity [16,17]. Moreover, the interaction among these factors can also increase the system productivity and corresponding organic carbon in soil [11]. This ultimately results in higher biomass production and carbon sequestration in above- and below-ground portions [18,19]. Furthermore, the species diversity in agroforestry systems also results in several other benefits, such as biodiversity conservation, provision of different marketable wood and non-wood products, and protection against several diseases [20,21]. Tree diversity and density can also play a vital part in soil carbon storage, and enhance its amount by maximizing the quantity of above- and below-ground carbon contributions to the soil [22,23].

Previous efforts to sequester carbon on land have mainly emphasized the management of already prevailing forests and the conservation tillage of cropland [1,18]. However, different practices on the farms, such as agroforestry, can be a viable option for C sequestration. The potential of sequestering atmospheric CO_2 is particularly greater in agroforestry systems than in cropland, pasture, or natural savannas [24]. Tree roots provide extensive C inputs to stabilize the soil organic carbon (SOC) in the deeper horizon. Besides the C inputs, tree roots can recover nutrients and enhance plant growth; as a result, nitrogen nutrition may enhance and increase SOC sequestration [22]. The potential of various agroforestry systems to sequester SOC in both above- and below-ground biomass has attracted increased attention to climate change mitigation adaptions. In addition, in agroforestry systems soils, the SOC stock is stored at 30 to 300 Mg C ha^{-1}, up to 100 cm depth [5]. Global estimates of the C sequestration potential of agroforestry systems documented 1.1 to 2.2 Pg C ha^{-1}, but the estimate for specific land use systems is extremely ambiguous. Further, the contribution from vegetation biomass to C sequestration is also inconstant. However, the importance of agroforestry systems for C sequestration and their contribution to climate change mitigation is well recognized and documented worldwide. However, very little information is available regarding the contribution and potentiality of specific agroforestry systems in the semi-arid region of Pakistan. Annual crops and forage make up most of the agricultural land use within the semi-arid region of Pakistan; however, perennial trees are found to be planted along the field boundaries, on the bunds, and sometimes scattered in the field. Therefore, in this study, we intended to examine the effect of commonly practiced agroforestry systems on biomass accumulation of carbon stock and sequestration, both in the plants as well as in soil, to assess the potential of these land use systems in the semi-arid region of Pakistan reduce climate change and improve soil quality.

2. Materials and Methods

2.1. Study Site and Sampling Procedure

The study was carried out from 2018 to 2019 in the Chiniot district (31°43′12.00″ N; 72°58′44.00″ E) of central Punjab, Pakistan. The study area is present at an elevation of 179 m from sea level, with a total area of 1020 square miles. The climate of the study area experiences semi-arid conditions with an average annual temperature of 24.1 °C and average annual precipitation of 336 mm. According to the Agricultural Department of Pakistan, the major crops cultivated in the area are wheat (*Triticum eastivum*), rice (*Oryza sativa*), maize (*Zea mays*), and sugarcane (*Saccharum officinarum*); however, pearl millet, sorghum, sunflower, and pulses are also grown on a smaller scale. Both canal and tube well irrigation is used for agricultural purposes by the farmers in the selected district. The soil of the study area was a sandy, loamy, hyperthermic, typical calciargid type.

The main traditional agroforestry systems practiced by the local farmers in the study region are bund, boundary, and scattered tree planting systems. In a bund planting system, trees are planted on the bunds of the agricultural land, while in a boundary planting system, trees are planted on the boundaries established around the agricultural land. However, in scattered planting system, scattered trees are present within the farm field. The major tree species in the study area were poplar (*Populus deltoides*), sufaida (*Eucalyptus camaldulensis*), kikar (*Vechillia nilotica*), shisham (*Dalbergia sissoo*), simal (*Bombax ceiba*), shatoot (*Morus alba*), neem (*Azadirachta indica*), bakain (*Melia Azedarach*), black siris (*Albizzia lebbek*), ber (*Zizyphus mauritiana*), fruit trees such as mango (*Mangifera indica*) and kinnow (*Citrus reticulata*). However, in terms of occurrence and density, poplar was found to be the dominant tree, mainly due to its fast growth rate, adaptability, and multiple uses. In the agri-horti system, citrus is planted more in the study area than other fruit trees, due to its economic significance. Therefore, in the present study, only poplar and citrus-based agroforestry systems were considered. Field data were collected from 25 rural union councils of the abovementioned district for the estimation of carbon in plant biomass (tree + crop) as well as in soil (Figure 1). By implementing the lottery method of stratified random sampling, a total of 50 plots, two from each union council (0.405 ha/1 acre) of each practiced agroforestry system, were chosen. Among agricultural crops, maize was found to be the main crop cultivated in the study area. Soil analysis of the selected agroforestry systems was carried out in order to find the variation among soil properties; the soil of those selected agroforestry systems was of a sandy loam texture (Table 1).

2.2. Estimation of Biomass and Carbon

2.2.1. Tree Biomass and Carbon Estimation:

Tree inventory was performed on each selected agroforestry system in all the rural union councils of the Chiniot district, and all the poplar trees were measured. For biomass calculation, a non-destructive approach was used. A Haga altimeter was used to estimate the tree height from the ground level to the tip of the tree, and a digital caliper was engaged to measure the diameter at breast height (DBH, in ft) from ground level. Each measured tree's diameter (ft) was converted to meters. Each tree's above-ground biomass was computed using species-specific allometric equations, as described by [25], which was then extrapolated to a hectare basis, considering all the poplar trees in each system. Below-ground tree biomass was taken as 26% of the above-ground biomass [26,27]. The trees' carbon content was computed by taking 48% of the dry biomass as carbon [12,28].

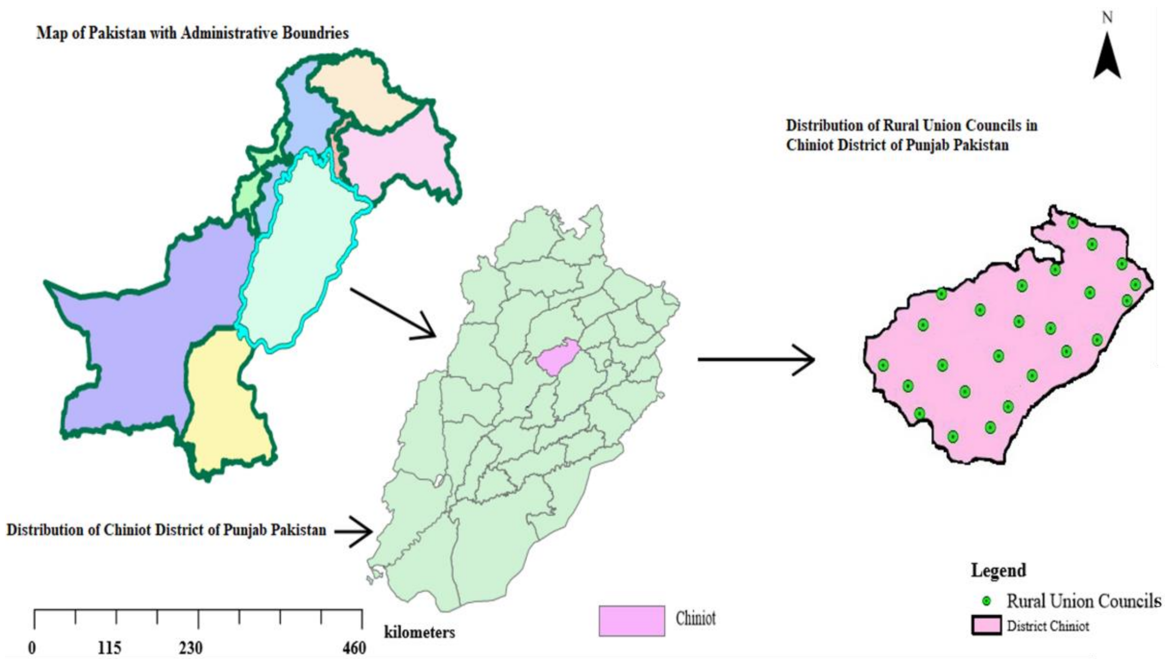

Figure 1. Map of the study area indicating the distribution of sampling points.

2.2.2. Crop Biomass and Carbon Estimation

The maize crop's biomass and grain yield were measured using a two-meter quadrate. After 20 rows of distance, two quadrates were placed in the selected plot of each agroforestry system. The complete plant of maize present in the quadrate was harvested, air-dried, and weighed. The above-ground portion of the crop was divided into four parts, leaf, stalk, cob, and grain, for calculation of above-ground biomass. Plant excavation was performed up to 40 cm to calculate below-ground biomass, until no further roots were examined. The total biomass was then converted to biomass ha^{-1} for all selected agroforestry systems [13]. For computing crop carbon content, sub-samples were shifted to the laboratory, oven-dried at 70 °C, grounded, and packed in sealed plastic bags. A wet combustion procedure with $K_2Cr_2O_7$, as explained by [29], was used to estimate carbon concentration, which was then scaled by crop carbon ha^{-1} throughout the study region.

2.2.3. Estimation of Soil Carbon

Soil samples were collected randomly by using a soil auger from the four cardinal directions near the base of trees at three different depths, 0–15 cm, 15–30 cm, and 30–45 cm, and were then mixed to make a composite sample to estimate the soil carbon across all selected agroforestry systems While in a sole agricultural system, soil was sampled in a random subset of plots. Overall, 375 soil samples were collected, 125 for each depth and 75 for each agroforestry system. Soil bulk density was also measured separately, using 100 cm^3 stainless steel cylinder for each depth. After air-drying the samples, organic carbon contents were measured, adopting the procedure explained by Walkley [30]. In the end, values of bulk density, soil depth, and percentage of organic carbon (OC) were used to calculate the SOC stock using the following equation, as explained by [4,13]:

$$\text{SOC stock (t ha}^{-1}) = \text{SOC content (g kg}^{-1}) \times \text{bulk density (g cm}^{-3}) \times \text{depth (m)} \times 10^{-1}$$

Table 1. Soil properties and a textural class of different agroforestry systems in the semi-arid region.

Sr. #	Agroforestry Systems	Soil Particle Size Class (%)			Textural Class	EC (ds m^{-1})	pH	OM (%)	*N* (%)	*p* (mg kg^{-1})	K (mg kg^{-1})
		Sand	Silt	Clay							
1	Boundary planting	72.44	16.23	11.33	Sandy loam	4.11 ± 0.14^{b}	7.96 ± 0.61^{b}	0.91 ± 0.08^{b}	0.052 ± 0.004^{ab}	7.43 ± 0.23^{b}	152.06 ± 6.22^{a}
2	Bund planting	68.32	19.72	11.96	Sandy loam	4.02 ± 0.22^{c}	7.89 ± 0.34^{bc}	0.83 ± 0.07^{c}	0.045 ± 0.003^{c}	7.10 ± 0.52^{cd}	136.42 ± 7.65^{c}
3	Scattered planting	65.43	21.45	13.12	Sandy loam	3.96 ± 0.17^{c}	8.10 ± 0.59^{a}	0.77 ± 0.11^{d}	0.044 ± 0.002^{c}	6.92 ± 0.66^{d}	141.26 ± 3.54^{b}
4	Agri-horti system	69.09	18.76	12.15	Sandy loam	3.80 ± 0.19^{d}	7.69 ± 0.41^{d}	0.99 ± 0.13^{a}	0.055 ± 0.001^{a}	7.62 ± 0.16^{a}	150.32 ± 8.22^{a}
5	Agricultural systems (only crop)	71.12	16.14	12.74	Sandy loam	4.16 ± 0.26^{aa}	8.05 ± 0.48^{a}	0.70 ± 0.09^{de}	0.049 ± 0.002^{b}	7.24 ± 0.43^{c}	145 ± 6.98^{b}
LSD						0.082	0.073	0.091	1.09	0.71	2.09

2.3. Statistical Analysis

Variations in plant biomass, carbon stock, and soil in the different agroforestry systems were compared by one-way analysis of variance using the Statistics 10 package. Means were compared for the significant difference by implementing the least significant difference (LSD) test at a 5% probability level. Graphs were plotted using Microsoft Office software (version 2016; Microsoft Corporation, Albuquerque, NM, USA).

3. Results

3.1. Tree Inventory and Plant Biomass

The basic information regarding inventory data, tree diameter (DBH, cm), tree height (m), and age and tree basal area (m^2 ha^{-1}), in the traditional agroforestry systems of the study district are mentioned in Table 2. The mean maximum tree DBH (20.82 cm), height (17.18 m), age (4.41 years), and basal area (2.36 m^2 ha^{-1}) were estimated in boundary planting, followed by scattered planting, bund planting, and the agri-horti system. Among all the selected agroforestry land use systems, the minimum mean values of DBH (11.65 cm), height (5.27 m), age (3.36 years), and basal area (0.72 m^2 ha^{-1}) were computed for the agri-horti system. Maximum mean tree density (114.56 trees ha^{-1}) was observed in agri-horti systems compared to other agroforestry land use systems.

The highest plant biomass (87.12 t ha^{-1}) was reported in the boundary planting system, which was increased by 46%, 17%, 78%, and 339% more than the bund, scattered, agri-horti, and sole agricultural land use system, respectively (Table 3). Across the five land use systems, the maximum contribution of trees to biomass accumulation was estimated in the boundary planting system (81.85%), followed by the scattered planting system (76.71%) and the bund planting system (71.72%), whereas the minimum percentage of trees contribution to biomass accumulation was measured in the agri-horti system (71.04%). In sole cropping, the order of biomass accumulation in the above- and below-ground parts was agricultural system > scattered planting system > bund planting system > boundary planting system > agri-horti system. The maximum total crop biomass (19.31 t ha^{-1}) was measured in the agricultural land use system, whereas the minimum total crop biomass (15.81 t ha^{-1}) was computed in the boundary planting agroforestry system.

3.2. Biomass Carbon Stock

The carbon concentrations of the above- and below-ground plant biomass of the five traditional agroforestry land use systems were significantly ($p < 0.05$) different from each other, and followed the following trend: boundary planting system > scattered planting system > bund planting system > agri-horti system > agricultural system (only crop). The maximum above-ground carbon stock (33.44 t ha^{-1}) was found in the boundary planting system and was 48.29%, 33.44%, 79.49%, and 338.48% higher than in the bund, scattered, agri-horti and agricultural land use systems, respectively (Figure 2). Similarly, the boundary planting system computed the maximum below-ground carbon stock (9.33 t ha^{-1}). The minimum carbon stock (1.46 t ha^{-1}) was measured in the agricultural system (Figure 2). A strong linear relationship was observed between the tree carbon and basal area at plot level for each of four selected agroforestry land use systems (R^2 = 0.47–0.86; Figure 3). The slope of the regression showed the relationship of carbon stock to the basal area was lower for the bund planting system as compared to that for the boundary, scattered and agri-horti system ($p = 0.0002$; Figure 3).

Table 2. Growth parameters (mean ± SD) of poplar trees of different agroforestry systems in the semi-arid region.

Sr. #	Agroforestry Systems	DBH (cm)			Height (m)			Age (Years)			Basal Area (m^2/ha^{-1})			Tree Density (Trees ha^{-1})		
		Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD	Mean	Range	SD
1	Boundary planting	20.82	0–24.87	2.70	17.18	0–25.14	3.98	3.41	0–9	2.52	2.36	0–3.37	0.61	34.65	0–91.40	13.65
2	Bund planting	17.15	0–22.56	3.18	15.49	0–20.36	2.65	2.90	0–7	2.37	1.62	0–2.77	0.56	25.47	0–87.61	14.98
3	Scattered planting	19.82	0–26.34	4.36	16.79	0–18.12	2.19	3.18	0–8	2.87	2.17	0–3.78	0.87	23.54	0–66.65	11.55
4	Agri-horti system	11.65	0–14.41	2.47	5.27	0–7.03	3.03	4.36	0–15	2.03	0.72	0–1.13	0.25	114.56	0–220	23.55
5	Agricultural systems (only crop)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 3. Distribution of biomass (above, below, and total biomass) among different agroforestry systems in the semi-arid region.

Sr. #	Agroforestry Systems	Above-Ground Biomass ($t\ ha^{-1}$)	Below-Ground Biomass ($t\ ha^{-1}$)	Total Biomass ($t\ ha^{-1}$)
1	Boundary planting + maize	69.68 ± 2.22 [a]	17.44 ± 0.83 [a]	87.12 ± 3.05 [a]
2	Bund planting + maize	46.99 ± 2.26 [b]	12.62 ± 0.61 [b]	59.61 ± 2.87 [b]
3	Scattered planting + maize	59.56 ± 2.47 [ab]	14.78 ± 1.01 [ab]	74.35 ± 3.48 [ab]
4	Agri-horti system + maize	38.82 ± 1.64 [c]	10.01 ± 0.70 [b]	48.83 ± 2.34 [c]
5	Agricultural systems (maize)	15.89 ± 1.21 [d]	3.42 ± 0.61 [c]	19.31 ± 1.82 [d]
LSD		4.42	1.61	6.03

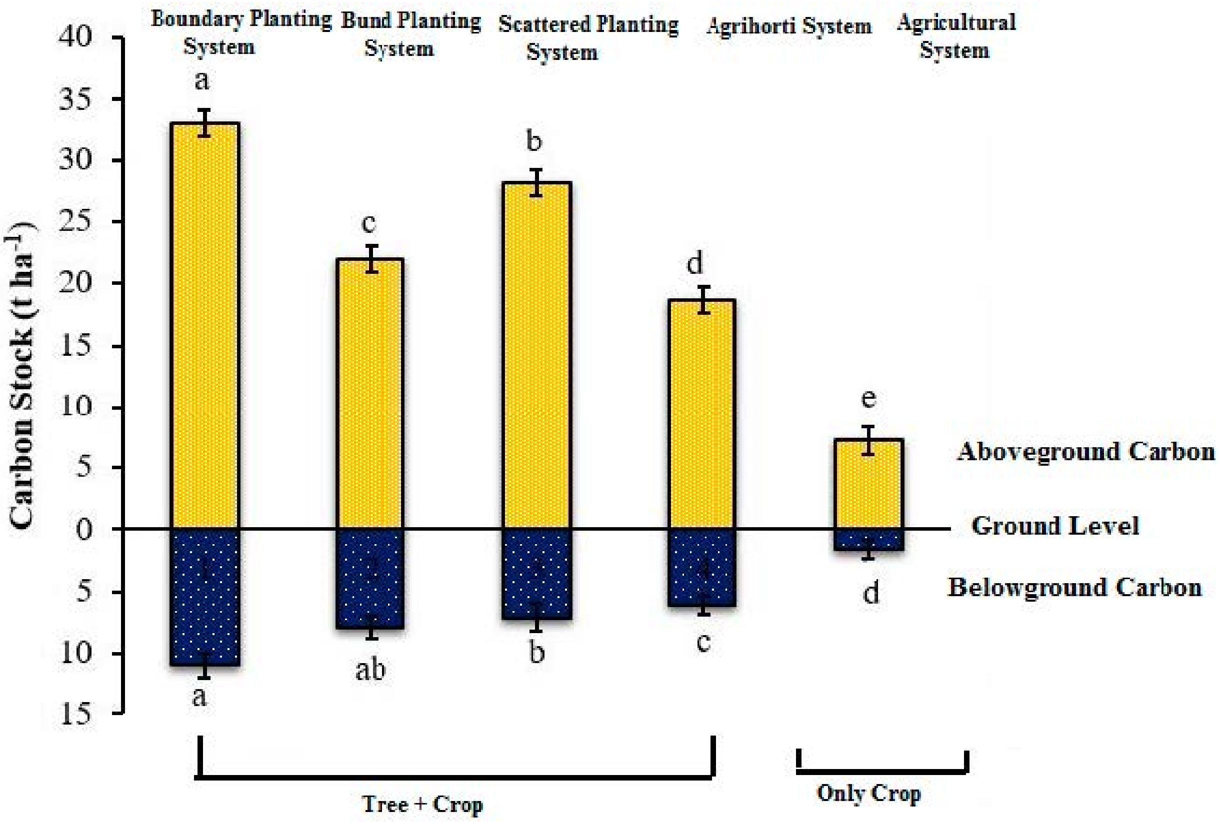

Figure 2. Distribution of biomass carbon stocks among different agroforestry systems in the semi-arid region.

3.3. Soil Organic Carbon Content and SOC Stocks

Soil organic carbon content decreased with the increase in soil depth, while bulk density ($g\ cm^{-3}$) increased with the increase in soil depth across all agroforestry land use systems and differed significantly ($p < 0.05$) from each other, as demonstrated in Table 4. The maximum bulk density (1.47 $g\ cm^{-3}$, 1.56 $g\ cm^{-3,}$ and 1.58 $g\ cm^{-3}$) was measured in the boundary planting system for all three depths, followed by the agri-horti system (1.44 $g\ cm^{-3}$, 1.50 $g\ cm^{-3,}$ and 1.53 $g\ cm^{-3}$), whereas minimum bulk density (1.36 $g\ cm^{-3}$, 1.40 $g\ cm^{-3,}$ and 1.44 $g\ cm^{-3}$) was computed in agricultural land use system. The SOC content was also higher in the upper soil layer (0–15 cm) in all agroforestry land use systems, and gradually decreased with the increasing soil depth. The highest SOC content (0.94%, 0.86%, and 0.74%) was measured in boundary planting systems as compared to other land use systems, at all three depths (0–15 cm, 15–30 cm, and 30–45).

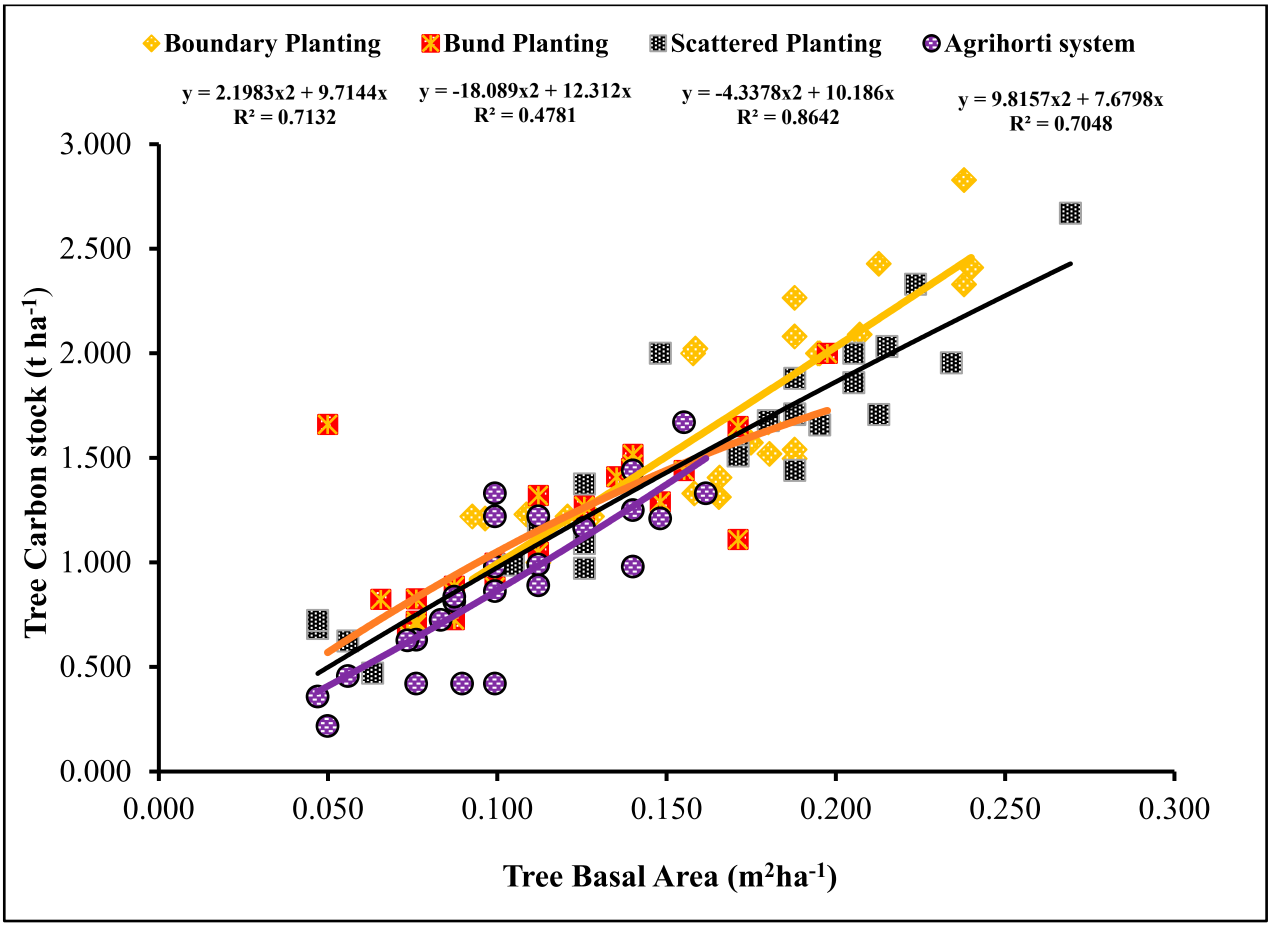

Figure 3. Relationship between tree biomass carbon stock (Mg ha^{-1}) and tree basal area (m^2 ha^{-1}) for agroforestry inventory plots in the study area.

Table 4. Soil organic carbon and bulk density of different agroforestry systems in the semi-arid region.

Sr. #	Agroforestry Systems	Soil Organic Carbon (SOC%)			Bulk Density (BD g cm^{-3})		
		0–15 cm	15–30 cm	30–45 cm	0–15 cm	15–30 cm	30–45 cm
1	Boundary planting	0.94 ± 0.05 ^{a}	0.86 ± 0.03 ^{a}	0.76 ± 0.08 ^{a}	1.47 ± 0.03 ^{a}	1.56 ± 0.02 ^{a}	1.58 ± 0.07 ^{a}
2	Bund planting	0.87 ± 0.04 ^{ab}	0.79 ± 0.07 ^{b}	0.68 ± 0.02 ^{b}	1.42 ± 0.02 ^{ab}	1.46 ± 0.03 ^{bc}	1.52 ± 0.03 ^{ab}
3	Scattered planting	0.75 ± 0.06 ^{c}	0.69 ± 0.04 ^{cd}	0.59 ± 0.04 ^{c}	1.38 ± 0.04 ^{b}	1.41 ± 0.02 ^{c}	1.46 ± 0.05 ^{b}
4	Agri-horti system	0.80 ± 0.06 ^{b}	0.72 ± 0.06 ^{c}	0.63 ± 0.05 ^{c}	1.44 ± 0.02 ^{a}	1.50 ± 0.01 ^{b}	1.53 ± 0.05 ^{ab}
5	Agricultural systems (only crop)	0.73 ± 0.03 ^{c}	0.65 ± 0.04 ^{d}	0.54 ± 0.02 ^{d}	1.36 ± 0.07 ^{b}	1.40 ± 0.05 ^{c}	1.44 ± 0.04 ^{b}

SOC stock was found in the order of boundary planting system > bund planting system > agri-horti system > scattered planting system > agricultural system for all soil depths, and was significantly different across all planting systems ($p < 0.05$; Table 5). Higher SOC stock (20.87 t ha^{-1}) was calculated in the boundary planting system, which was significantly increased by 10.24%, 22.11%, 34.21%, and 35.59% more than the bund planting, agri-horti, scattered planting, and agricultural system, respectively. Similarly, greater SOC stock (20.17 t ha^{-1} and 18.01 t ha^{-1}) was calculated at 15–30 cm and 30–45 cm depth in the boundary planting system, while the minimum SOC stock (13.77 t ha^{-1} and 11.68 t ha^{-1}) was determined in the sole agricultural system at both depths, respectively. (Table 5).

Table 5. Soil organic carbon stocks of different agroforestry systems at various depths in the semi-arid region.

Sr. #	Agroforestry Systems	Soil Organic Carbon Stock (t ha^{-1})		
		0–15 cm	15–30 cm	30–45 cm
1	Boundary planting	20.87 ± 0.98 ^{a}	20.17 ± 0.95 ^{a}	18.01 ± 1.05 ^{a}
2	Bund planting	18.93 ± 0.83 ^{b}	17.89 ± 0.85 ^{b}	15.44 ± 0.52 ^{b}
3	Scattered planting	15.55 ± 1.63 ^{c}	14.80 ± 0.45 ^{d}	13.02 ± 0.77 ^{c}
4	Agri-horti system	17.09 ± 1.49 ^{cd}	15.97 ± 0.72 ^{c}	14.37 ± 1.09 ^{b}
5	Agricultural systems (only crop)	14.95 ± 1.55 ^{d}	13.77 ± 1.03 ^{d}	11.68 ± 0.73 ^{d}

3.4. Ecosystem Carbon Stock

Ecosystem carbon stock, biomass carbon plus SOC (0–30 cm), as per IPPC guidelines, was measured to express the overall C sequestration potential of different agroforestry land use systems. Our estimates indicated that the ecosystem C stock was found in the order of boundary planting system > scattered planting system > bund planting system > agri-horti system > agricultural system. The total ecosystem C stock estimated in the boundary planting system was 85.09 t ha^{-1}, increased by 27.52%, 29.70%, 52.57%, 127.14% more than the scattered, bund, agri-horti and agricultural land use system, respectively (Table 6). Statistical analysis with the help of "PCA" presented that the first two axes have 99.11% variation, and "PC 1" and "PC 2" explained 88.09 % and 11.01% of the variation in the tree age, tree density, basal area, tree height, diameter, biomass carbon stock, soil organic carbon and total carbon stock, respectively. Data loaded onto "PC 1" include boundary planting (r = −24.39), bund planting (r = −22.64), scattered planting (r = −22.68), and agri-horti system (r = 69.72); while on "PC 2" included boundary planting (r = 22.60), bund planting (r = −7.38), scattered planting (r = −15.64), and agri-horti system (r = 0.42). Across all agroforestry land use systems, total biomass carbon stock was positively associated with total soil organic carbon stock (Figure 4).

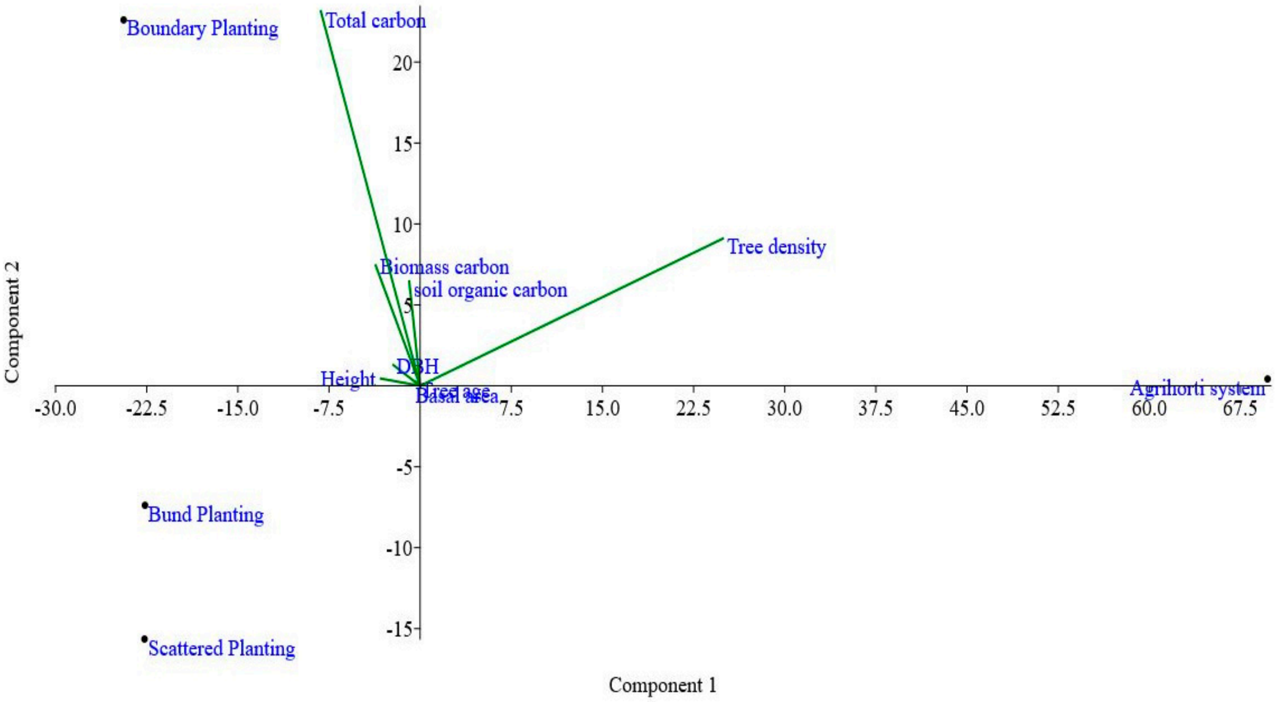

Figure 4. Principal component analysis (PCA) showing the relationship between tree carbon stocks and tree characteristics of different agroforestry systems in a semi-arid region.

Table 6. Total Biomass + Soil (ecosystem) carbon stock of different agroforestry systems under the semi-arid region.

Sr. #	Agroforestry Systems	Total Carbon Stock (t ha^{-1})		
		Total Biomass Carbon	Soil Carbon (0–30 cm)	Total Carbon
1	Boundary planting	44.05	41.04	85.09
2	Bund planting	29.88	36.82	66.70
3	Scattered planting	35.26	30.35	65.61
4	Agri-horti system	24.71	33.06	57.77
5	Agricultural systems (only crop)	8.74	28.72	37.46

4. Discussion

In the agroforestry system, the overall forested area stored significantly higher carbon (120 t ha^{-1}) than the cropland. This greater biomass carbon storage in agroforestry land use systems compared to contiguous cropland was estimated, and is consistent with several studies worldwide [3,7,11,23]. The carbon content of the above-ground tree biomass is higher than that of the below-ground tree biomass because the above-ground tree biomass includes the carbon content of the tree's trunk, stump, branches, twigs, and foliage, whereas the below-ground tree biomass only includes the carbon content of its fine and coarse roots, and makes up about 26% of the total tree biomass [27]. According to Kumar [31] and Askari [32], the above-ground tree biomass sequestered more carbon than the below-ground tree biomass. In the present study, on average, 32.38 t ha^{-1} above and below-ground biomass carbon is stored in the forested area. This amount of carbon is about 238% higher than crop biomass carbon. This level of biomass carbon content is in line with the 26.68 t ha^{-1} to 35.62 t ha^{-1} estimated in mature trees for various agroforestry systems with multiple tree species across different regions of the world [7,19,29,33,34]. However, biomass and carbon accumulation in agroforestry systems are extremely dependent on various factors such as tree species, species abundance, age, stand density, stand features, and management practices of that land use system [5,12,35]. The amount of biomass carbon indicates biomass accumulation in that tree species. In the present study, the amount of carbon in agroforestry land use systems was found in the order of boundary planting system > scattered planting system > bund planting system > agri-horti system > agricultural system (only crop). Among the agroforestry systems, boundary planting stored more carbon than scattered planting, followed by bund, agri-horti, and sole cropping systems. This might be due to the variations in tree densities, species types, tree ages, stand characteristics and management practices in various agroforestry systems, which result in different amounts of carbon accumulation among these systems [4,5,36]. Similar results regarding biomass carbon accumulation have been reported by various researchers in different land use systems such as [12] bund planting systems, [19] boundary planting and agroforestry systems in the semi-arid region, [36] and in different agroforestry land use systems both in rainfed and irrigated ecosystems. Our results showed that traditional agroforestry systems such as boundary and scattered planting captured more carbon than improved systems (home gardens and agri-horti) and barren lands. This is due to age variation, as trees in improved agroforestry systems are young and pruned regularly compared to those planted in traditional agroforestry systems [37–39].

Results at all three depths showed that a greater amount of SOC was measured across all agroforestry land use systems as compared to sole cropping systems. This possible increase in SOC stock in the forested area was mainly through roots, litter, and above-ground biomass. The total carbon stock in the soil (0–45 cm) was found in the order of boundary, planting > bund planting > agri-horti > scattered planting > agricultural system. The value of SOC declined with increasing soil depth, which was consistent with the conclusion of [40,41]. The soil type also plays an important role in SOC accumulation. Fine-textured soils generally have higher SOC than coarse-textured soils. Bonds that develop between organic matter and clay and silt protect organic matter before decomposition and form stable aggregates. Moreover, fine-textured soils have fewer pores and less oxygen, which also limits organic matter decomposition [22,42. This is because of a drop in microbial biomass, the weathering of parent materials, and a larger concentration of litter composition accompanied by soil depth. Several studies across the globe have demonstrated that agroforestry systems have greater soil organic carbon contents as compared to the mono-cropping system [3,5,36,42,43]; This can be attributed to a higher amount of biomass carbon, mostly as leaf litter reverted to soil, subsequently stabilizing the organic matter and decreasing the decomposition rates in agroforestry systems [44]. The tree-covered region has greater soil organic carbon than the crop or pastureland; this might be attributed to the higher plant carbon input to the soil from above and below-ground sources, and the detrimental effect of tillage on the carbon retention capacity of soil in the farmland [1,45,46]. These differences can also depend on various factors such as soil type, climate, topography, and management practices of various land use systems concerning space and time [47,48]. Moreover, soils with woody vegetation have a greater fraction of macronutrients, organic matter, and carbon in their topsoil portion compared to pastures or agricultural crops, as greater litter prompted by tree species enhances the organic matter content and ultimately improves the carbon fraction in the soil. Moreover, using fertilizers in agroforestry and sole cropping is also considered an important factor in increasing soil organic carbon [42,49]. The higher biomass of carbon stored in agroforestry land use systems compared to cropland is instinctual, as above, and the below-ground biomass of trees is much larger than the biomass of crops or herbaceous vegetation; around 50% of that biomass is carbon [1,50].

The total ecosystem carbon stock, vegetation + soil (0–30 cm), demonstrates an ecosystem's overall carbon sequestration capacity. Agroforestry systems can be taken as better land use options for capturing higher total carbon stocks than monoculture systems [42]. As hypothesized in this study, the total ecosystem carbon stock was significantly higher in all agroforestry land use systems compared to the sole cropping system (127.14%, 78.05%, 74.13%, and 54.21%, respectively), which plays an important role in sequestering a greater amount of atmospheric CO_2 and contributes to climate change mitigation. Therefore, conversion from monocultures to agroforestry systems can help increase carbon stocks and carbon sequestration potential. For example, an agroforestry system with oil palm and agarwood stored 224.4% more carbon than growing oil palm alone. The carbon content of the biomass ranged from 30 to 50 Mg C ha^{-1}, which is consistent with the results of the present study [38]. Similarly, Li [51] showed that poplar-based agroforestry systems could increase carbon sequestration twofold compared to monocultures. The measured ecosystem carbon stock in this study was in the range of 37.46 t ha^{-1} to 85.09 t ha^{-1}. This amount of stored carbon is comparable to the overall stored carbon in agroforestry systems in Southeast Asia [52], northwest China [29], and the western and central Himalayan region of India [34,53]. The amount of ecosystem carbon measured in the present study is higher than the ecosystem carbon (15–18 Mg C ha^{-1}) stored in silvopastoral systems in the low-humidity tropics of northern Asia [54]. Moreover, the overall carbon stock of the ecosystem varied from 31 t C ha^{-1} to 173.90 t C ha^{-1} in various agroforestry systems in different Indian states [25,35,55,56]. The modifications in the climate of the study area, type of practiced system, functional and structural characteristics, type of species, stand configuration, density, and soil properties were responsible for these discrepancies in carbon storage in different agroecosystems worldwide [7,57]. In summary, agroforestry systems in semi-arid regions proved to be a bottleneck strategy for reducing atmospheric CO_2 concentrations, improving SOC stock, and mitigating climate change.

5. Conclusions

Agroforestry systems that use a variety of tree species serve numerous purposes for the environment and the local population in meeting their daily requirements, including generating revenue. We conclude that managing and promoting agroforestry systems can be useful for achieving climate change mitigation objectives for underdeveloped countries such as Pakistan, having forest cover <2%. Depending on the findings of this study, we endorse that governments at various stages formulate and apply a planned agenda for encouraging agroforestry systems, for example, by providing funds to private landlords throughout the country. Traditional as well as improved agroforestry systems can play a significant role in sequestering larger amounts of carbon dioxide from Pakistan's agricultural lands. We emphasize the management as well as the conservation of current agroforestry systems as their carbon stock increases with time. Additionally, we recommend that tree species used in agroforestry systems be selected to maximize the ecological and socioeconomic advantages for a particular area or ecological zone. Future research should have considered an LFH (litter, partially decomposed litter) layer to estimate carbon stocks of agroforestry systems, and should use the ESM technique to assess soil organic carbon stock variations in mineral soils, especially when comparing the effects of different land use strategies.

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