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RESEARCH ARTICLE

Tree diversity and regeneration dynamics toward forest conservation and environmental sustainability: A case study from Nawabganj Sal Forest, Bangladesh

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Abstract
The objective of this study was to examine the regeneration dynamics and population structure of the most prevalent tree species, *Shorea robusta* (Sal), alongside four other dominant tree species (*Tectona grandis*, *Syzygium cumini*, *Trema orientale*, and *Cassia fistula*) in the Nawabganj Sal Forest in Bangladesh. The regeneration status and tree diversity of all documented tree species were assessed using a simple random sampling technique. Among the 30 species, 5 species (*Shorea robusta*, *Tectona grandis*, *Trema orientale*, *Gmelina arborea*, and *Artocarpus heterophyllus*) exhibited favorable regeneration state, whereas 15 species had moderate regeneration status. However, the absence of the condition 'no regeneration' was due to the absence of the adult stage, which resulted in the absence of seedlings and saplings. The quantity of seedlings was greater during the rainy season compared to the dry season. The girth class distribution of *Shorea robusta* and all other studied tree species combined exhibited a reverse J-shaped population curve. There was a decline in tree density as the girth class increased, and trees with a larger girth class accounted for 34 individuals per hectare, indicating a strong ongoing regeneration capability. The Shannon-Wiener diversity index, Simpson's dominance index, Pielou's evenness index, and Margalaf's species richness index had values of 0.223, 0.937, 0.077, and 2.249, respectively. These values imply a limited diversity of tree species in the examined forest. *Shorea robusta* has the highest dominance (m^2/ha), followed by *Tectona grandis* (0.091), *Syzygium cumini* (0.087), *Trema orientale* (0.022), and *Cassia fistula* (0.008). The cumulative basal area of the tree species examined amounted to 40.04 m^2/ha, with Shorea robusta accounting for 39.81 m^2/ha. This indicates that Sal is the prevailing tree species in the forest. Nevertheless, this study offers fundamental data regarding the current condition of the tropical Sal Forest toward forest conservation and environmental sustainability.

Keywords: Regeneration; Tree diversity; Population structure; *Shorea robusta*; Forest conservation; Environmental sustainability

Introduction

Deforestation is the second most significant contributor to the increase in human-caused carbon emissions, which in turn leads to global warming and climate change (Abdallah et al., 2023;). Tropical forests are more vulnerable, and biodiversity is being threatened due to deforestation and forest degradation (Lapola et al., 2023;). Therefore, the significance of preserving forests for the purpose of maintaining environmental sustainability is on the rise because of the expanding global consciousness regarding the environment (Koulelis et al., 2023). The process of natural regeneration is crucial for the maintenance and growth of plant populations in a forest ecosystem (Latterini et al., 2023). Both natural regeneration and artificial regeneration are essential for forest conservation because of the unpredictability of multiple causes (Li & Xu, 2023). Tree regeneration is a crucial aspect of forest dynamics and has a significant impact on the structure, composition, and variety of forest ecosystems (Ma et al., 2023). The process is intricate and comprises a sequence of processes, commencing with pollination and culminating in the successful establishment of a single plant (Bullones et al., 2023). Regeneration refers to the process of renewal by which forest trees and other organisms are able to survive and perpetuate themselves (Calvia et al., 2023). Natural regeneration is a vital process in tropical forest dynamics that is necessary for the preservation and maintenance of biodiversity (Elliott et al., 2023). The reclamation behavior of tree species in a forest can be inferred from the population structure and growth (Bergsagel & Heisel, 202). Population structure refers to the distribution of individuals within different size classes of tree species (Jamloki et al., 2023) as well as the classification of a species based on many characteristics such as diameter, girth, height, and age. Biological diversity refers to the assortment of different life forms found on Earth, encompassing animals, plants, and even microorganisms (Hald-Mortensen, 2023). Tree diversity is a crucial component of plant diversity as it enhances the variety of other organisms by providing them with food and shelter (Haq et al., 2023).

A tropical moist deciduous forest, often known as a Sal Forest, is characterized by the dominance of a single plant species, specifically the Sal tree (*Shorea robusta* Gaertn.), along with other associated plants (Kumar & Saikia, 2021). Sal is a type of tree that is native to the Indian subcontinent (Sharma et al., 2022). It can be classified as deciduous, semi-deciduous, or evergreen. Sal trees are found in the southern region of the Himalayas, extending from Myanmar in the east to Nepal, India, and Bangladesh (Mishra et al., 2021). Sal is a versatile tree species that is categorized as endangered by the International Union for Conservation of Nature (IUCN). It has significant socio-economic potential and is primarily utilized for lumber, medicinal uses, animal feed, fuelwood, dried leaves for cooking and heating, fresh leaves for producing plates, edible seeds, and religious practices (Kumar & Saikia, 2021). Seedlings and saplings play a vital role in the forest ecosystem as they are essential for the regeneration, diversity, and future population structure (Maletha et al., 2023). The productivity and regeneration of the Sal Forest are contingent upon the optimal abundance of seedlings, saplings, and mature trees (Iskandar et al., 2023). Successful regeneration is shown by the presence of a sufficient quantity of seedlings, saplings, and young trees within a particular population (Gonçalves & Fonseca, 2023).

The regeneration of tree species is influenced by a range of biotic and abiotic variables (Ibáñez et al., 2022). Biotic variables encompass the living organisms present within the ecosystem (Costas-Selas et al., 2023). Human beings, insects, and animals are all biotic components. Nevertheless, it is humans who bear the primary responsibility for the disruptions in a forest. Unmanaged animals have an impact on both the decrease and increase of forest regeneration. However, in most situations, people living near the forest allow their livestock to graze in the forest to meet their livestock's feed requirements. Human-induced disruptions impact the ability of Sal Forest to regenerate and alter the composition of its population (Behera et al., 2023). The regeneration of the Sal Forest is influenced by the presence or absence of termite mounds, as well as the impact of the Sal borer on Sal regeneration (Kumar & Saikia, 2021). In addition, abiotic variables, which are nonliving components, also impact the reclamation status,

population structure, diversity, and species composition of the Sal Forest in Bangladesh, Nepal, and India. Slope and aspect are abiotic elements that influence the regeneration, diversity, and growth of Sal trees in the Pragatisil community forest in Nepal (Bhatta & Devkota, 2020). The regeneration of Sal Forest is influenced by the nature of the site and the availability of sunshine (Behera et al., 2023). The composition of Sal forests is influenced by the gradient of light, as light plays a crucial role in the germination, growth, and survival of seedlings in the lower layers of tropical forests (Sharma et al., 2019). The presence of sunlight, a crucial factor for the optimal development of plants, is contingent upon the extent of crown cover and the degree of tree canopy opening (Liu et al., 2023). The regeneration of Sal is influenced by the opening in the tree canopy and the cover of the crown (Baral & Ghimire, 2020). The reverse J-shaped girth class distribution in the case of population structure signifies a healthy regeneration of the forest (Kumar & Saikia, 2021).

The Sal Forest in Bangladesh spans over 0.12 million hectares of land, accounting for approximately 4.7% of the country's total forest area (Roshni et al., 2023). The distribution of Sal forests in Bangladesh is primarily concentrated in the central and northern regions of the country. The Sal Forest ecosystem in northern Bangladesh spans an area of 26.5 thousand acres, primarily located in three districts: Dinajpur (69.42%), Thakurgaon (9.28%), and Panchagar (21.30%). The Sal Forest is located in three forest ranges within the Dinajpur district, including the Madhdhapara, Chorkai, and Sadar Dinajpur ranges. Deforestation is a significant environmental issue in Bangladesh (Ullah et al., 2022). The presence of cut stumps serves as evidence of forest disturbances. Although the government of Bangladesh has taken appropriate measures to mitigate this issue, it has not been completely eradicated. The disturbance index has a positive or negative correlation with the density and basal area of trees inside the forest (Liu et al., 2022). Forest-dependent people in Bangladesh have a significant impact on the regeneration of Sal forests since they rely on them to meet their diverse needs (Ray et al., 2023). Additionally, they also engage in livestock grazing within the forest regions. This woodland habitat has suffered extensive degradation due to both human activities and natural events (Saha et al., 2021).

Currently, there is a need for regeneration research to restore and conserve forests. The forest area of Bangladesh is decreasing steadily. Therefore, it is imperative to implement appropriate measures for the preservation and safeguarding of forests in order to enhance environmental sustainability. Prior to engaging in conservation efforts, it is necessary to possess knowledge regarding the diversity, regeneration state, and population structure of the forest. Additionally, understanding the variables that contribute to forest regeneration is crucial. Prior to implementing effective measures for the conservation of the Sal Forest, it is imperative to ascertain the current state of regeneration of the forest. Previous studies focusing on tree diversity, population structure, and regeneration dynamics of the Sal Forest were carried out in the center portion of Bangladesh (Roshni et al., 2023). However, there is a research gap exploring the tree diversity and regeneration dynamics in the Sal Forest in the northern region of Bangladesh, specifically the Nawabganj Sal Forest, Dinajpur. The climate, altitude, and edaphic elements in the northern region of Bangladesh differ not only from the central part of the country but also from the Sal Forest area in India and Nepal. Given the aforementioned considerations, the current investigation was undertaken to fill up the existing research gap. The study aims to assess the population structure and regeneration status of *Shorea robusta*, focusing on four dominant tree species (*Tectona grandis*, *Syzygium cumini*, *Trema orientale*, and *Cassia fistula*). This assessment was based on both density and dominance. Furthermore, this study seeks to ascertain the current state of regeneration and the level of biodiversity among all documented tree species inside this forest. This study offers fundamental data on the current condition and prospective sustainability of the tropical Sal Forest in the northern region of Bangladesh. The findings of the study would help take necessary actions for improving the Sal Forest conservation and management toward environmental sustainability.

Methodology

Study area

The research was carried out in the Nawabgonj Sal forest located in the Dinajpur district of Bangladesh. Figure 1 displays the map of the research area. The Nawabgonj Sal forest, also known as Nawabgonj National Park, is located at coordinates 25.4517524°N and 89.0534941°E. It spans a total area of 517.61 hectares. The declaration of the national park took place on October 24, 2010, and it was subsequently renamed Sheikh Rasel National Park in 2016. Dinajpur is located approximately 37 meters above sea level in Bangladesh. The district is defined by a level plain formed by the deposition of sediment carried by rivers, and it is interrupted by the slightly elevated. This region is covered with a type of forest known as tropical moist deciduous forest or Sal Forest, which is primarily composed of a single species of tree called Sal tree (*Shorea robusta*). The soil of Dinajpur is characterized as sandy clay loam, with medium-high elevation, 51-60% soil porosity, medium organic matter content, severely acidic pH levels, no salinity, and non-calcareous brown floodplain with black terai soils. Dinajpur has a tropical climate characterized by high temperatures, abundant rainfall, and high humidity. Dinajpur is classified under the Köppen climate classification as having a tropical wet and dry climate. The mean temperature recorded in Dinajpur district from 2019 to 2022 was 28.38˚C. Figure 2 displays the annual rainfall, duration of sunlight, number of rainy days, and number of sunny days in the study area from 2019 to 2022.

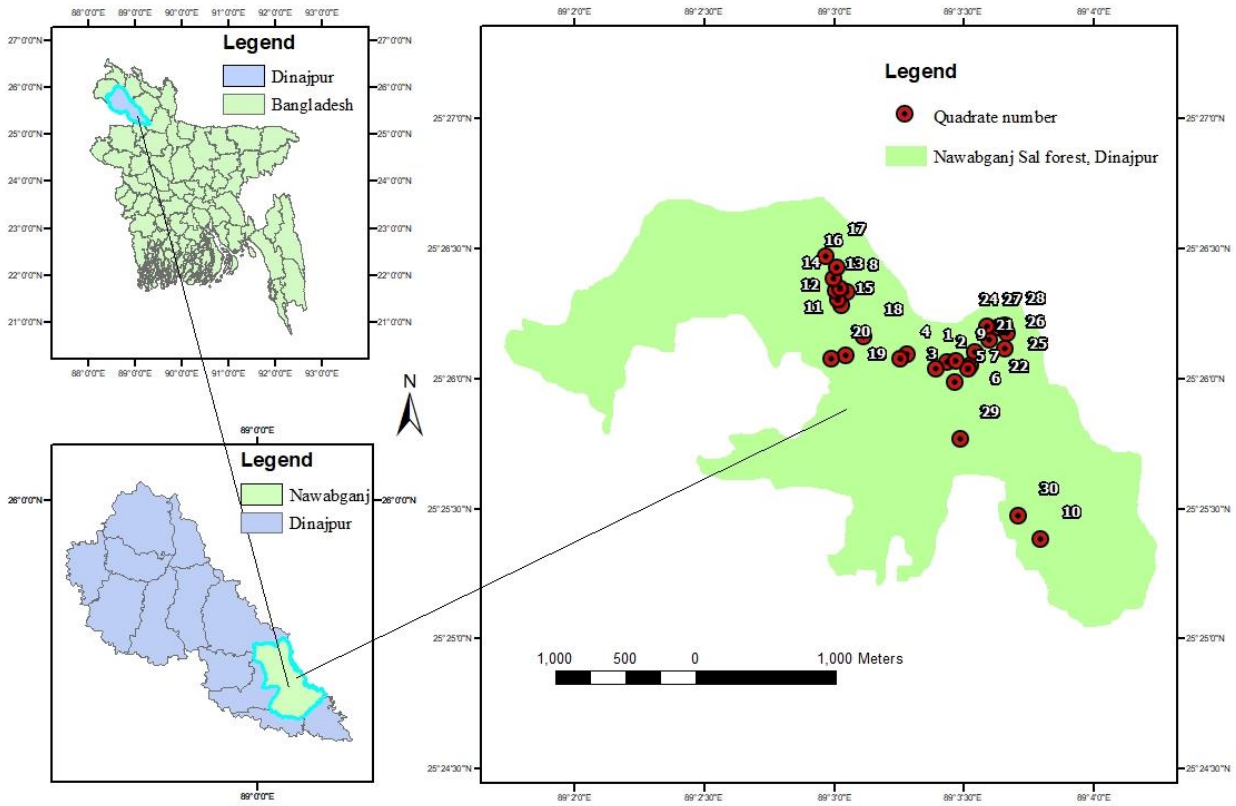


Figure 1. Map of the study area (The sampling site is indicated by a round red icon).

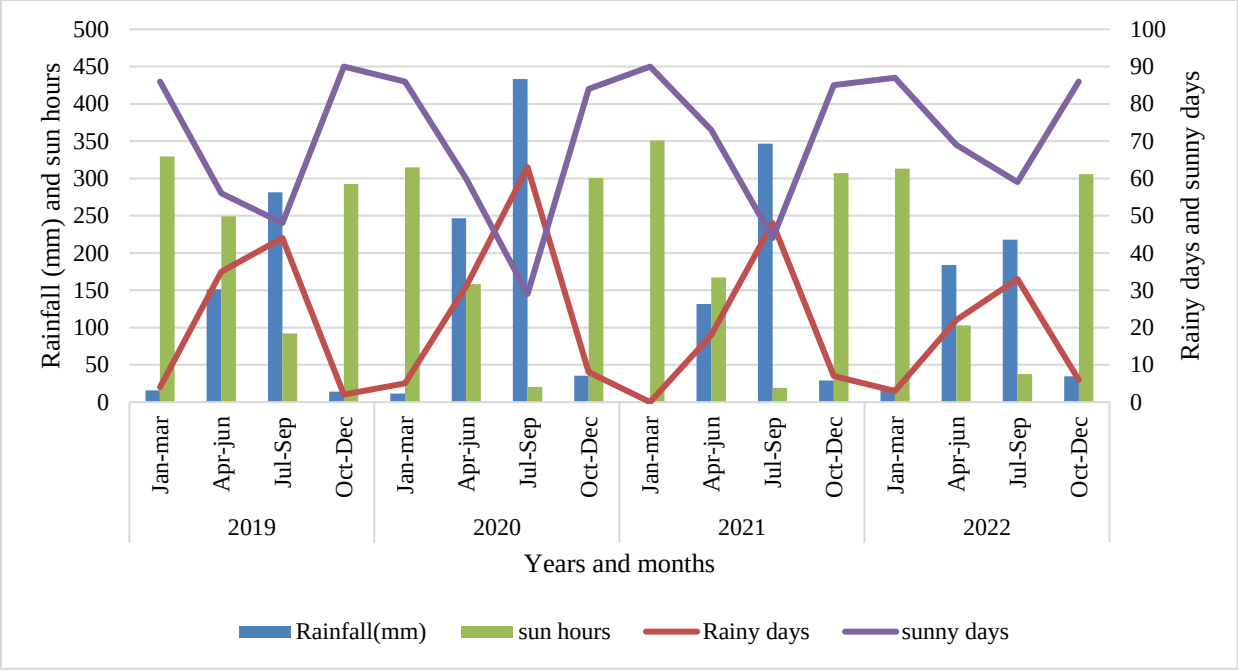


Figure 2. The annual rainfall, duration of sunlight, number of rainy days, and number of sunny days in Dinajpur, Bangladesh.

Sampling and data collection

Field sampling was conducted in Nawabganj Sal Forest from July 2021 to December 2022 using the quadrat method by Mishra (1968). 30 quadrats were randomly sampled from Nawabganj National Park using a simple random sampling procedure. Random sampling is a sampling technique where any population within a given area has an equal chance of being selected as part of the sample. The determination of the number and size of the quadrats was based on the species-area curve method (Mishra, 1968; Scheiner, 2003). Plants with a girth at breast height (GBH) greater than 10 cm were classified as trees. Plants with a GBH less than or equal to 10 cm and a height greater than 30 cm were classified as saplings. Individuals with a height less than or equal to 30 cm were classified as seedlings (Kumar & Saikia, 2020). A 20 m × 20 m square was used to count the number of adult plants. Additionally, a smaller 5 m × 5 m square was nested within the larger square to count the number of saplings and seedlings. Within the 20 m × 20 m square, four diagonally opposed 1 m × 1 m squares were nested to collect data. The dimensions of each square were measured using a 30-meter-long measuring tape. The GBH of trees, measured 1.37 meters above the ground, and the height of all adult individuals was determined in each quadrate. The GBH was measured using a thin measuring tape with a length of 1.5 meters, while the Haga-Altimeter was used to measure the height.

The assessment of the regeneration status of tree species was conducted by evaluating the population sizes of seedlings, saplings, and mature trees (Sarkar & Devi, 2014; Pokhriyal et al., 2010). If the population hierarchy is such that seedlings have a greater number than saplings, and saplings have a greater number than adults, then the regeneration status of tree species can be classified as "good regeneration". If the population consists of seedlings that are either greater than or equal to saplings, and saplings that are less than or equal to adults, with the additional condition that seedlings are less than or equal to saplings and saplings are greater than adults, and if there are no adults present, then the regeneration status of the tree species is classified as "fair regeneration". If a tree species only survives in the sapling stage and not as seedlings (with saplings potentially being larger, smaller, or equal in

size to adults), then the regeneration status of that tree species is considered to be "poor regeneration". If a species is exclusively found in its mature form, it is classified as "non-regenerating". A species is classified as "new" or a "new arrival" if it is exclusively found in the seedling or sapling stage without any adult individuals present.
The individual trees were categorized into seedlings, saplings, and mature trees based on their girth and height. This research followed the proposed method by Kumar and Saikia (2020) for studying the population structure of Sal and other allied tree species by categorizing individuals into different age groups based on their girth at breast height (GBH in cm) and height (in meters). This classification into five separate classes (Table 1) was done to facilitate a more thorough investigation and understanding of the population structure. Figure 3 illustrates the sampling methodology employed in the study.

Table 1. Different age groups based on tree GBH and height for population structure study.

GBH (cm) / Height (cm)	Age group on GBH	Height (m)	Age based on mean height
Height ≤30	Seedling	<1	Seedling
GBH ≤10 and Height >30	Sapling	1-5	Sapling
GBH >11-30	Pole	>5-10	Understory
GBH >31-60	Young	>10-20	Canopy
GBH >61-90	Adult	>20	Emergent
GBH >91-120	Mature		
GBH >121	Old		

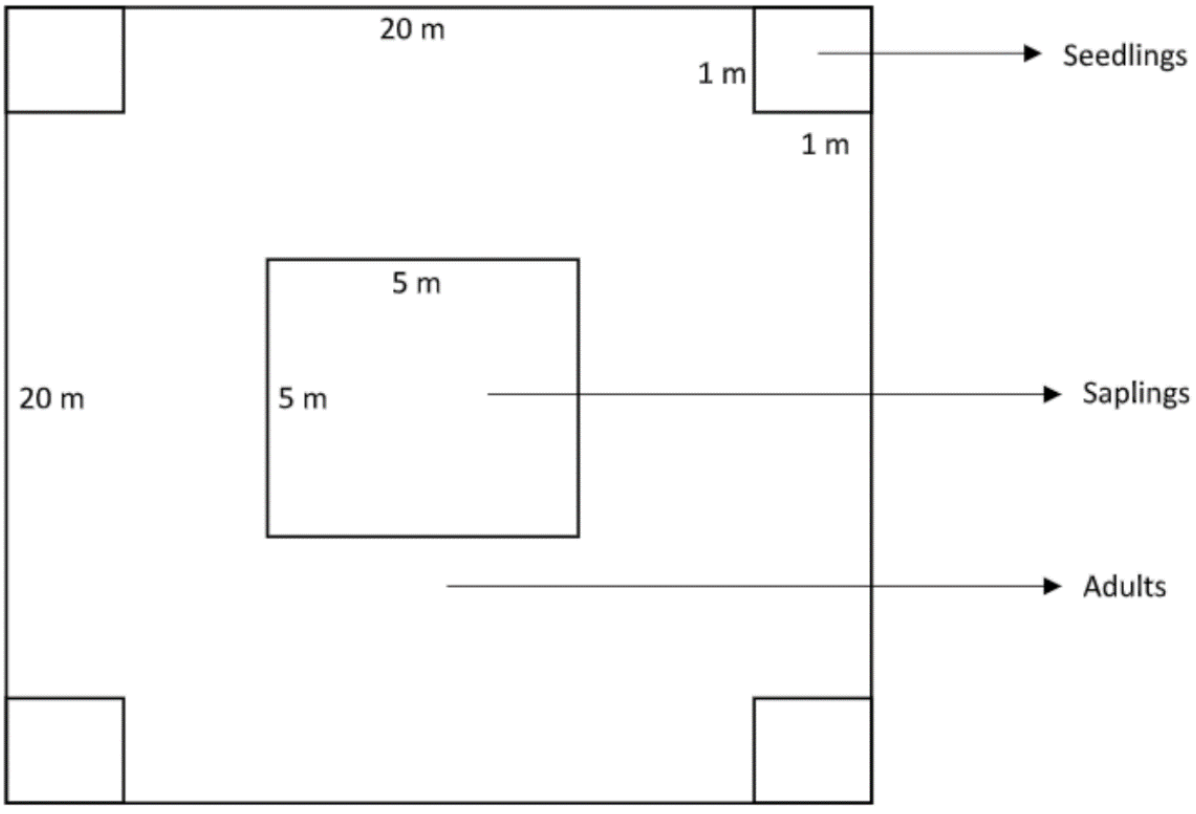


Figure 3. The sampling design of the study.

Data analysis

The data recorded were quantitatively analyzed for frequency, density, dominance, abundance and the relative values of these parameters were calculated and summed up for the Importance Value Index (IVI) (Mishra, 1968; Chhetri et al., 2019; Kunwar et al., 2020). The number of plants were converted into individuals/ha. The equations for the data analysis are presented below:

$$\text{Frequency (\%)} = \frac{\text{Number of quadrates of species occurrence}}{\text{Total number of quadrates studied}} \times 100 \quad (1)$$

$$\text{Density} = \frac{\text{Total number of individuals of a species present in all quadrates}}{\text{Total number of quadrates studied}} \times 100 \quad (2)$$

$$\text{Density} = \frac{\text{Total number of species present in all quadrates}}{\text{Total number of quadrates studied}} \times 100 \quad (3)$$

$$\text{Abundance} = \frac{\text{Total number of individuals of a species present in all quadrates}}{\text{Total number of quadrates studied}} \times 100 \quad (4)$$

$$\text{Dominance} = \sum \text{Basal area of all individuals of a species in all the studied quadrates} \quad (5)$$

$$\text{Relative frequency} = \frac{\text{Frequency of a species}}{\text{Sum of the frequency of all specie}} \times 100 \quad (6)$$

$$\text{Relative density} = \frac{\text{Density of a species}}{\text{Sum of the density of all specie}} \times 100 \quad (7)$$

$$\text{Relative abundance} = \frac{\text{Abundance of a species}}{\text{Sum of the abundance of all specie}} \times 100 \quad (8)$$

$$\text{Relative dominance} = \frac{\text{Dominance of a species}}{\text{Sum of the dominance of all specie}} \times 100 \quad (9)$$

$$\text{Importance Value Index (IVI)} = \text{Relative frequency} + \text{Relative density} + \text{Relative abundance} \quad (10)$$

Also, the index was calculated using dominance in place of abundance.

$$\text{Importance Value Index (IVI)} = \text{Relative frequency} + \text{Relative density} + \text{Relative dominance} \quad (11)$$

Margalef's index was used as a simple measure of species richness (Margalef, 1958) using the formula Margalef's index of richness (R).

$$R = \frac{S-1}{\ln N} \quad (12)$$

where S is the total number of species and N is the total number of individuals. A value of zero indicates a very low diversity of species. A value Greater than 8 indicates very high diversity of species.

Moreover, the study used the Shannon–Wiener diversity index (Shannon & Wiener, 1963) presented in the equation below:

$$H' = -\sum(p_i \ln p_i) \quad (13)$$

where, p_i is the proportion of individuals of one particular species (n) found divided by the total number of individuals (N) found. The higher index indicates more diversity of species in the habitat. If the index is zero, only one species is present in the forest.

The concentration of dominance CD was assessed using Simpson's index (Simpson, 1949) presented in the equation below:

$$CD = \sum_{i=1}^{s} P_i^2 \quad (14)$$

The value of Simpson's dominance index ranges from 0 to 1 in which 1 represents no diversity but 0 represents infinite diversity.

For calculating the evenness of species E, Pielou's evenness index was used (Pielou, 1966).

$$E = \frac{H'}{Hmax'} \quad (15)$$

where H' is the Shannon–Wiener diversity index and Hmax' is ln of total number of species. The calculated value of Pielou's evenness index ranges from 0 (No evenness) to 1 (Complete evenness).

Basal area of standing trees was calculated using following formula:

$$\text{Basal area} = \pi \times \left(\frac{DBH}{2}\right)^2 \quad (16)$$

where, DBH is the diameter at breast height.

This research performed the data analysis by using Microsoft Excel and Statistical Package for the Social Sciences (SPSS, Version 22.0) software. The maps of the study area were generated with the help of ArcGIS (Version 10.3) and Google Earth.

Results

The present study recorded a total of 1918 individuals of trees (of 30 species) in Nawabganj Sal Forest of Dinajpur in which 944 (49.22%) individuals were pole, 361 (18.82%) individuals were young, 397 (20.70%) adult, 175 (9.12%) mature and 41 (2.14%) old. Small-sized trees (poles and young) had dominated the tree population, while the maximum density (787 individuals/ha) recorded of pole individuals (> 10-30cm girth class). In terms of density (Individuals/ha), *Shorea robusta* was the most dominant tree 1548 individuals/ha followed by *Tectona grandis* (9 individuals/ha), *Syzygium cumini* (8 individuals/ha), *Trema orientale* (7 individuals/ha), *Cassia fistula* (6 individuals/ha). The density of seedlings was the highest, followed by the density of saplings in case of *Shorea robusta*, *Tectona grandis*, *Trema orientale* and *Cassia fistula*, while the density of saplings was highest, followed by seedlings in case of *Syzygium cumini*. This study found that the number of *Shorea robusta* seedlings per hectare (28923) is higher than sapling (4267) and adult trees (1548). Figure 4 presents the seedlings, saplings, and adult density of *Shorea robusta* in Nawabganj Sal Forest.

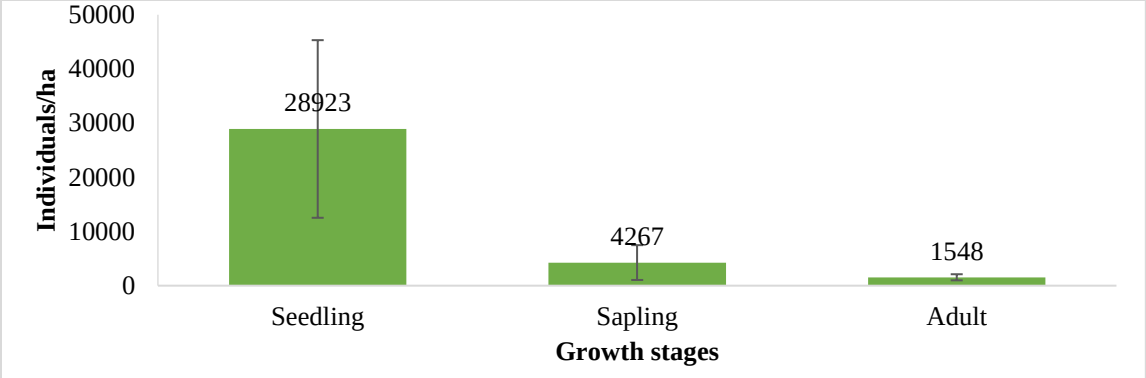


Figure 4. Seedlings, saplings, and adult density of *Shorea robusta*.

Figure 5 presents the density of tree species in different girth classes recorded in Nawabganj Sal Forest. There was a minimization in tree density with an increase in girth class in *Shorea robusta* indicating a reverse J-shaped pattern. A reverse J-shaped pattern signifies good natural regeneration. The girth class distribution of all the trees of Nawabganj Sal Forest also had a reverse J-shaped curve. A reverse J-shaped curve is a mathematical model that represents the capacity of a forest site to regenerate. This phenomenon is marked by a substantial population of seedlings, which is then followed by a decline at the subsequent stage. The reverse J-shaped morphology is also regarded as a reliable sign of old-growth woods in a state of balance. The requirement is upheld by the presence of equal death rates among all diameter classes. In undisturbed natural forests, regenerating species that are considered to be of high quality generally have an inverted J-shaped curve. The majority of studies on the population structure of tree species in tropical forests have indicated that most of these species exhibit an inverted J-shaped curve.



Figure 5. Density of tree species in different girth classes.

In addition, Figure 6 presents the population structure of the most dominant tree species *Shorea robusta* in Nawabganj Sal Forest. Furthermore, Figure 7 presents the population structure of four dominant tree species recorded, which are *Tectona grandis*, *Syzygium Cumini*, *Trema orientale*, and *Cassia fistula*. For *Syzygium Cumini*, the number of saplings was higher than the number of seedlings. Within a tropical forest, the population structure is expected to have an inverted J shape as it reaches its climax. This indicates that there is a higher number of seedlings compared to juveniles, and a higher number of juveniles compared to adults. A population characterized by the absence of seedlings and an abundance of adults is indicative of a population in decline. An insufficient quantity of seedlings, saplings, and young trees within a population signifies a deficiency in regeneration. The lack of young plants and trees suggests a lack of new growth.

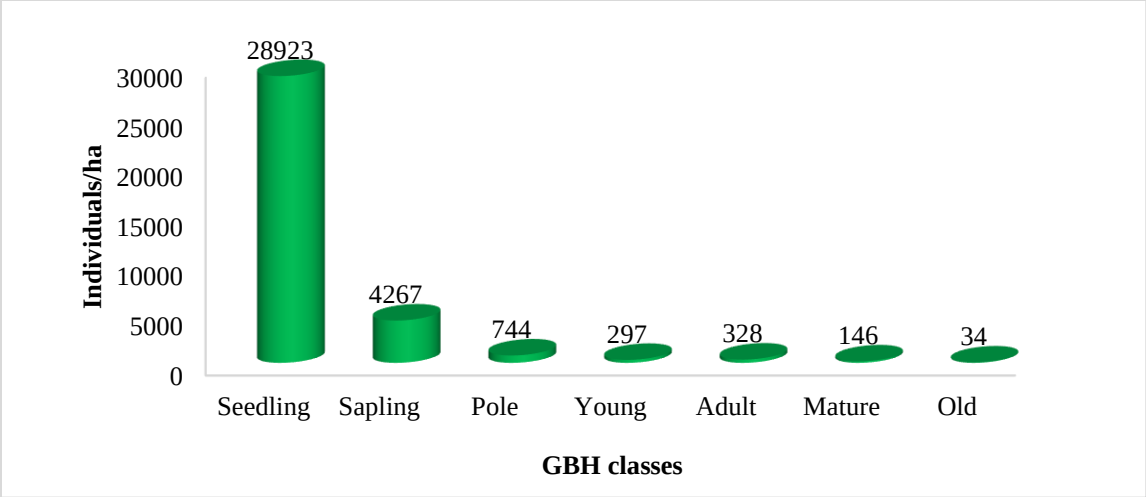


Figure 6. The population structure of the most dominant tree species *Shorea robusta*.

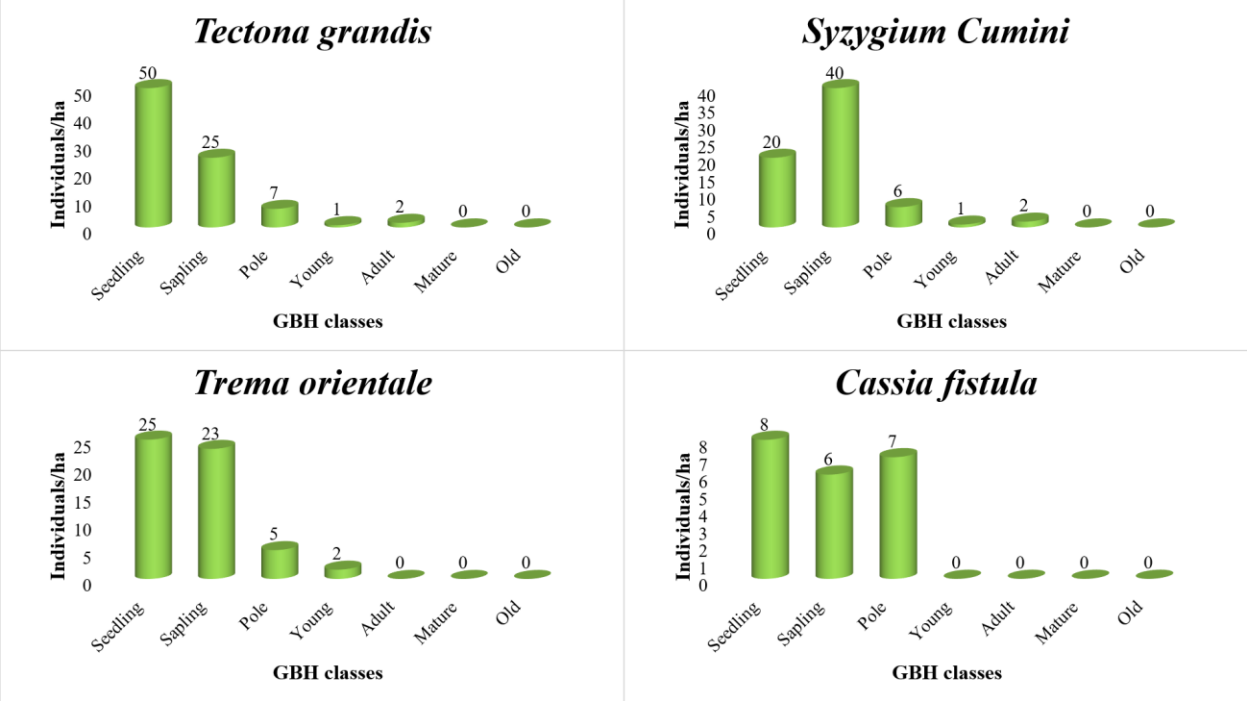


Figure 7. The population structure of four dominant tree species.

The density of trees varies significantly based on their height position. Figure 8 presents the density and percentage of tree species in different height classes in Nawabganj Sal Forest. The height of tree species ranged from 1 to 23 m (mean 5.38 ± 4.52), and the distribution of individuals was not uniform among five different height class. On the contrary, maximum percentage of species (96%) and the second highest density (1902.5/ha individuals) were found in 1–5-meter height class (saplings). The density 438 individuals/ha (13.33%) and 468 individuals/ha (6.67%) were respectively recorded in > 5-10 m (understorey) and > 10-20 m (canopy) height class. The lowest percentage (3.33%) of species was recorded in the top height class (>20 m) with a density of 21 individuals/ha. In addition, the highest density (134130 individuals/ha) and maximum percentage of species (51.61%) were recorded in < 1m height class.

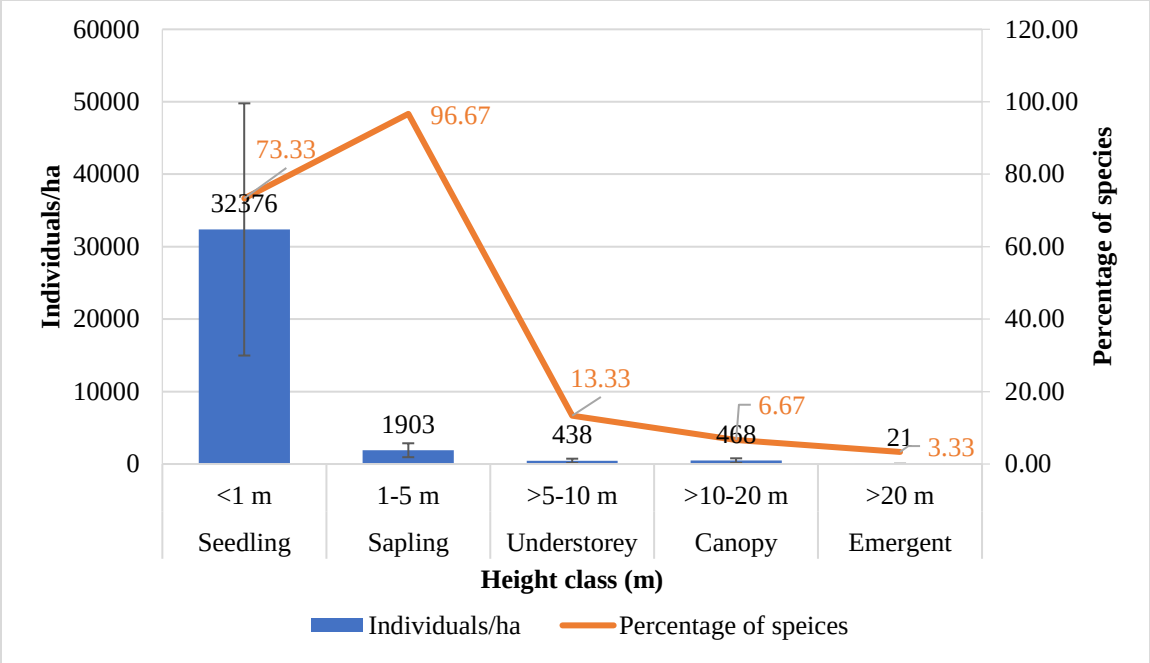


Figure 8. Density and percentage of tree species in different height classes.

The regeneration state of a tree species is assessed by the population sizes of its seedlings, saplings, and adult trees. Table 2 presents the seedling, sapling and adult density of tree species density and its regeneration status in Nawabganj Sal Forest. Among the 30 tree species, 5 species (16.67% species of total), 15 species (50% species of total), 2 species (6.67% species of total), and 8 species (26.67% species of total) respectively showed good, fair, poor, and new regeneration (Figure 9). Only adult stage was not found in all the species, so status “no regeneration " was not shown in the present study. However, the maximum species (50%) was under ‘fair’ status. Besides, *Shorea robusta* showed good regeneration status.

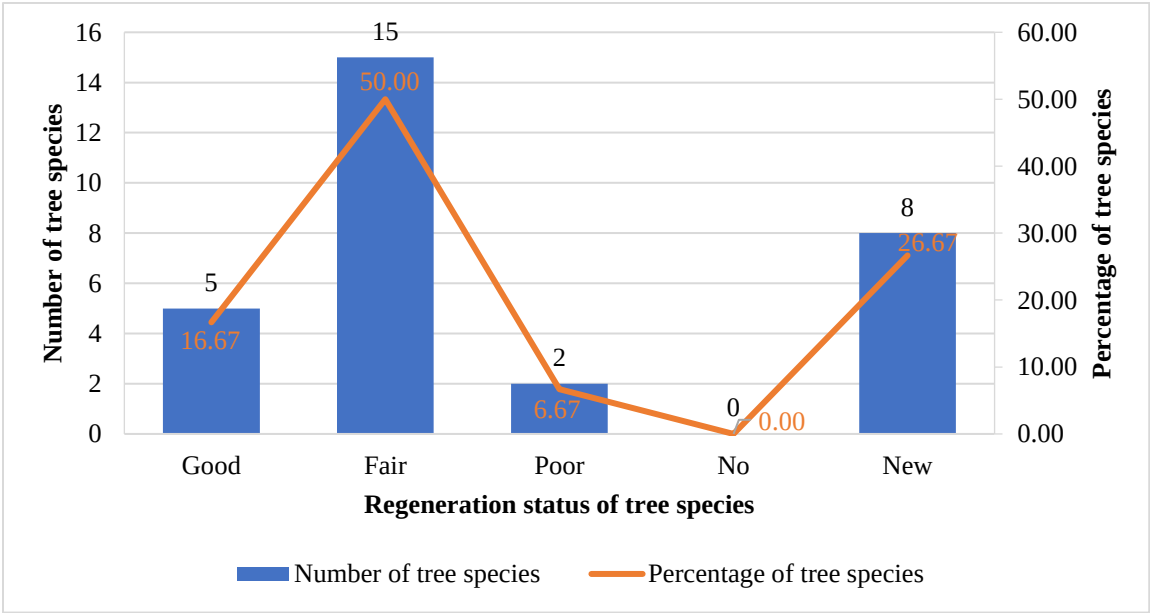


Figure 9. Regeneration status of all recorded tree species.

Table 2. The tree species density and their regeneration status.

Sl no	Common name	Species	Density (Individuals/ha)			Regeneration status
			Seedlings	Saplings	Adults	
1	Sal	*Shorea robusta*	28923	4266.67	1548.33	Good
2	Segun	*Tectona grandis*	50	25	9.17	Good
3	Jam	*Syzygium Cumini*	20	40	8.33	Fair
4	Jhingon	*Trema orientale*	25	23.33	6.67	Good
5	Sonalu	*Cassia fistula*	6.67	5.00	5.83	Fair
6	Akashmoni	*Acacia auriculiformis*	8.33	8.33	4.17	Fair
7	Pitali	*Trewia nudiflora*	8.33	20.83	3.33	Fair
8	Amloki	*Phyllanthus emblica*	0.00	3.33	2.50	Poor
9	Palash	*Butea monosperma*	8.33	13.33	1.67	Fair
10	Gamari	*Gmelina arborea*	8.33	5.00	1.67	Good
11	Kadam	*Neolamarckia cadamba*	0.00	15.00	1.67	Poor
12	Raj Koroi	*Albizia richardiana*	2.50	3.33	1.67	Fair
13	Garjon	*Dipterocarpus turbinatus*	5.83	6.67	0.83	Fair
14	Kanchan	*Bauhinia acuminata*	4.17	10.00	0.83	Fair
15	Bohera	*Terminalia bellirica*	4.17	8.33	0.83	Fair
16	Chalta	*Dillenia indica*	3.33	0.83	0.83	Fair
17	Deoa	*Artocarpus lacucha*	2.50	21.67	0.83	Fair
18	Kanthal	*Artocarpus heterophyllus*	6.67	2.50	0.83	good
19	Am	*Mangifera indica*	8.33	2.50	0.00	Fair
20	Peyara	*Psidium guajava*	0.00	1.67	0.00	New
21	Shimul	*Bombax ceiba*	0.00	1.67	0.00	New
22	Misti Amra	*Spondias pinnata*	0.00	1.67	0.00	New
23	Boroi	*Ziziphus mauritiana*	0.00	4.17	0.00	New
24	Arjun	*Terminalia arjuna*	7.50	7.50	0.00	Fair
25	Jarul	*Lagerstroemia speciosa*	0.00	0.83	0.00	New
26	Jalpai	*Elaeocarpus serratus*	0.00	0.83	0.00	New
27	Pakur	*Ficus rumphii (Pakur)*	0.00	6.67	0.00	New
28	Horitoki	*Terminalia chebula*	8.33	4.17	0.00	Fair
29	Khude Jam	*Syzygium jambos*	4.17	3.33	0.00	Fair
30	Eucalyptus	*Eucalyptus globulus*	0.00	0.83	0.00	New

Moreover, Table 3 presents a comparison of Sal seedlings regeneration in the rainy season and dry season. The p-value is greater than 0.05 which indicates the relation is not significant. Seedling shoots die back repeatedly during the long drought that follows the monsoon rain.

Table 3. Comparison of Sal seedlings regeneration in the rainy season and dry season.

Variable	Seedling numbers (Ind./ha)		Calculated value	Tabulated value	p-value
	Rainy season	Dry season			
The seedling density of Sal (Individuals/ha)	35000 ± 16583	27708 ± 16420	0.91	2.05	0.37

Table 4 presents the relative frequency, relative density, relative abundance, and IVI of the regenerating tree species. The IVI of a species is the sum of its relative frequency, relative density, and relative dominance. It's a measure of how dominant a species is in a given forest area. In terms of frequency, density and abundance, the *Shorea robusta* is completely dominated among 30 tree species by comprising highest IVI (206.83) compares to others. The other subdominant species of the site are *Tectona grandis* (13.36), *Trema orientale* (11.15), *Syzygium Cumini* (9.32), and *Cassia fistula* (8.40). In contrast, *Artocarpus heterophyllus*, *Terminalia bellirica*, *Dillenia indica*, *Artocarpus lacucha*, *Dipterocarpus turbinatus* and *Bauhinia acuminata* showed lowest IVI (2.635) values of the regenerating tree species.

Table 4. Regenerating tree species with relative frequency, relative density, relative abundance, and IVI.

Species	Relative frequency	Relative density	Relative abundance	IVI
Shorea robusta	46.875	96.771	63.186	206.832
Tectona grandis	1.563	0.573	11.223	13.358
Trema orientale	9.375	0.417	1.360	11.152
Syzygium Cumini	6.250	0.521	2.551	9.321
Cassia fistula	6.250	0.365	1.785	8.400
Trewia nudiflora	6.250	0.208	1.020	7.479
Acacia auriculiformis	1.563	0.260	5.101	6.924
Phyllanthus emblica	3.125	0.156	1.530	4.812
Gmelina arborea	3.125	0.104	1.020	4.249
Neolamarckia cadamba	3.125	0.104	1.020	4.249
Butea monosperma	1.563	0.104	2.040	3.707
Albizia richardiana	1.563	0.104	2.040	3.707
Artocarpus heterophyllus	1.563	0.052	1.020	2.635
Terminalia bellirica	1.563	0.052	1.020	2.635
Dillenia indica	1.563	0.052	1.020	2.635
Artocarpus lacucha	1.563	0.052	1.020	2.635
Dipterocarpus turbinatus	1.563	0.052	1.020	2.635
Bauhinia acuminata	1.563	0.052	1.020	2.635

Table 5 presents the regenerating tree species with frequency, density, basal area (m^2/ha) and IVI of Nawabganj Sal Forest. In case of frequency, density and basal area or dominance, maximum IVI value was also found for *Shorea robusta* (243.05) followed by *Trema orientale* (9.85), *Syzygium Cumini* (6.99), *Cassia fistula* (6.64) and *Trewia nudiflora* (6.47). On the other hand, *Terminalia bellirica*, *Dillenia indica*, *Artocarpus lacucha*, *Dipterocarpus turbinatus* and *Bauhinia acuminata* showed lowest IVI (1.62) values of the regenerating tree species. Furthermore, the Shannon-Wiener index score is positively correlated with biodiversity. Conversely, the Simpson index quantifies the proportional prevalence of species, where a greater value signifies greater dominance and lower biodiversity. The calculated value of Shannon-Weiner Index (H') and Simpson's Index in the study site were 0.223 and 0.937 respectively.

Table 5. Regenerating tree species with frequency, density, basal area (m²/ha), and IVI.

Species	Family	Frequency	Density (individuals/ha)	Basal area (m²/ha)	IVI
Shorea robusta	Dipterocarpaceae	100.000	1548.333	39.8080	243.048
Trema orientale	Cannabaceae	20.000	6.667	0.0220	9.847
Syzygium Cumini	Myrtaceae	13.333	8.333	0.0874	6.989
Cassia fistula	Fabaceae	13.333	5.833	0.0083	6.635
Trewia nudiflora	Euphorbiaceae	13.333	3.333	0.0041	6.468
Phyllanthus emblica	Phyllanthaceae	6.667	2.500	0.0016	3.285
Gmelina arborea	Lamiaceae	6.667	1.667	0.0018	3.234
Neolamarckia cadamba	Rubiaceae	6.667	1.667	0.0018	3.234
Tectona grandis	Lamiaceae	3.333	9.167	0.0913	2.364
Acacia auriculiformis	Fabaceae	3.333	4.167	0.0045	1.834
Butea monosperma	Fabaceae	3.333	1.667	0.0072	1.685
Albizia richardiana	Leguminosae	3.333	1.667	0.0016	1.671
Artocarpus heterophyllus	Moraceae	3.333	0.833	0.0035	1.623
Terminalia bellirica	Combretaceae	3.333	0.833	0.0010	1.617
Dillenia indica	Dilleniaceae	3.333	0.833	0.0010	1.617
Artocarpus lacucha	Moraceae	3.333	0.833	0.0010	1.617
Dipterocarpus turbinatus	Dipterocarpaceae	3.333	0.833	0.0008	1.617
Bauhinia acuminata	Fabaceae	3.333	0.833	0.0008	1.617

Discussion

The present study investigated the seedling, sapling and adult density of Shorea robusta in Nawabgonj Sal forest, Bangladesh. This study found that pole and young trees are dominated in the study are. Similarly, pole and young trees had also dominated in Ranchi Sal forests, Jharkhand, India as well as the young individuals were recorded in maximum density in this forest (Kumar & Saikia, 2020). Moreover, this research found that, in terms of density *Shorea robusta* was the most dominant tree followed by *Tectona grandis*, *Syzygium cumini*, *Trema orientale*, and *Cassia fistula*. Kumar and Saikia (2020) reported that, in case of density, *Shorea robusta* was the most dominant tree followed by *Diospyros melanoxylon, Buchanania cochinchinensis*, *Madhuka longifolia*, and *Butea monosperma* in Ranchi Sal forests, Jharkhand, India.

However, the seedling density (28923±16392) of individuals/ha of *Shorea robusta* in the present study was higher than the seedling density (22071 individuals/ha) of Ranchi Sal forests, Jharkhand, India (Kumar & Saikia, 2021), Madhupur National Park, Bangladesh (18046 seedlings/ha) (Rahman et al., 2020), Lalgarh forest range of west Bengal, India (16550 seedlings/ha) (Manna & Mishra, 2017), Sal forests of Satpura Tiger reserve, Madhya province, India (6372 seedlings/ha) (Chaubey & Sharma, 2013) and Sal forests of West Bengal, India (670 seedlings/ha) (Nag & Gupta 2014). But lower than the managed Sal Forest area (35834 individuals/ha) of Terai Sal Forest, Western Nepal (Baral & Ghimire, 2020). On the contrary, the adult density of *Shorea robusta* (1548 individuals/ha) in the present study was lower than the adult density (2431 individuals/ha) of the Sal forests of Assam, India (Deka et al., 2012), Ballavpur Wildlife Sanctuary of west Bengal, India (1414 to 2233 individuals/ha) (Nag & Gupta, 2014) but higher than the Ranchi Sal forests, Jharkhand, India (416 individuals/ha) (Kuamr and Saikia, 2021), Lalgarh forest range of west Bengal, India (318 individuals/ha) (Manna & Mishra, 2017).

There was a minimization in tree density with an increase in girth class in *Shorea robusta* indicating a reverse J-shaped pattern. A Reverse J-shaped pattern signifies good natural regeneration. A reverse J-shaped pattern in the case of *Shorea robusta* was also found by Kumar and Saikia (2021). Moreover, the girth class distribution of all the trees of Nawabganj Sal Forest also had a reverse J-shaped curve. A reverse J-shaped curve also found in Ranchi Sal forests, Eastern India (Kumar & Saikia, 2021) Madhupur and Bhawal National Park (Rahman & Vacik, 2010). The average height of tree species in Nawabganj Sal Forest is 5.38 meter, which is lower than the height (14.2 meter) of the tree species of Ranchi Sal Forest, Eastern India (Kumar & Saikia, 2021). The lowest percentage of species was recorded in the top height class and a similar result was also found in Ranchi Sal Forest (Kumar & Saikia, 2021). In accordance with Kumar and Saikia (2021) the highest density and maximum percentage of species were recorded in < 1m height class.

This study found good, fair, poor, and new regeneration of 17%, 50%, 7%, and 27% of the total species, respectively. Maximum species (50%) was under 'fair' status and the same result was also found by Manna and Mishra (2017) in Lalgarh forest range of West Bengal, India. In the present study *Shorea robusta* showed good regeneration status which is similar to the status of *Shorea robusta* found in tropical moist deciduous forest in Northern India (Mishra et al., 2023) and Ranchi Sal Forest in Eastern India (Kumar & Saikia, 2020), whereas the fair regeneration status of Sal was found in Lalgarh forest range of west Bengal, India (Manna & Mishra, 2017). In the current investigation, the adult stage was absent in all species, so the condition of "no regeneration" was not observed. Nonetheless, Kumar and Saikia (2021) conducted a study on the regeneration of Sal Forest in Ranchi Forest, India. Their findings revealed that 50 species had a "no regeneration" status.

Moreover, this research presents a comparison of Sal seedlings regeneration in the rainy season and dry season. The finding indicates that the relation is not significant. However, the result is different from the Troup (1921) as he stated that drought is a major cause of poor seedling survival of *Shorea robusta* and germination of freshly dispersed seeds used to be high during June and July and recruitment is high during August as well as seedling population minimizes after the rainy season with increased mortality in the dry winter although the death and dying back disease of Sal seedlings were high in the rainy season. According to Rao and Singh (1985), most shoots die during the dry season, and shoots establish merely if rainfall starts.

This study found that *Shorea robusta* is completely dominated among 30 tree species by comprising highest IVI (206.83) compares to others. The other subdominant species of the site are *Tectona grandis* (13.36), *Trema orientale* (11.15), *Syzygium Cumini* (9.32), and *Cassia fistula* (8.40). In contrast, *Artocarpus heterophyllus*, *Terminalia bellirica*, *Dillenia indica*, *Artocarpus lacucha*, *Dipterocarpus turbinatus* and *Bauhinia acuminata* showed lowest IVI (2.635) values of the regenerating tree species. However, Rahman et al. (2020) studied regeneration of Madhupur National Park, where they recorded the IVI values of regenerating tree species. The highest IVI values was for *Shorea robusta* (66.25 out of 300) followed by *Mallotus philippensis* (27.33), *Aporosa* sp. (17.82), *Terminalia bellirica* (14.75), *Grewia nervosa*, *Bridelia tomentosa* (14.10). On the contrast, *Grewia asiatica*, *Derris robusta*, *Lagerstroemia glutinosa* showed the lowest regeneration IVI (0.93) of the regenerating tree species.

In case of frequency, density and basal area or dominance, maximum IVI value was also found for *Shorea robusta* (243.05) followed by *Trema orientale* (9.85), *Syzygium Cumini* (6.99), *Cassia fistula* (6.64) and *Trewia nudiflora* (6.47). Conversely, *Terminalia bellirica*, *Dillenia indica*, *Artocarpus lacucha*, *Dipterocarpus turbinatus* and *Bauhinia acuminata* showed lowest IVI (1.62) values of the regenerating tree species. Manna and Mishra (2017) found that *Shorea robusta* was completely dominated among the 52 tree species by comprising highest IVI (119.32) compared to others and followed by *Diospyros melanoxylon* (27.49), *Madhuca longifolia* (18.85), *Terminalia bellirica* (13.9), *Terminalia tomentosa* (13.67) and *Terminalia tomentosa* (10.67), while *Glochidon ferdinandii* showed lowest IVI (0.02). Moreover, Kumar and Saikia (2020) also found the maximum IVI for *shorea robusta* (167.29) followed by *Diospyrus melanoxylon* Roxb. (13.04), *Buchanania cochinchinensis* (11.04), *Madhuca*

longifolia (10.05), *Lagerstroemia parviflora* (8.50) and so on. The calculated value of Shannon-Weiner Index (H') and Simpson's Index in the study site were 0.223 and 0.937 respectively. Table 6 presents a comparison of vegetation characteristics of the studied Sal Forest with Bangladeshi Sal Forest and Indian Sal Forest.

Table 6. Comparison of vegetation characteristics of the studied Sal Forest with other Sal forests in Bangladesh and India.

Forest type and location	Plot size (ha)	Size class (cm)	Species richness	Stand density (Individuals/ha)	Basal area (m^2/ha)	Sources
Nawabganj Sal forest, Dinajpur, Bangladesh (Tropical moist deciduous forest)	1.200	≥ 10 GBH	30	1600	44.11	Present study
Madupur National Park, Tangail, Bangladesh	3.600	> 10 DBH	52	331	19.2	Rahman and Vacik (2010)
Bhawal National Park, Gazipur, Bangladesh	3.600	> 10 DBH	13	742	16.5	Rahman and Vacik (2010)
Tropical moist deciduous forests of Ranchi District, Jharkhand, India	23.500	≥ 10 GBH	137	397	262.5	Kumar and Saikia (2020)
Shorea robusta -Schima wallichii, South district, Tripura, India	4.000	≥ 10 GBH	152	872	38.6	Majumdar et al. (2014)
Moist Sal Forest (Eastern Himalayan Terai Sal) West Bengal, India	3.200	≥ 30 GBH	134	438	56.5	Kushwaha and Nandy (2012)
Sal forest of Gorakhpur Division, India	24.000	≥ 30 GBH	93	404	22.23	Pandey and Shukla (2003)
Sal forest of Gorakhpur Division, India	24.000	< 30 GBH	115	20413	0.83	Pandey and Shukla (2003)
Sal forest of Eastern Himalayas, India	2.000	≥ 10 GBH	87	484	263	Shankar (2001)
Sal forest of central Himalayas doon Valley, India	0.020	≥ 10 GBH	13.00-21.00	1150-1920	22.3-37.8	Pande (1999)
Corbett National Park, India	2.900	≥ 31.5 GBH	3.00-20.00	180-860	14.5-71.8	Singh et al. (1995)
Sal forest in Central India dry tropical, Vindhya region, India		≥ 30 GBH		294-559	7.00-23.00	Jha and Singh (1990)

The range of the Shonon-Wiener diversity index (H') was 0.83-4.10 for Indian tropical forest (Jha & Singh, 1990; Ayyappan & Parthasarathy, 1999; Pandey, 2000). Shannon-Weiner Index (H') value of the present study is higher than the Shannon-Weiner Index (H') value (0.09) of Bhawal National Park but lower than the value (1.99) of Madhupur National Park studied by Rahman and Vacik (2010). The range of Simpson's index value for a tropical forest of India was 0.21-0.92 (Visalakshi, 1995). Simpson's index value in the present study is higher than the value

(0.36) of Madhupur National Park (Rahman & Vacik, 2010), Ranchi Sal Forest, Jharkhand, India (Kumar & Saikia, 2020). In contrast, the value is lower than the Simpson's index value (0.98) of Bhawal National Park (Rahman & Vacik, 2010). Species (Pielou's) evenness index found by the current study is 0.077 whereas Margalaf's species richness index is 2.25. Species (Pielou's) evenness index of the current study is lower than the Ranchi Sal Forest, Jharkhand, Eastern India (Kumar & Saikia, 2020) as well as the index (0.50) in Madhupur National Park (Rahman & Vacik, 2010). In contrast, the value is higher than the value (0.03) found for the Bhawal National Park (Rahman & Vacik, 2010). According to Kumar and Saikia (2020), the Margalaf's species richness index was 10.28 but, in this study, it is 2.25 which is much lower than Ranchi Sal Forest, Jharkhand, Eastern India.

Global warming and climate change is a burning issue due to the increasing carbon emissions from deforestation and energy use. Nevertheless, the Sal forests in Bangladesh have seen significant degradation and currently the tree density is decreasing (Ray er al., 2023). At this critical juncture, it is imperative to enhance the existing management practices of the Sal Forest ecosystem for the future advantage of all parties involved. The viability of this ecosystem hinges upon the successful and efficient execution of a sustainable forest management strategy. To effectively manage and safeguard the current Sal Forest regions from the existing dangers, it is necessary to develop and execute a forest management plan that adheres to sustainable forest management principles. In order to safeguard and preserve the Sal forests of Bangladesh, it is imperative to contemplate a number of steps. Enhancements to silvicultural systems are necessary to facilitate successful regeneration. Simultaneously, it is worth considering sustainable alternatives to livelihoods that rely on forests, such as engaging in activities like home gardening, establishing small cottage industries that utilize forest products, engaging in beekeeping, and chicken farming. Technical and institutional education and training might also generate alternate employment prospects. In order to develop effective management strategies, it is necessary to have access to growth and yield data obtained from a suitable forest inventory. This data will enable the calculation of an annual allowable harvest that can be extracted from the Sal forests, while ensuring the long-term sustainability of their ecological, economic, and social values.

Moreover, it is necessary to conduct a precise assessment of the invaded Sal woodland in order to formulate an effective strategy for reclaiming the land. Furthermore, it is imperative to establish comprehensive safeguards to address the unlawful practices of converting forest land for agriculture, engaging in unauthorized tree cutting, smuggling timber, and hunting protected wildlife. It is imperative to enhance the management of the Sal Forest by hiring highly skilled and motivated forestry experts, allocating adequate funding, and improving infrastructure. The Sal woods should be designated as community reserves, allowing local residents to actively participate in the conservation and management efforts. At present, there is a lack of a structured framework for the extraction of timber or the collection of wild medicinal and aromatic plants. Unregulated logging frequently leads to the deterioration of forests and the decline in habitat quality. The preservation and conservation of the Sal Forest in Bangladesh hinges on the formulation and effective execution of a sustainable management strategy to safeguard these vital forest resources. The government has implemented several attempts to safeguard these crucial ecosystems, but the long-term viability of these resources has not been attained due to a dearth of effective management strategies. An inclusive and efficient sustainable management strategy should be formulated, engaging all beneficiaries and stakeholders, to effectively preserve these significant ecosystems for both current and future generations. Besides, strict law enforcement is necessary for the protection and conservation of the Sal Forest which would enhance the natural regeneration as well as the environmental sustainability.

Conclusion

The Sal forests in Bangladesh are very diverse ecosystems with significant forest biodiversity. Nevertheless, the scientific community, policymakers, and local residents have limited knowledge about the extent of diversity,

resulting in inadequate documentation. The forests are under significant threat from human activities, as individuals who rely on forest resources for their social well-being directly or indirectly disrupt the forest ecosystems. Due to the lack of recognition of the value of these forests, the growing human population in the surrounding areas is expected to pose a significant threat to their survival. Large areas of forest have been cut down for the purpose of establishing human settlements, engaging in agricultural activities, constructing roads, and establishing industrial facilities. Despite being legally protected, the remaining patches are still not secure. Illegal logging and harvesting of fuelwood, gathering of non-timber products, grazing, and hunting also present a significant hazard. Nevertheless, the Sal Forest is a highly significant ecosystem due to its exceptional species richness and diversity. Therefore, this study aims to examine the regeneration dynamics and population structure of Nawabganj Sal Forest in Bangladesh toward forest conservation and environmental sustainability. The result indicates that overall regeneration status of *Shorea robusta* is good in the studied Sal Forest and the regeneration of seedlings is almost same in the rainy and the dry season. Reverse J-shaped girth class distribution shows good regeneration capacity of the forest. The Shonnon-Winner diversity index and Simpson's dominance index reveal the very low diversity of tree species as well as the basal area of tree species. The finding indicates that the Sal is the most dominant tree species followed by *Tectona grandis*, *Syzygium Cumini*, *Trema orientale* and *Cassia fistula* in Nawabganj Sal Forest, Bangladesh.

Human-caused disruptions have a substantial effect on the social and environmental welfare of society. The present study documents the population structure and regeneration status of tree species in the Nawabganj Sal Forest, which can offer essential insights for designing effective protection and management measures for these diversified forests that contain several tree species of significant ecological and economic importance. Forest management methods should prioritize fulfilling the growing demands for various wood and non-timber forest products, while simultaneously preserving the plant diversity found in these natural forests. Additionally, the results can offer administrators valuable insights into the significance of maintaining a harmonious distribution of undisturbed Sal forests for the purpose of developing biodiversity conservation strategies. Gaining a more profound comprehension of the variety of plants in Sal Forest ecosystems can also assist the country in implementing international legal agreements, such as the Convention on Biological Diversity.

However, stopping anthropogenic disturbances is needed to augment the regeneration and diversity of the forest. The diversity of shrubs, herbs, and factors that influence the regeneration of forest species have not been studied by this research, which can be explored by future studies. Moreover, it is important to prioritize minimizing disturbance, as extensive disturbance has been shown to have negative effects on the regeneration of Sal trees and the overall diversity of the forest. There is a deficiency in assessing the impact of disturbances and identifying the specific life stages of trees that are most vulnerable to disturbances. Conducting in-depth research on these inquiries would yield crucial data for holistic forest management and enhance our understanding of ecological responses to disturbances in Sal forests.

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References

Abdallah, S., Akayim, A. R., Amedor, E. N., & Afetsu, J. Y. (2023). Climate Change, Who Is Responsible?. Open Journal of Applied Sciences, 13(12), 2431-2446.

Ayyappan, N., & Parthasarathy, N. (1999). Biodiversity inventory of trees in a large-scale permanent plot of tropical evergreen forest at Varagalaiar, Anamalais, Western Ghats, India. Biodiversity & Conservation, 8, 1533-1554.

Baral, S., & Ghimire, P. (2020). Effect of tree canopy opening in the regeneration layer of Terai Sal (Shorea robusta Gaertn.) forest in Western Nepal: A case study. Tropical Plant Research, 7(2), 502-507.

Behera, M. C., Sahoo, U. K., Mohanty, T. L., Prus, P., Smuleac, L., & Pascalau, R. (2023). Species composition and diversity of plants along human-induced disturbances in tropical moist Sal forests of Eastern Ghats, India. Forests, 14(10), 1931.

Bergsagel, D., & Heisel, F. (2023). Structural design using reclaimed wood–A case study and proposed design procedure. Journal of Cleaner Production, 420, 138316.

Bhatta, S. P., & Devkota, A. (2020). Community structure and regeneration status of Sal (Shorea robusta Gaertn.) forests of Dadeldhura district, Western Nepal. Community Ecology, 21(2), 191-201.

Bullones, A., Castro, A. J., Lima-Cabello, E., Fernandez-Pozo, N., Bautista, R., Alché, J. D. D., & Claros, M. G. (2023). Transcriptomic Insight into the Pollen Tube Growth of Olea europaea L. subsp. europaea Reveals Reprogramming and Pollen-Specific Genes Including New Transcription Factors. Plants, 12(16), 2894.

Calvia, G., Casula, P., Farris, E., Fenu, G., Fantini, S., & Bacchetta, G. (2023). Shrub cover and soil moisture affect Taxus baccata L. regeneration at its southern range. Plants, 12(9), 1819.

Chaubey, O. P., & Sharma, A. (2013). Population structure and regeneration potential of sal (Shorea robusta Gaertn. f.) and its associates in sal bearing forests of Satpura Tiger Reserve. International Journal of Bio-Science and Bio-Technology, 5(6), 63-70.

Chhetri, N. B. K., & Shrestha, K. K. (2019). Floristic diversity and important value indices of tree species in lower Kanchenjunga Singhalila ridge Eastern Nepal. American Journal of Plant Sciences, 10(1), 248-263.

Costas-Selas, C., Martínez-García, S., Logares, R., Hernández-Ruiz, M., & Teira, E. (2023). Role of bacterial community composition as a driver of the small-sized phytoplankton community structure in a productive coastal system. Microbial Ecology, 86(2), 777-794.

Deka, J., Tripathi, O. P., & Khan, M. L. (2012). High dominance of Shorea robusta Gaertn. in alluvial plain Kamrup sal forest of Assam, NE India. International Journal of Ecosystem, 2(4), 67-73.

Elliott, S., Tucker, N. I., Shannon, D. P., & Tiansawat, P. (2023). The framework species method: harnessing natural regeneration to restore tropical forest ecosystems. Philosophical Transactions of the Royal Society B, 378(1867), 20210073.

Gonçalves, A. C., & Fonseca, T. F. (2023). Influence management and disturbances on the regeneration of forest stands. Frontiers in Forests and Global Change, 6, 1123215.

Hald-Mortensen, C. (2023). The Main Drivers of Biodiversity Loss: A Brief Overview. Journal of Ecology and Natural Resources, 7(3), 000346.

Haq, S. M., Pieroni, A., Bussmann, R. W., Abd-ElGawad, A. M., & El-Ansary, H. O. (2023). Integrating traditional ecological knowledge into habitat restoration: implications for meeting forest restoration challenges. Journal of Ethnobiology and Ethnomedicine, 19(1), 33.

Ibáñez, T. S., Wardle, D. A., Gundale, M. J., & Nilsson, M. C. (2022). Effects of soil abiotic and biotic factors on tree seedling regeneration following a boreal forest wildfire. Ecosystems, 25(2), 471-487.

Iskandar, M., Siregar, I. Z., & Krisnawati, H. (2023). Potential of carbon sequestration enhancement through intensive silvicultural techniques using Shorea leprosula plantation in Central Kalimantan, Indonesia. Biodiversitas Journal of Biological Diversity, 24(8), 4699-4513.

Jamloki, A., Singh, A., Chandra, S., Shukla, V., Nautiyal, M. C., & Malik, Z. A. (2023). Population structure, regeneration potential and leaf morphological traits of Rhododendron campanulatum D. Don along an altitudinal gradient in Western Himalaya. Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology, 157(1), 159-174.

Jha, C. S., & Singh, J. S. (1990). Composition and dynamics of dry tropical forest in relation to soil texture. Journal of Vegetation Science, 1(5), 609-614.

Koulelis, P. P., Proutsos, N., Solomou, A. D., Avramidou, E. V., Malliarou, E., Athanasiou, M., ... & Petrakis, P. V. (2023). Effects of climate change on greek forests: A review. Atmosphere, 14(7), 1155.

Kumar, R., & Saikia, P. (2020). Floristic analysis and dominance pattern of sal (Shorea robusta) forests in Ranchi, Jharkhand, eastern India. Journal of Forestry Research, 31(2), 415-427.

Kumar, R., & Saikia, P. (2021). Population structure and regeneration status of Shorea robusta and associated trees in Sal forests of Ranchi, Eastern India. Tropical Ecology, 62(1), 34-51.

Kunwar, R. M., Fadiman, M., Thapa, S., Acharya, R. P., Cameron, M., & Bussmann, R. W. (2020). Plant use values and phytosociological indicators: Implications for conservation in the Kailash Sacred Landscape, Nepal. Ecological Indicators, 108, 105679.

Kushwaha, S. P. S., & Nandy, S. (2012). Species diversity and community structure in sal (Shorea robusta) forests of two different rainfall regimes in West Bengal, India. Biodiversity and Conservation, 21, 1215-1228.

Lapola, D. M., Pinho, P., Barlow, J., Aragão, L. E., Berenguer, E., Carmenta, R., ... & Walker, W. S. (2023). The drivers and impacts of Amazon forest degradation. Science, 379(6630), eabp8622.

Latterini, F., Mederski, P. S., Jaeger, D., Venanzi, R., Tavankar, F., & Picchio, R. (2023). The Influence of Various Silvicultural Treatments and Forest Operations on Tree Species Biodiversity. Current Forestry Reports, 9(2), 59-71.

Li, K., & Xu, E. (2023). Differentiating effects of salvage logging and recovery patterns on post-fire boreal forests in Northeast China using a modified forest disturbance index. GIScience & Remote Sensing, 60(1), 2188674.

Liu, D., Zhou, C., He, X., Lei, X., Zhang, H., & Liu, X. (2023). Exploring the role of canopy triangular units in analysing canopy effects on saplings. Forest Ecology and Management, 552, 121572.

Liu, D., Zhou, C., He, X., Zhang, X., Feng, L., & Zhang, H. (2022). The effect of stand density, biodiversity, and spatial structure on stand basal area increment in natural spruce-fir-broadleaf mixed forests. Forests, 13(2), 162.

Ma, L., Du, W., Shu, H., Cao, H., & Shen, C. (2023). Spatial Pattern of Deadwood Biomass and Its Drivers in a Subtropical Forest. Forests, 14(4), 773.

Majumdar, K., Shankar, U., & Datta, B. K. (2014). Trends in tree diversity and stand structure during restoration: a case study in fragmented moist deciduous forest ecosystems of Northeast India. Journal of Ecosystems, 2014.

Maletha, A., Maikhuri, R. K., & Bargali, S. S. (2023). Population structure and regeneration pattern of Himalayan birch (Betula utilis D. Don) in the timberline zone of Nanda Devi Biosphere Reserve, Western Himalaya, India. Geology, Ecology, and Landscapes, 7(3), 248-257.

Manna, S. S., & Mishra, S. P. (2017). Diversity, population structure and regeneration of tree species in Lalgarh forest range of West Bengal, India. International Journal of Botany Studies, 2(6), 191-195.

Margalef, R. (1958) Temporal succession and spatial heterogeneity in phytoplankton. In: Buzzati-Traverso A (ed) Perspectives in marine biology. University of California Press, Berkeley, (pp. 323–347).

Mishra, G., Meena, R. K., Kant, R., Pandey, S., Ginwal, H. S., & Bhandari, M. S. (2023). Genome-wide characterization leading to simple sequence repeat (SSR) markers development in Shorea robusta. Functional & Integrative Genomics, 23(1), 51.

Mishra, R. (1968). Ecology Work Book. Oxford and IBH Publications, Co. New Delhi.

Mishra, S. N., Gupta, H. S., & Kulkarni, N. (2021). Impact of climate change on the distribution of Sal species. Ecological Informatics, 61, 101244.

Nag, A., & Gupta, H. (2014). Population structure and natural regeneration of sal (Shorea Robusta Gaertn. F.) in dry deciduous forests of West Bengal. International Journal of Scientific Research in Environmental Sciences, 2(11), 421.

Pande, P. K. (1999). Comparative vegetation analysis and sal (Shorea robusta) regeneration in relation to their disturbance magnitude in some Sal forests. Tropical Ecology, 40(1), 51-61.

Pandey, S. K. (2000). Population status and regeneration strategy of some perennial legumes in plantation forests of North-Eastern Uttar Pradesh (Doctoral dissertation, Ph. D. Thesis, DDU Gorakhpur University, Gorakhpur, India).

Pandey, S. K., & Shukla, R. P. (2003). Plant diversity in managed sal (Shorea robusta Gaertn.) forests of Gorakhpur, India: species composition, regeneration and conservation. Biodiversity & Conservation, 12(11), 2295-2319.

Pielou, E. C. (1966). The measurement of diversity in different types of biological collections. Journal of theoretical biology, 13, 131-144.

Pokhriyal, P., Uniyal, P., Chauhan, D. S., & Todaria, N. P. (2010). Regeneration status of tree species in forest of Phakot and Pathri Rao watersheds in Garhwal Himalaya. Current science, 171-175.

Rahman, M. M., & Vacik, H. (2010). Vegetation analysis and tree population structure of Sal (Shorea robusta CF Gaertn) forests: A case study from the Madhupur and Bhawal National Park in Bangladesh. In National parks: vegetation, wildlife and threats (pp. 193-206). Nova Science Publishers New York.

Rahman, M. R., Hossain, M. K., Hossain, M. A., & Hasan, M. E. (2020). Natural regeneration potential of Madhupur National Park, Bangladesh. Bangladesh Journal of Botany, 49(4), 989-996.

Rao, P. B., & Singh, S. P. (1985). Population dynamics of a foot-hill Sal (Shorea robusta Gaertn. f.) forest in Kumaun Himalaya. Acta Oecologica Oecologia Plantarum (France).

Ray, P. C., Hasan, M. F., Hossan, M. S., & Hanif, M. A. (2023). Forest co-management for improvement of livelihood and forest cover: Experience from Sal Forest of Bangladesh. Trees, Forests and People, 14, 100450.

Roshni, N. A., Hasan, M. K., Wadud, M. A., Hasan, A. K., Akter, R., Khan, R. N. A., & Hemel, S. A. K. (2023). Toxic Metal Levels in Forest Soils Caused by Industrialization and Impacts on Tree Biomass Carbon Stock. Environmental Processes, 10(3), 45.

Saha, S., Hasan, S. S., Haque, M. E., & Ahamed, T. (2021). Perception based assessment of ecosystem services of Madhupur Sal Forest in Bangladesh. European Journal of Agriculture and Food Sciences, 3(1), 39-44.

Sarkar, M., & Devi, A. (2014). Assessment of diversity, population structure and regeneration status of tree species in Hollongapar Gibbon Wildlife Sanctuary, Assam, Northeast India. Tropical plant research, 1(2), 26-36.

Scheiner, S. M. (2003). Six types of species-area curves. Global ecology and biogeography, 12(6), 441-447.

Shankar, U. (2001). A case of high tree diversity in a sal (Shorea robusta)-dominated lowland forest of Eastern Himalaya: Floristic composition, regeneration and conservation. Current Science, 776-786.

Shannon, C. E., & Wiener, W. (1963). The mathematical theory of Communication University. Urbana: Illinois Press, 125.

Sharma, L. N., Adhikari, B., Watson, M. F., Shrestha, B. B., Paudel, E., Karna, B., & Rijal, D. P. (2022). Forest canopy resists plant invasions: a case study of Chromolaena odorata in Sal (Shorea robusta) forests of Nepal. Journal of Tropical Ecology, 38(2), 49-57.

Sharma, L. N., Shrestha, K. B., & Måren, I. E. (2019). Tree regeneration in gap-understory mosaics in a subtropical Shorea robusta (Sal) forest. Journal of Forestry Research, 30, 2061-2068.

Simpson, E. H. (1949). Measurement of diversity. nature, 163(4148), 688-688.

Singh, A., Reddy, V. S., & Singh, J. S. (1995). Analysis of woody vegetation of Corbett National park, India. Vegetatio, 120, 69-79.

Troup, R.S. (1921). The silviculture of Indian trees. Claredon press, Oxford, 1-3.

Ullah, S. A., Tsuchiya, J., Asahiro, K., & Tani, M. (2022). Exploring the socioeconomic drivers of deforestation in Bangladesh: The case of Teknaf Wildlife Sanctuary and its surrounding community. Trees, Forests and People, 7, 100167.

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REVIEW ARTICLE

A review of climate change mitigation and agriculture sustainability through soil carbon sequestration

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Abstract

As a result of human activities such as burning fossil fuels, organic materials, and engaging in unsustainable land practices, atmospheric carbon dioxide (CO_2) levels have been steadily rising, heightening worldwide concerns about climate change. It is expected concentrations to grow and changes in CO_2 sequestration in agricultural soils as a result of the industrial revolution's acceleration of CO_2 emissions. These emissions have been intensified by changes in land use, such as cutting down trees, burning biomass, altering farming operations, draining natural wetlands, and using the wrong methods for managing soil. The present study utilized the systematic literature review method to investigate soil carbon sequestration options as a possible means of reducing the impact of climate change and improving agriculture sustainability. As a result of soil degradation and poor management, soil organic carbon (SOC) levels have decreased, which in turn has increased atmospheric CO_2 levels. But cutting-edge land application and modern agricultural management methods have the ability to reduce CO_2 emissions. Several methods exist for replenishing depleted SOC, such as repurposing marginal lands for restoration purposes, advocating for reduced or zero-tillage methods in conjunction with cover as well as residue crops, and introducing nutrient cycling through composting, manure usage, and other environmentally friendly approaches to managing soil and water. One holistic approach to fighting climate change is long-term soil carbon sequestration. Soil carbon sequestration offers a comprehensive and efficient strategy for reducing the impact of climate change by recharging depleted soils, increasing biomass production, cleaning surface and underground water sources, and compensating for CO_2 emissions through fossil fuels. Soil carbon sequestration presents an exciting opportunity for management of the problems caused by contemporary changes in the environment, and the adoption of these novel approaches is essential for meeting these issues.

Keywords: Agriculture; Environment; Climate change: Mitigation; Carbon sequestration; Sustainability

Introduction

One of the most important ways to lower CO_2 levels in the air is through soil carbon sequestration, which is basically just putting carbon into the ground (Ali et al., 2022; Don et al., 2024). In order to reduce the overall rate of emissions into the atmosphere, this process incorporates elements from the ocean, petrology, biology, and geology.

Carbon sequestration can be aided by both natural and human-caused processes; the latter seeks to keep the world's carbon budget under check so that there are no net releases of carbon in the future (Saarikoski et al., 2023). Converting marginal areas to recover depleted soil carbon reserves is one promising method (Csikós & Tóth, 2023). Significant steps can be taken to reduce the impact of climate change by implementing conservation agriculture practices such as cover cropping, protecting crop residues, recycling nutrients, using compost, and efficiently managing water, energy, and nutrients used in agriculture (Francaviglia et al., 2023). These methods lessen the production of GHGs and encourage the growth of sustainable farming systems that can withstand the effects of climate change (Balasundram et al., 2023). Increased soil fertility, productivity, quality, biodiversity, and less compaction are just a few of the many advantages of soil carbon sequestration (Rodrigues et al., 2023). Soil management techniques that promote plant growth and microbial activity, such as cover cropping, crop rotation, no-tillage, and organic matter absorption, can increase soil carbon sequestration (Singh et al., 2024). The breakdown of stable carbon is the end result of these activities, which keep it out of the air. Several studies highlight the possibility of SOC sequestration to lessen the impact of contemporary agriculture on climate change by lowering GHG emissions (You et al., 2024). Offsetting about 10% of yearly GHG emissions, soil carbon sequestration might store large amounts of carbon for long periods (Paul et al., 2023). Climate, soil type, and management practices are just a few of the variables that affect how well the plan works, so it's important to choose methods that are specific to the area.

In the last hundred years, climate change—defined as the long-term shifts in Earth's average temperature, precipitation, as well as weather patterns—has received a lot of attention (Subramanian et al., 2023; Raihan & Bari, 2024). Most of the acceleration is due to human actions, such as burning fossil fuels, rapid industrialization, and deforestation (Nunes, 2023; Ahmad et al., 2024). Overproduction of greenhouse gases (GHGs), most notably CO_2, causes the planet's surface to warm because it traps more heat (Petrov et al., 2023; Ridwan et al., 2023). These changes are worsened by extreme weather events, which affect soil temperature and moisture, species distribution and composition in ecosystems, and, most significantly, soil vegetation (Furtak & Wolińska, 2023; Akter et al., 2023). Human health, ecosystems, food security, along with global poverty are all gravely threatened by the modern agricultural practices that have hastened the warming trend (Fenner & Cernev, 2021).

Deforestation, changes in land use, excessive fertilizer usage, and the burning of fossil fuels are some of the key anthropogenic actions that are causing climate change (Raihan & Tuspekova, 2022a; 2022b; 2023a). Consequently, one practical way to lessen the effect of contemporary farming on the environment is soil carbon sequestration (Tan & Kuebbing, 2023). Soil amendments, root exudation, biochar, and leaf litter all increase carbon inputs, which can be absorbed by plants and used as a buffer against soil carbon changes (Pandao et al., 2023). There is tremendous potential for soil to reduce carbon emissions because it contains around 2500 Pg of carbon worldwide and is 3.3 times larger than the pool of carbon in the atmosphere (Wang et al., 2024). It is possible to cut soil carbon emissions in half from 2010 levels by 2050 if the right mitigation strategies are put in place (Marvin et al., 2023). The objectives of this review study is to examine soil carbon sequestration's potential in light of current agricultural challenges; evaluate the ways in which modern agriculture has altered SOC sequestration and its broader implications; and determine how soil carbon sequestration contributes to the fight against climate change.

Methodology

This study delve into the relationship between soil carbon management and climate change challenges in agriculture sustainability. The current study utilized the systematic literature review process as recommended by Raihan and Bijoy (2023). The systematic literature review framework is widely regarded as a reliable and

trustworthy approach (Raihan, 2023a; 2023b; 2023c; 2023d; 2023e; 2023f; 2023g; 2023h; 2023i; 2024a; 2024b). As can be seen in Figure 1, the review adhered to the tenets of the systematic review methodology. This helped to reveal how crucial soil carbon sequestration is to achieve environmental and agricultural sustainability beside reducing the negative consequences of global warming and climate change through mitigation activities. By deconstructing the research questions into their component concepts, the study developed a set of keywords that allowed to conduct a thorough and representative search of the literature on the topic of soil carbon and its relation to climate change mitigation and agriculture sustainability. Database classification terms have also been taken into account, along with synonyms, single and plural models, broader terms, alternative spellings, and more specific terms. The selected keywords used for searching documents for the review analysis are soil carbon, carbon sequestration, carbon emission, agricultural practices, tillage, cropping system, lobal warming, climate change, mitigation, modern agriculture, crop management, and sustainability.

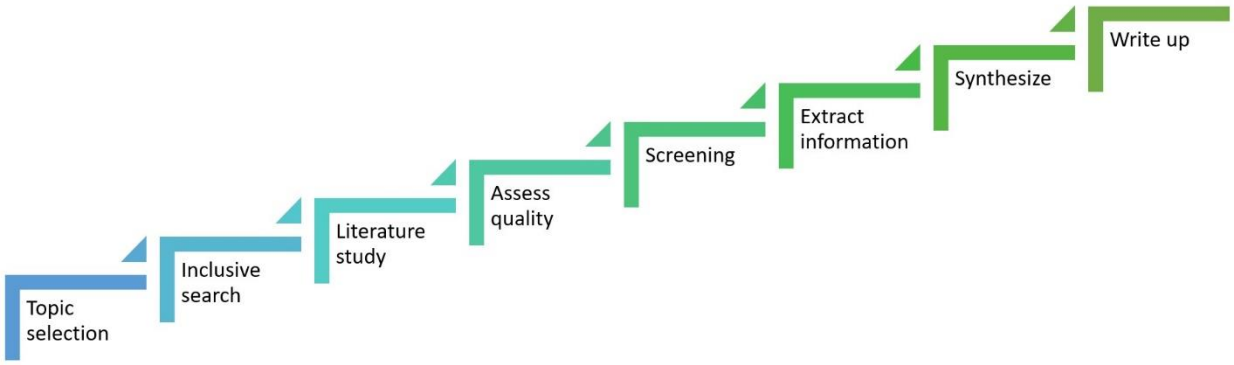


Figure 1. The procedure of systematic review conducted by the study.

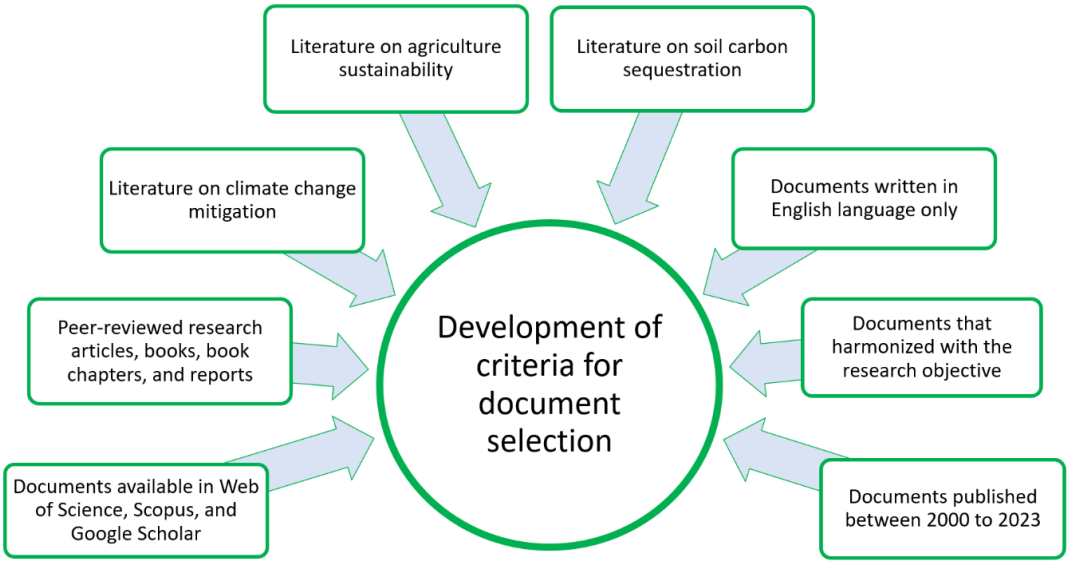


Figure 2. The development of criteria for document selection.

The initial search with the keywords led to 5398 documents. After scanning the documents based on the selection criteria and to remove possible duplication, 453 articles were selected for the next step of scanning.

After screening those article's title and abstract, the comprehensive literature review encompassed a total of 129 distinct scholarly articles published between 1990 and 2023 were chosen for further analysis. The papers came from the academic aggregators Google Scholar, Scopus, and Web of Science (WOS).

Figure 2 depicts the evolution of review criteria used to choose appropriate documents for analysis. This investigation solely used research articles published in peer-reviewed journals to assure the quality of the results, which provide a foundation for future agricultural research and management taking into account soil carbon sequestration, climate change mitigation, and environmental sustainability. These papers were then reviewed to determine if their primary topic was similar to that of the current investigation.

Although a specific instrument for quality assessment was not used, the review ensured that the evidence extracted from the research papers (that met the inclusion criteria) was relevant and accurate by evaluating the research methodology and questions, sources of information, and the selection of the evaluation criteria. The quality of the studies was assessed based on several criteria, including the extent to which the research objectives were achieved through the study design, the accuracy of measuring the study variables, the appropriate use of statistics, the effectiveness of the intervention, the presence of generalizations, and any conflicts of interest among the authors. Nevertheless, it was crucial to consider the amount of time and effort invested in the search process in relation to the possible advantages of discovering all pertinent studies.

Contemporary Agriculture

Tillage and SOC

The ability of tillage management to significantly increase soil carbon absorption has garnered a lot of interest in agricultural practices (Bogale et al., 2023). Farmers commonly burn crop wastes, which contributes to air pollution. However, these residues can be managed to store carbon in the soil profile. Conservation of soil moisture through covering 30% of soil surface with crop stubble and leaf litter is one agricultural strategy that helps decrease wind and water erosion (Xiao et al., 2023). The nutrient composition of crop residues, the instruments used for tillage, and the specific tillage procedure all affect how much residue stays on the soil surface. To improve carbon sequestration, plant pulses and other leguminous crops as part of your crop rotation. Pulses absorb nitrogen and carbon and store them in the soil's deeper layers. Conventional tillage, residue burning, and over-input farming have all contributed to degraded soil health and lower crop yields in the past. Even with carefully chosen crop species and the necessary amounts of fertilizer and pesticide, crop failure can occur due to these antiquated practices, which impact the physical qualities of the soil and impede biodegradation (Khangura et al., 2023).

Conservation tillage, if widely used on croplands, has the potential to greatly enhance carbon sequestration (Thapa et al., 2023). SOC sequestration was found to be considerably affected by tillage systems in the surface layer (0-5 cm) of a Bhopal study by Hati et al. (2020). After three crop cycles, no-tillage and limited tillage had greater SOC levels than conventional tillage. Additional aid in preserving SOC came from combining residue retention with reduced tillage operations. While traditional tillage may boost output in the near term, it has the potential to deplete soil microorganisms, disrupt biogeochemical cycles, and exhaust mineral elements if used for too long.

Soils that have been farmed for a century or more have had their carbon levels lowered by 30–50% due to conventional agricultural cropping methods and intense tillage (Francaviglia et al., 2023). An essential component for long-term sustainability and productivity, soil organic matter (SOM) is intimately related to soil fertility. Hot zone soils can benefit from lower tillage methods and residue retention when it comes to SOC

sequestration. These technologies can help reduce the impact of traditional soil agriculture on climate change and global warming by sequestering atmospheric CO_2 in the soil. Some have proposed reintroducing 500 Pg of carbon to Earth's ecosystem. The merits of SOC sequestration have been well-documented and generally acknowledged by scientists. Because reduced tillage approaches store more SOC than conventional tillage, they are incorporated into the first principle. Soil productivity can be reduced by using older tools, such as chisel plows and moldboard plows, which disturb the soil structure more than current tools (Mumah et al., 2023). How much carbon is sequestered by soil under various methods is proportional to the depth of tillage. As an example, SOC rose by 40% when no tillage was used for 20 years instead of reduced tillage (Waring et al., 2023).

In far too many research, the main reason soil carbon is being lost and moved from the higher slopes of farmed highland landscapes is due to tillage-induced soil erosion. Soil carbon stability is affected by the tillage system chosen; conventional tillage increases carbon storage, while decreased tillage increases it. Because reduced tillage is a reversible method of soil carbon sequestration, a transient shift in tillage practices would not lead to an obvious uptick in SOC accumulation right away. SOC sequestration and restoration are both negatively impacted by intensive tillage methods, which weaken the soil structure and release C pools into the atmosphere. Soil plowing, however, may have less of an exhausting impact on total SOC content if done once in a long-term cultivation utilizing shallow tillage procedures. In these situations, it is expected that a single shallow plowing will raise SOC because of increased inputs of carbon from crop residues, leading to an increase in crop production. Because undisturbed soils differ from tillage soils in terms of soil microbiology, fauna, and biochemical processes, changes in tillage methods can have an impact on carbon sequestration in both types of soils. Numerous international meta-analyses have shown that no-till farming increases carbon sequestration (Lockhart et al., 2023). To a given depth in the soil, the tillage system has a major impact on the dispersion of carbon. There is some evidence that tillage techniques have no detrimental effect on soil carbon in the upper 40 cm of the soil (Zhang et al., 2023).

Fertilizer impact on SOC

One known way to learn about the impacts of continual fertilizer and manure treatment on soil fertility along with ecological dynamics is to use fertilizers in soil for a long time. Applying the prescribed amount of fertilizer increased SOC concentrations from 7.9 to 10.5 g per kg, but using too much fertilizer can have detrimental effects (Yin et al., 2023). Incorporating fertilizer into soil can disrupt nutrient cycle, giving native microbial species a foothold to thrive even in stressful conditions and perhaps increasing SOC and microbial biomass. The saturation of organic carbon is increased by nitrogen fertilizer (Zuo et al., 2023). In addition, many soils have the potential to retain carbon as organic matter and become carbon-absorbing reservoirs after implementing conservation agriculture practices. Research in grasslands has shown that nitrogen enrichment does not affect soil carbon sequestration much, but in temperate, tropical, subtropical, and boreal forests, it actually accelerates sequestration (Ngaba et al., 2023). N enrichment also reduces litter decomposition in N-rich settings but has little effect in N-limited ones. Nitrogen addition typically has an effect on litter quality, speeds up the breakdown of labile C, and slows down the decomposition of resistant C in soil. Due to the diverse range of ecosystems and settings studied in N-enrichment research, it is not feasible to generalize the results of a single experiment to the entire world. Nitrogen deposition in the atmosphere has increased three- to fivefold throughout the last century due to the combustion of fossil fuels and the usage of inorganic chemical fertilizers (Raihan & Said, 2022; Pereira et al., 2023). An increasing amount of nitrogen is expected to be deposited on land, with a substantial fraction of this nitrogen being stored in ecosystems around the world. Plants can't develop without nitrogen, and while low amounts can reduce plant biomass, higher levels are thought to increase ecosystems' carbon pools

(Khan et al., 2023a). Additional research is needed to clarify the impact of nitrogen additions on soil carbon sequestration. As a natural reservoir for carbon and a source of CO_2 emissions, soils store approximately twice as much carbon as the atmosphere (Rodrigues et al., 2023). Soil carbon reactions to nitrogen additions may, therefore, have a significant impact on the trajectory of atmospheric CO_2 levels going forward (Jaafar et al., 2020; Begum et al., 2020; Jubair et al., 2023).

Mycorrhizal fungi, cover crops, mulching, farmyard manure, root exudates, plant litter, and roots are the main sources of soil C inputs. Concurrently, nutrient leaching, soil erosion, CO_2 emissions, and organic matter decomposition all contribute to soil C depletion (Francaviglia et al., 2023). Soil C sequestration can be enhanced by increased plant growth, litter formation, and N inputs caused by higher C inputs from human activities (Rodrigues et al., 2023). Soil pH can be decreased and lignin-modifying enzyme activity inhibited by nitrogen addition, which in turn slows the breakdown of organic materials (Neupane et al., 2023). The majority of N-enrichment studies fail to quantify the native SOM, which hinders their capacity to explain how soil carbon is sequestered mechanistically. It is important to understand how nitrogen addition affects soil carbon sequestration and how different carbon pools behave with the help of isotope labeling methods.

Irrigation and carbon storage

Despite a worldwide rise in crop irrigation over the past 60 years, little is known about how irrigation practices affect soil structure and carbon sequestration. More than 20% of the world's arable land is now irrigated, and this practice is responsible for 40% of the world's food supply (Zhao et al., 2023). Blanco-Canqui et al. (2010) looked at dryness's impact on SOC levels and aggregate stability in croplands during five to eight years. Soil macroaggregates were shown to grow as irrigation flows increased from 66 to 217 mm per year. The authors postulated that the elevated SOC content brought about by irrigation—linked to higher plant biomass input and soil microbial community carbon in the form of microbial biomass carbon—was responsible for the observed improvement in aggregate stabilization. There were no statistically significant changes in aggregate stabilization across the two irrigation treatments in the study of flood and drip irrigation's effects on soil structure in organic and conventionally managed citrus orchards conducted by Hondebrink et al. (2017). Some research indicated that irrigation contributed to larger organic carbon imports, while others shown higher SOC decomposition because of enhanced microbial activity; these findings were part of a literature review undertaken by Trost et al. (2013). Campos et al. (2020) performed a long-term experiment with three main conclusions: (i) irrigated sandy agricultural lands have restored SOC to a level comparable to native vegetation and continue to sequester carbon, (ii) rainfed agricultural lands with clayey soils also sequester carbon, even though these soil profiles don't represent the broader regional soil characteristics, and (iii) rainfed agricultural lands with sandy soils, the most common type of soil and management practice in Western Bahia, do not act as a CO_2 sink. Nevertheless, additional investigation into the effects of different irrigation schedules on SOC and improved carbon sequestration is necessary.

SOC Sequestration Types

Biocarbon sequestration

The conventional wisdom holds that agricultural inputs are crucial to crop production. However, with the rise of sustainable agriculture, there has been a movement toward more effective and eco-friendly methods (Gawande et al., 2023). Biological pest and disease management, soil regeneration, nutrient cycling, and nitrogen fixation are

all components of sustainable agriculture (Khangura et al., 2023). The goal of these approaches is to maximize productivity while minimizing environmental impact (Isfat & Raihan, 2022). Sustainable land management relies on agricultural conservation, a relatively recent tactic for preserving agricultural practices (Francaviglia et al., 2023). Reducing soil disturbance, using crop rotations, and sustaining soil cover through agroforestry, cover crops, and crop residues are all part of this. Sustainable agriculture is based on these principles and seeks to keep soil healthy, make ecosystems more resilient, and encourage agriculture to be viable in the long run (Çakmakçı et al., 2023). The importance of these methods in soil carbon sequestration cannot be overstated. Sustainable agriculture is a way to increase output without compromising environmental quality or depleting natural resource stocks (Raihan &Tuspekova, 2022c; 2022d; 2022e; 2022f; 2022g; 2022h; 2022i).

Extremely variable and unpredictable rainfall, soils that are structurally unstable, and poor crop yield are major obstacles in semiarid and arid regions. Soil erosion and runoff can be exacerbated by tillage methods that do not leave agricultural waste on the soil surface (Fajeriana et al., 2024). This puts soil health at risk. The significance of soil cover in promoting conservation agriculture practices is emphasized by this. Thus, conservation farming methods that lessen soil disturbances—like less tillage—in conjunction with sufficient soil cover and varied cropping systems aid in decreasing runoff and erosion while enhancing soil aggregation, penetration, and lasting carbon sequestration.

Geological SOC

When it comes to soil depth, the top 40 cm of soil usually holds the most SOC, with the deepest levels found between 0 and 20 cm (Navarro-Rosales et al., 2023). The stratification structure of SOM is altered by tillage methods, which in turn affects the distribution of SOC. Since SOC is mostly added to the top layer of soil, tillage has less of an effect on carbon distribution further down the soil profile. In order to comprehend the total advantages of conservation tillage, it is crucial to assess changes in carbon sequestration in subterranean layers. Using data from 69 pooled studies, Wang et al. (2023) performed a meta-analysis that looked at the impacts of tillage deeper than 40 cm. According to the results, changes in the soil's carbon distribution significantly affected the outcome. For example, in most studies, the top layer of soil showed the effects of nitrogen additions within the first decade of the experiment. There was no accumulation of SOC in deeper soil layers over a 28-year long-term experiment that used the same traditional tilling strategy; nevertheless, tilled soils with lower native organic carbon levels had a greater mineralization proportion of SOC. This discovery emphasizes how soil management approaches in semiarid areas can improve soil quality. Soil carbon ratios are an important indicator of soil quality, but it would be a mistake to focus on them in isolation and ignore how the variable has changed over time (Reichenbach et al., 2023). Notwithstanding these constraints, organic matter addition can aid in soil quality restoration.

Technology-based SOC

Improved SOC distribution in soil fractions across the soil profile and stabilization of SOC inside stable micro and macro soil aggregates are two goals of recent technical developments that aim to raise SOC density and, by extension, SOC deposition. Soil carbon pool increases and decay constant values for carbon are decreased by this novel approach, which protects carbon from microbes and prolongs its persistence. One of the most important ways to increase the SOC pool and sequester carbon on land is to manage agroecosystems (Rattan, 2023). Uptake, fixation, emission, and transport among different carbon reservoirs are all aspects of carbon that humans have artificially manipulated in agricultural techniques (Raihan &Tuspekova, 2022j; 2022k; 2023b). SOC

sequestration can be enhanced through the adoption of new agricultural techniques, irrigation schedules, erosion control measures, and mulch farming, among other RMPs.

Recovering degraded soils alongside ecosystems, repurposing marginal agricultural soils for restoration-promoting land uses like perennial vegetation replanting, and enacting RMPs on agricultural lands are all ways to increase SOM's ability to act as a CO_2 sink in the atmosphere. Although there are common RMPs like precision farming, integrated pest management, integrated nutrient management, mulch farming, and decreased tillage, site-specific adaptation is of utmost importance (Jayara et al., 2023). The key to making RMPs work better and last longer is tailoring them to each site's unique qualities and needs. Optimizing soil carbon sequestration and agricultural productivity requires consideration of factors such as soil type, local ecosystems, climate, and current agricultural methods (Rodrigues et al., 2023). In order to repair and maintain soil health, these ecological techniques take advantage of the interdependencies and connections within ecosystems. Sustainable soil management and long-term carbon sequestration can both be significantly improved by implementing these ideas into land management strategies.

Climate Change Mitigation through SOC Sequestration

More and more people are looking to SOC sequestration as a way to lessen the impact of climate change and cut down on emissions of GHGs (Paul et al., 2023). It is imperative that measures be taken to decrease atmospheric CO_2 concentrations, which have risen substantially (by 31% globally) due to the combustion of fossil fuels and shifts in land use patterns (Raihan, 2023j; 2023k; 2023l; 2023m; 2023n; 2023o; 2023p; 2023q; 2023r; 2024c; 2024d; 2024e; 2024f; 2024g). Global carbon emissions have been around 136 Pg from soil cultivation and 270 Pg from fossil fuel use since the industrial revolution (Chataut et al., 2023). The SOC pool has lost about 78 Pg of carbon due to human activities such as deforestation, agricultural conversion, biomass burning, wetland drainage, and soil cultivation (Bhattacharyya et al., 2023). Significant carbon losses have occurred as a result of SOC depletion; in fact, some agricultural soils have lost as much as two-thirds of their natural SOC pool (Don et al., 2024).

For agricultural sectors, sustainability, food security, water quality, and the rate of atmospheric enrichment of CO_2 to be reduced, restorative methods of land use and RMPs applied to agricultural soils are essential. SOC can be restored through techniques including conservation tillage, cover cropping, composting, mulching with crop leftovers, and manure application (Shah et al., 2023). When implemented properly, these solutions can capture 0.9 Pg of SOC per year, which is enough to counteract 25% to 30% of the projected 3.3 Pg per year rising atmospheric CO_2 levels (Subramanian et al., 2023). Soil carbon sequestration has the potential to naturally store 30-60 Pg C over a 25-50 year period (Rodrigues et al., 2023). Restoring damaged soils isn't the only benefit of using soil carbon sequestration tactics. These methods also boost biomass production, enhance groundwater quality, and reduce overall emissions to the environment, which helps to equalize CO_2 emissions from fossil fuels.

SOC Sequestration through Cropping Systems

SOC sequestration by crop rotation

Unlike continuous monoculture, crop rotation calls for a specific pattern of crops grown in the same area on a regular basis. This method changes nitrogen cycling, soil structure including aggregation, and SOC concentration, all of which have a major impact on soil quality (Hartmann & Six, 2023). Crop rotations benefit

SOM and carbon sequestration, decrease soil erosion, and influence soil phosphorus and carbon retention (Francaviglia et al., 2023). A key factor in SOC sequestration is the quantity of crop residues restored to the soil throughout crop rotation, the impact of which varies among crop rotations (Kroschewski et al., 2023). Hordeum vulgare monoculture resulted in far lower SOC concentrations than a rotation with Vicia sativa in the arid parts of Spain (Holder et al., 2019).

SOC sequestration with crop residue

To reduce erosion and improve SOC sequestration, it was helpful to combine tillage with fertilizer with crop residue additions (Ren et al., 2024). The retention of crop residue and other conservation agricultural measures, such as reduced or no-tillage methods, improve SOC sequestration (Francaviglia et al., 2023). Surprisingly, the top 0-5 cm of soil layer exhibits the maximum SOC sequestration irrespective of these techniques. Restoring SOC content is another way that organic manure and other residue management strategies can help with C sequestration (Thapa et al., 2023). According to Ghimire et al. (2008), conventional tillage removed 7.86 kilogram C m^{-3} from the top 0-50 cm of soil, while no-tillage methods kept 8.24 kg C m^{-3}. It is worth mentioning that compared to the other treatments, crop residue preservation in no-tilled soils absorbed a much higher amount of SOC in the upper 15 cm of soil. Based on these results, it seems that using zero- or minimum-tillage methods and keeping crop residues could improve SOC sequestration. Figure 3 illustrates conservation agriculture as a method for improving ecosystem services including carbon sequestration.

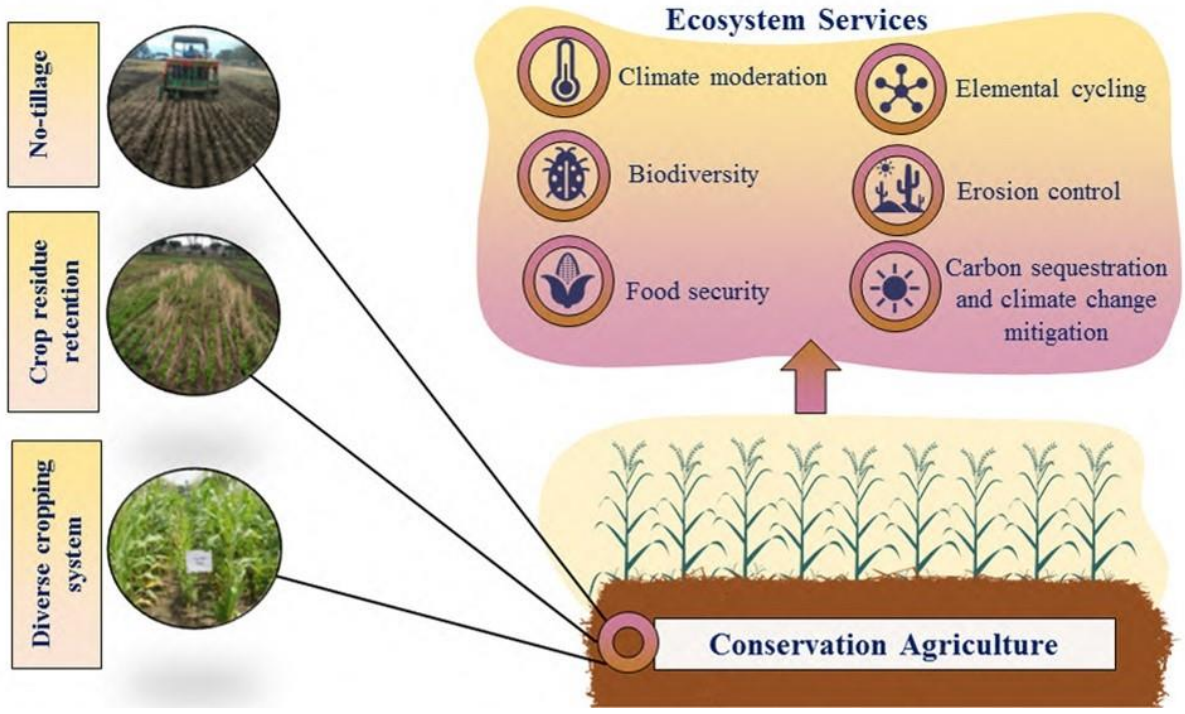


Figure 3. Conservation agriculture as a method for improving ecosystem services (Jayaraman et al., 2021).

SOC sequestration with cover crops

Soil carbon storage can be greatly improved by growing cover crops in between primary crops (Seitz et al., 2023). By boosting carbon inputs via photosynthesis and their own breakdown (root and leaves), cover crops help soils sequester carbon (Raihan et al., 2018; 2019; 2021a; 2021b; 2022a; 2023a). Reduced nitrogen losses through leaching, increased crop yields, and improved soil quality are just a few of the agroecosystem functions provided by cover crops (Arlauskienė & Šarūnaitė, 2023). A number of factors determine the precise effects and advantages of cover crops. These include the type of cover crop, the timing of planting and harvesting, the cropping system, the length of time the crop is allowed to develop, the amount and quality of cover crop residue, and the weather (Scavo et al., 2022). Assessing the efficacy of cover crops in various agricultural systems requires constant monitoring of the SOC pool in reaction to cover crop application. It needs long-term studies to find out how cover crops affect SOC sequestration in the long run. Cover crops have the potential to store almost 60 million tons of carbon, according to a review and analysis by Chahal and Van Eerd (2019) of data from 26 trials drawn from five sources of literature. Figure 4 presents the benefits of cover crops including carbon sequestration.

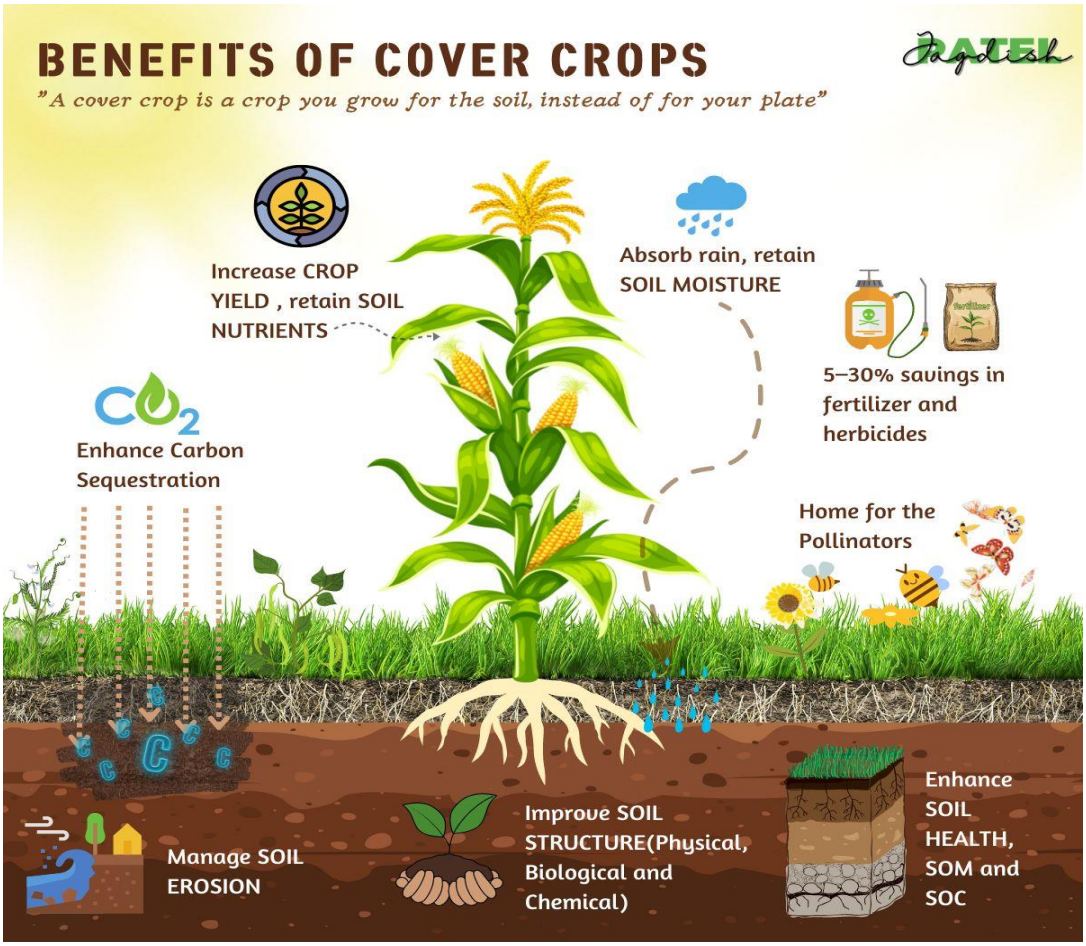


Figure 4. Benefits of cover crops including carbon sequestration (Patel, 2023).

Modern Agriculture's Climate Impact

Soil carbon fluctuations affect sequestration

Soil carbon sequestration, an important part of the global carbon cycle and climate change, can be greatly affected by changes in soil carbon (Rodrigues et al., 2023). In order to effectively manage soil carbon, it is crucial to understand the factors that impact soil carbon variations. These factors include changes in land use, climate change, alongside soil management methods (Rodrigues et al., 2023). Over time, SOC decreases due to inefficient land use management, leading to a soil carbon deficit compared to the quantities of carbon that were previously present (Gutierrez et al., 2023). A key approach to re-normalize the worldwide carbon balance is land management that avoids soil carbon loss and promotes storage. Another successful strategy to enhance soil carbon storage is to increase inputs of carbon via natural ecosystems (Wiltshire & Beckage, 2022). Some major tactics for carbon sequestration include making carbon inputs easier and preventing the rate of carbon decomposition from increasing (Mäkipää et al., 2023). To deepen our comprehension of soil carbon dynamics, future studies ought to center on wetlands and soil carbon budgets.

Mitigation by reducing SOC depletion

Efforts to slow down climate change include using land management techniques that make soil more effective at soaking up carbon (Sünnemann et al., 2023). Climate change, changes in land use, and soil management methods are three of the many factors that affect soil and, by extension, the soil carbon pool (Raihan, 2023s; 2023t; 2024h). A small number of factors or even individual ecosystems have frequently been the center of attention in earlier research. In order to better understand the worldwide soil carbon cycle and how to manage it, a thorough analysis is required that takes into account the combined impact of multiple factors on soil carbon sequestration.
The rapid decline of the SOC pool, mostly as a result of human activities, has led to an increase in atmospheric CO_2 concentrations, which has had devastating impacts on both the environment and the economy (Dong & Huang, 2023). In terms of soil quality, the SOC reservoir is vital because it does things like absorb moisture at low moisture levels to make more water available to plants and encourage the formation of soil aggregates, contribute to charge density, and play a role in ion exchange processes. It also acts as a sink for important plant nutrients like N, P, Zn, Mo, and S (Rodrigues et al., 2023).

Atmospheric accumulation of CO_2

An increase in the average surface temperature of the Earth is only one of several environmental problems brought about by the dramatic increase in atmospheric concentrations of GHGs such as CO_2, methane (CH_4), and nitrous oxide (N_2O) during the industrial revolution (Raihan et al., 2022b; 2022c; 2022d; 2022e; 2022f; 2022g; 2023b; 2023c; 2023d; 2023e; 2023f; 2023g; 2023h; 2024a; 2024b). Take atmospheric CO_2 levels as an example; they jumped from 280 to 367 parts per million in just one year. Temperatures are currently rising at a rate of 0.17 ◦C per decade, which is higher than the threshold of 0.1 ◦C per decade and is making it harder for ecosystems to adapt, while global warming has been going on throughout the late 19th century (Sultana ey al., 2023a; 2023b). Following the worldwide policies and trends specified by various regulatory bodies, the latest trends focus on CO_2 reduction (Voumik et al., 2022; 2023a; 2023b; 2023c).
Droughts are becoming more common as a result of global warming, with the northern hemisphere seeing an increase of 0.5-1% every decade and the subtropical land regions experiencing a decrease of 0.3% per decade.

Impacts on soil stability, organic carbon sequestration, runoff and erosion, water, nitrogen, carbon, phosphorus, and sulfur cycles, biomass production, biodiversity, and the environment as a whole are negative outcomes of these altered precipitation patterns.

Soil erosion

Deterioration in soil quality leads to changes in physical and chemical properties that make it less effective at retaining SOC on farms (Francaviglia et al., 2023). These changes include things like aggregation, crust formation, soil texture, compression as well, water infiltration capacity, and water/air ratio. Soil erosion also causes carbon losses, which makes the effect of contemporary agriculture on global warming even worse (Roy et al., 2023).

Low SOM

To lessen the impact of agriculture on global warming, more people need to know about SOM. There has been a marked decline in the global absorption of SOC due to the transformation of natural environments to agricultural land. The conversion of tropical forests along with savannas into farms perpetuates this troubling trend. There is an imbalance in soil carbon sequestration in agricultural systems compared to natural ecosystems like prairies and forests (Moradi & Shabanian, 2023). Soil carbon sequestration can drop by 1500 ppm during the changeover from natural to agricultural ecosystems, especially in the first few years after the land is converted. Even with RMPs in place, the yearly rate of SOC loss in farming can be higher. Therefore, in order to enhance soil health and boost carbon input, it is crucial to restore the SOM pool in agricultural lands. In addition, nitrogen inputs and other agrochemicals are a major source of GHG emissions, which makes carbon sequestration attempts more difficult.

Climate Smart Agriculture (CSA) and SOC

Climate-smart agriculture (CSA) is an approach that strategically controls the cultivation of crops, rearing of livestock, maintenance of forests, and management of fisheries in order to mitigate the adverse impacts of climate change on agricultural activities (Ariom et al., 2022). Implementing CSA methods can enhance soil fertility, boost crop yields, and mitigate GHG emissions by promoting soil carbon sequestration (Tadesse et al., 2021). This can assist small-scale farmers in adjusting to the vagaries of climate change (Raihan, 2023u; 2023v; 2023w; 2023x). CSA practices can partially counteract previous soil carbon losses and aid in mitigating climate change. Additionally, it has the potential to improve the resilience and adaptive ability of production. The adoption of CSA methods, such as no-tillage, cover cropping, organic soil fertilization, and crop-livestock and crop-livestock-forestry systems, has been widespread (Raihan et al., 2022h; 2022i; 2022j; 2023i; 2023j; 2023k; 2023l; 2024c). These practices aim to increase soil carbon accumulation and improve soil quality, all while maintaining agricultural yield (Anghinoni et al., 2021).

Several exclusive activities in CSA that can enhance soil carbon include the use of soil additives, analysis of soil data, cultivation of salinity-resistant and high-yielding crop types, and use of carbon farming techniques (Jat et al., 2020). Composting and using biochar have the potential to enhance soil composition and augment the amount of organic matter in the soil. Enhancing the soil's water retention and permeability can ameliorate the effects of droughts, heatwaves, and heavy precipitation events. Soil amendments can additionally enhance biological activity and supply nutrients, thereby fostering the growth of healthier plants that exhibit reduced

vulnerability to pests and diseases (Akanmu et al., 2021). In addition, farmers have the ability to utilize instruments to assess and track soil characteristics in order to execute specific strategies aimed at enhancing soil health and its ability to capture and store carbon. Furthermore, the utilization of salinity-resistant and high-yielding crop types can assist farmers in mitigating the impact of climatic hazards on their crops (Haque et al., 2021). In addition, carbon farming practices encompass the application of soil additives, conservation tillage, agroforestry, whole orchard recycling, and the use of cover crops that optimize the presence of living roots (Quintarelli et al., 2022).

In contrast, non-CSA practices prioritize maximizing crop output by relying heavily on chemical fertilizers, pesticides, and weedicides. However, this approach can have detrimental effects on the ecosystem and soil quality. Monoculture methods that are not part of a CSA system might result in the spread of diseases and increased vulnerability to predation, necessitating the usage of pesticides. Moreover, the act of clearing forested areas for agricultural techniques that are not part of CSA might result in the depletion of wildlife populations. The use of non-CSA techniques results in soil erosion, a decline in water levels, reduced soil fertility, and a decrease in the soil carbon pool. Therefore, the adoption of non-CSA techniques increases agricultural emissions and contributes to the phenomenon of global warming and climate change.

CSA in developing countries

Agriculture serves as the primary economic driver for numerous emerging nations. The phenomenon of climate change poses multifaceted challenges to agricultural production and food security in developing nations. Therefore, it is imperative to prioritize the enhancement of agricultural production efficiency, the assurance of food security, and the promotion of economic growth when establishing goals for the development of CSA in these developing countries. Simultaneously, the mitigation of GHG emissions within agricultural systems should be incrementally achieved by allocating supplementary financial resources (Leng et al., 2023). In accordance with the concept of CSA, emerging nations have devised appropriate solutions tailored to the specific circumstances of various locations. The state of Maharashtra in India is considered to be a region of considerable climatic vulnerability. One of the primary challenges encountered in agricultural production within the state of Maharashtra is the insufficiency of irrigation water during periods of drought. Hence, the mitigation of drought conditions can be achieved by using irrigation water management technologies, including techniques such as well excavation, pipe wells, rainwater harvesting, drip irrigation, and various types of groundwater extraction. The integration of nutrient management techniques, such as the application of farmyard manure, earthworm compost, and straw residue incorporation, along with the implementation of sprinkler irrigation and other micro irrigation technologies, has the potential to enhance the efficiency of water and fertilizer utilization, as well as agricultural productivity. Additionally, this approach can contribute to the reduction of overall agricultural water and fertilizer usage, as well as greenhouse gas emissions (Khatri-Chhetri et al., 2019).

The implementation of high-quality rice cultivars, strategic adjustments to sowing and harvesting schedules, decreased reliance on chemical fertilizers, and modifications to irrigation strategies in the Mekong Delta region of Vietnam have collectively contributed to the enhancement of crop productivity, reduction in production expenses, and the establishment of food security for farmers (Ho & Shimada, 2019). In Nepal, agricultural practitioners employ many management strategies, including but not limited to no tillage, crop rotation, and straw incorporation into the soil, with the aim of enhancing soil biological activity, water utilization efficiency, and soil physical characteristics (Gairhe et al., 2021). Enhanced soil quality has the potential to augment the tiller count, plant stature, and grain productivity of wheat, while concurrently mitigating erosion. In the context of Pakistan, it has been observed that indigenous cotton producers have embraced the concept of CSA by

employing bed seeders and laser technology to achieve field leveling. According to Imran et al. (2018), the implementation of strategies such as reduced tillage and fallow practices, as well as the cultivation of enhanced cotton varieties that are resistant to drought and waterlogging, have led to enhancements in the local cotton quality and a subsequent indirect reduction in greenhouse gas emissions.

In the African context, addressing the intertwined challenges of food security and climate change necessitates the implementation of substantial agricultural reforms (Khan et al., 2023b). In the context of Zambia in Southcentral Africa, agricultural practices aimed at protection are implemented. These practices include the use of organic mulch on surface crops in farms, the rotation of legumes and cereals, and the utilization of enhanced crop varieties (Kaczan et al., 2013). The implementation of these measures in Zambia has the capacity to enhance soil fertility and carbon sequestration capabilities, leading to a significant increase in average grain yields and effectively ensuring local food security. Furthermore, it should be noted that Malawi, a country located in Africa, has used a strategy known as continuous agroforestry intercropping, which involves the cultivation of two primary fertilizer species. Additionally, they have also employed the practice of orderly agroforestry fallow, which entails the deliberate planting of fast-growing leguminous trees or shrubs. Another approach utilized in Malawi is the agroforestry complex system, as discussed by Harawa et al. (2006). The implementation of these techniques in Malawi has been found to enhance soil nitrogen fixation, enhance soil nutrient levels, and effectively mitigate the release of greenhouse gases, including CO_2 and N_2O (Kaczan et al., 2013). Farmers in Namibia have effectively augmented their income by implementing several strategies, including the collection of nutrient-rich earthworm compost leachate, engaging in hydroponic agriculture, and cultivating mushrooms in the coastal regions of the Namib Desert. To conserve irrigation water, the researchers additionally collected fog water for the purpose of agricultural irrigation in coastal desert regions. Alternatively, they combined seawater with fog water to implement precision drip irrigation at the crop root level (Mupambwa et al., 2019). By implementing these supplementary measures, Namibia has successfully mitigated the issue of food scarcity and bolstered its capacity to cope with the impacts of climate change.

CSA in developed countries

Developed countries have advanced agricultural systems characterized by efficient production, high-quality agricultural products, abundant per capita land resources, and well-established mechanization and intensification techniques. Consequently, the development objectives of the CSA in these industrialized nations generally revolve around the reduction of GHG emissions and the enhancement of agricultural ability to effectively cope with the impacts of climate change. Simultaneously, it is imperative to include advanced and innovative technologies, prioritize the development and execution of regulations, bolster the adaptability of the agricultural system, and mitigate greenhouse gas emissions while concurrently enhancing production efficiency (Long et al., 2016). California, situated in the United States, is widely recognized as a highly productive and resource-abundant agricultural area on a global scale. The state places significant importance on the sustainable administration of water resources and the mitigation of GHG emissions as part of its efforts to attain CSA objectives (Lewis & Rudnick, 2019). The California government has successfully achieved the objective of lowering GHG emissions through the implementation of a range of laws, regulations, and relevant agricultural technological measures facilitated by the public research system. As an illustration, the most recent legislation pertaining to methane mandates a 40% reduction in methane emissions from the dairy sector by the year 2030, as outlined in the study conducted by Vechi et al. (2023). The California government considers enhancing agricultural water usage efficiency as a viable approach to address the water resources challenge within the context of water resources management. The local government provides assistance to farmers in addressing the

challenges of high investment costs, GHG emissions reduction, and water restrictions. This assistance involves the upgrading of underground water pumps and the installation of drip irrigation or micro sprinkler irrigation systems, which aim to enhance water storage and recovery capacity (Ayars et al., 2015).

In the European context, there is a heightened focus on the effects of climate change on agricultural development, as evidenced by the research conducted by Lehtonen et al. (2021). As a result, European countries primarily leverage the service activities provided by agricultural ecosystems. The utilization of satellite data inside agricultural models, wherein remote sensing techniques are merged with agricultural models to facilitate the advancement of precision agriculture, was implemented in France. The utilization of technological advancements to enhance our ability to adapt to climate change has the potential to yield several benefits, including improved decision-making in the face of variable weather conditions, enhanced time management, increased savings on expenditures, and perhaps reduced greenhouse gas emissions (Zilberman et al., 2018). Switzerland implements a waste recycling system wherein the farm's waste is directed to the biogas plant at no cost. This initiative serves to mitigate GHG emissions by facilitating the generation of renewable energy. Additionally, the biogas plant enhances the quality of fertilizers and feed additives provided to the farm (Loboguerrero et al., 2019). The implementation of LED horticulture technology in the Netherlands has enhanced the sustainability of horticultural practices, hence reducing its susceptibility to the impacts of climate change. In contrast to conventional lighting methods, the utilization of LED technology yields a reduction in both heat generation and energy consumption. Furthermore, it enhances the dispersion of light and exerts a favorable influence on the cultivation of plants (Engler & Krarti, 2021). According to Adamides (2020), Cyprus employs agricultural robots for the purpose of applying pesticides to crops. This practice serves to enhance crop protection and productivity, while concurrently diminishing the reliance on pesticides and advancing the sustainability of agricultural ecosystems.

The nations described above have implemented a range of methods focused on the development goals of the CSA in response to different regional circumstances. Additionally, they have separately assessed the implementation of the CSA to different extents. The aforementioned findings demonstrate that the implementation of CSA has been effectively carried out in multiple nations. Certain countries have effectively achieved their goals through reducing greenhouse gas emissions, increasing economic growth and productivity, enhancing resilience to climate change, and implementing improved agricultural methods.

Socioeconomic Advantages

Sustainable growth and alleviating poverty evaluate the socioeconomic benefits along with trade-offs of SOC sequestration. This is especially true in low-income societies, where farms frequently encounter social and financial issues. To stop land degradation and keep carbon in the air, ecosystem restoration is essential (Roy et al., 2023). Land that is no longer used for farming has the potential to act as a large-scale carbon sink, reducing atmospheric CO_2 levels (Ruehr et al., 2023). Nevertheless, there is a spectrum of land restoration solutions available, from active restoration methods that are more costly to less expensive minimal management approaches. Planting seeds on land that has been farmed in the past is one example of active restoration, which aims to speed up carbon recovery and return different ecological functions (Jakovac et al., 2024). A new worldwide study, however, reveals that tropical forests may see a quicker return to primary produce via natural regeneration—that is, by letting abandoned crops recover naturally—than through intensive restoration (Elliott et al., 2023). The results show that aggressive restoration, which requires substantial investment, does not necessarily result in more carbon sequestration than inexpensive spontaneous regeneration.

Return on investment optimization for ecosystem restoration remains a highly unknown subject. It has been difficult to distinguish the effect of restoration techniques with changing environmental circumstances since studies evaluating active restoration with natural regeneration have frequently looked at different treatments performed at different locations. This has led to a lack of confidence in the results of these studies and an absence of agreement on how to best use scarce management resources to increase soil carbon sequestration. The Chinese government's 'Grain for Green' initiative is a massive ecological restoration effort on a global scale (Li et al., 2023). Converting farmland back into a semi-natural habitat like a woodland, shrubland, or grassland is the ultimate goal of the project. So that it may compare the two restoration methods side by side, this study includes several locations that use both active restoration and natural regeneration. In order to determine what parameters, such as recovery period, climate, ecological type, SOC, and soil depth, impact carbon recovery following fallow cropland, researchers conducted a large-scale pairwise comparison utilizing the distinctive dataset from the Grain for Green project (617 observations). This research was useful in determining when and how active restoration and natural regeneration are most effective for SOC sequestration.

SOC Sequestration Factors

There are a number of elements that affect soil carbon sequestration, and they include soil characteristics, management elements, and environmental considerations (Elkhlifi et al., 2023). For carbon sequestration, soil texture is key. Soils with a coarser texture tend to mineralize nitrogen and carbon at a faster pace than those with a finer texture (Vaidya et al., 2023). This is probably because finer textures are better able to protect organic carbon from microbes. Under different land uses, such as forests, shrublands, and croplands, the soil's texture affects the carbon equilibrium in the deeper soil layers. Soil bacteria in clay-dominated soils have a harder time getting to organic carbon than in sandy soils because clay minerals adsorb carbon chemically and microaggregates physically occlude it (Stoner et al., 2023). SOC aids in mineral binding and aggregate formation, which in turn protects carbon from degradation, and both processes are intrinsic to soil structure (Kunmala et al., 2023). In contrast to fine-textured soils, natural ecosystems, or soils produced by minimal tillage, the carbon preservation capacity of soil aggregates with low consistency is lower in soils with coarse textures and soils that have been intensively tilled (Francaviglia et al., 2023). Soil carbon sequestration or accumulation is a function of land management methods. Soil carbon stores can be achieved through practices which boost carbon inputs while decreasing heterotrophic respiration (Kudeyarov, 2023). For example, shifting from traditional tillage methods to no-tillage ones might lengthen the time that SOC stays in the soil. Causes of SOC stock loss due to tillage include enhanced water or wind erosion, leaching of dissolved carbon, and mineralization of exposed carbon after aggregate breakdown (Francaviglia et al., 2023).

The net SOC balance, which is the difference between inputs and outputs, is influenced by environmental factors like temperature, humidity, and aeration (Longo et al., 2023). Even at ideal soil moisture levels, SOC breakdown is accelerated by higher temperatures. To facilitate microbial growth, which in turn affects respiration rates and carbon turnover, sufficient soil aeration is critical for carbon sequestration (Rodrigues et al., 2023). Figure 5 presents the factors influencing SOC.

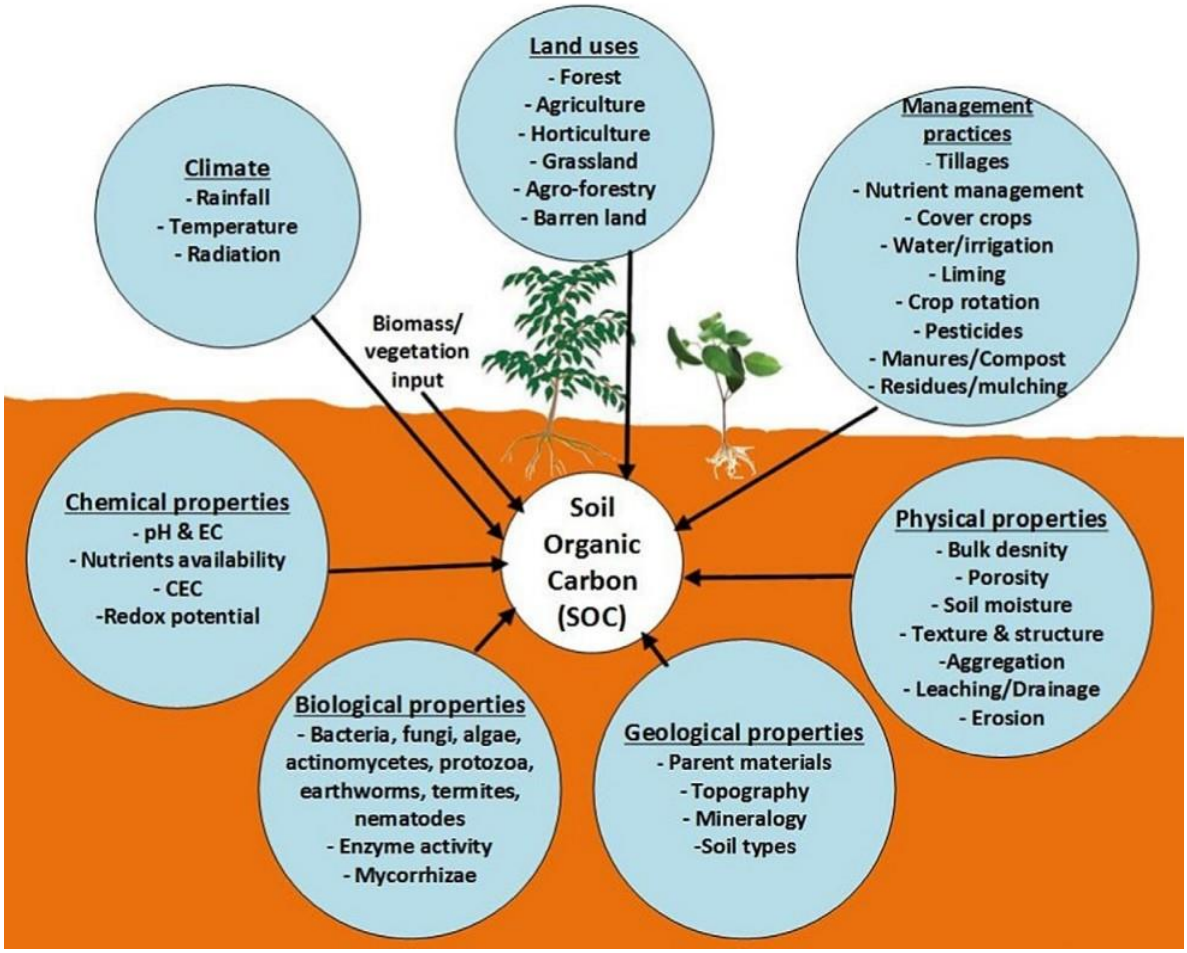


Figure 5. Factors influencing SOC (Ramesh et al., 2019).

Crop Management to Sequester SOC

Soil carbon sequestration and soil quality are greatly improved by many crop management strategies. These include crop rotations, agroforestry, cover cropping, nitrogen fertilizer, precision farming, tillage, applications of manure and biosolids, irrigation, and more (Mohanty et al., 2024). Soil fertility, productivity, and carbon sequestration are three factors that farmers can control in their fight against climate change. By implementing these techniques, farmers can also secure food supplies for the future (Balasundram et al., 2023).

Ecosystem management to restore carbon

All organic matter in the soil, including decomposing plant and animal matter, chemicals produced by microbes and other living organisms, and the biomass of soil microbes and other fauna, as well as their metabolic products, are collectively known as SOM (Wani et al., 2023). Plants cover, temperature, species, management techniques, and human activities are some of the variables that affect an ecosystem's capacity to sequester carbon in soil and plants, whether it's an aquatic or terrestrial ecosystem (Rodrigues et al., 2023). Enhancing soil carbon sequestration and mitigating excess atmospheric CO_2 are two key components of ecosystem management for carbon restoration (Rodrigues et al., 2023; Ghosh et al., 2023). Soil carbon sequestration effects may be

compared on a broad scale since numerous restored sites have used both active restoration and spontaneous regeneration at the same time (Jakovac et al., 2024). The soil, history, climate, and amount of disturbance in these locations are very comparable. For croplands, naturally restored locations, and actively restored sites, data on soil carbon has been provided, including mean values, sample sizes, and recovery timeframes for up to 60 years (Tian et al., 2023).

SOC concentration and bulk density are the main variables that impact soil carbon stock (Ameer et al., 2023). Almost 40% of the studies included bulk density data, while a small number of them solely reported SOC concentrations (Gholamahmadi et al., 2023). SOC concentration fluctuations can provide light on changes in soil carbon stock when bulk density is taken into account when evaluating the consequences of active restoration with natural regeneration on the same site (Cheng et al., 2023). One way to increase the residence time of SOC is to return crop residues along with other biosolids at a rate that is higher than their rate of decomposition. Another way is to reduce the degradation of the natural vegetative structure and the groundwater table, both of which have an impact on the carbon dynamics of the ecosystem. Loss of biodiversity is another consequence of converting forests to plantations or grasslands (Prangel et al., 2023). By developing deep root systems and engaging in bioturbation, SOC is integrated into the subsoil, reducing the impact of plowing and other human activities on the soil (Sierra et al., 2024). Providing the necessary nutrients (nitrogen, phosphorus, and sulfur) while also influencing soil properties (such as clay content and landscape orientation) to preserve the soil's intrinsic C sink capacity. The systemic implications of ecosystem management for carbon restoration are shown in Figure 6.

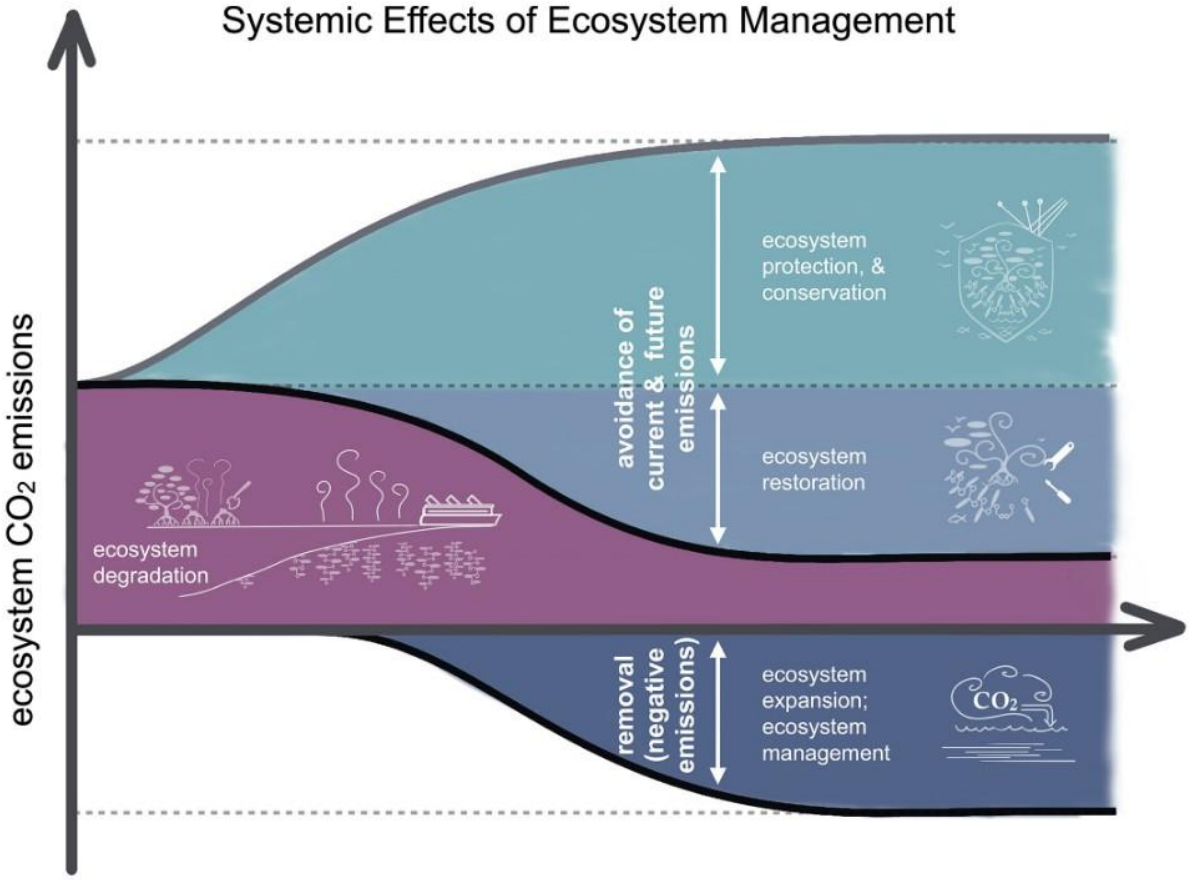


Figure 6. The systemic implications of ecosystem management for carbon restoration (Mengis et al., 2023).

Optimizing SOC sequestration in grasslands

Soil processes, especially biogeochemical cycling, have been significantly transformed as a result of human-induced modifications in around 60% of the grassland ecosystem worldwide (Meng et al., 2024). Depending on the level of grassland management, different factors like stocking concentrations, mineral fertilizer usage, possible irrigation methods, and animal species are taken into account (Puech & Stark, 2023). In remote areas, farmers use intensive land management techniques like applying fertilizers, reseeding annual and preferred perennial plant species, and using a variety of stocking strategies, including changing the timing of the grazing season, among other things.

Soil carbon sequestration is already a major function of grasslands and managing them can make this function even more efficient (Norderhaug et al., 2023). Soil carbon sequestration and plant growth can both be enhanced by establishing long-term plant shields and efficiently adding subsurface biomass. A number of management strategies and environmental factors affect the relative contributions of carbon sequestration and respiration of soil, which in turn determines the extent to which grassland soils sequester carbon (Rodrigues et al., 2023). Ranches often utilize grasslands for cattle grazing and hay production. SOC sequestration and soil microbial populations are both influenced by these methods. Soil carbon sequestration can be improved through grassland management practices, leading to more efficient release of CO_2 and other GHGs. The SOC stock (surface layer of 24 + 6 cm) was estimated to be 31.1 Mg C ha^{-1}, grasslands at 47.4 Mg C ha^{-1}, and forestland at 49.9 Mg C ha^{-1} based on an analysis of wide land use classifications throughout 28 studies in the southeastern United States, which is a warm-humid area with comparatively weathered as well as coarse-textured soils (Franzluebbers and Poore, 2023).

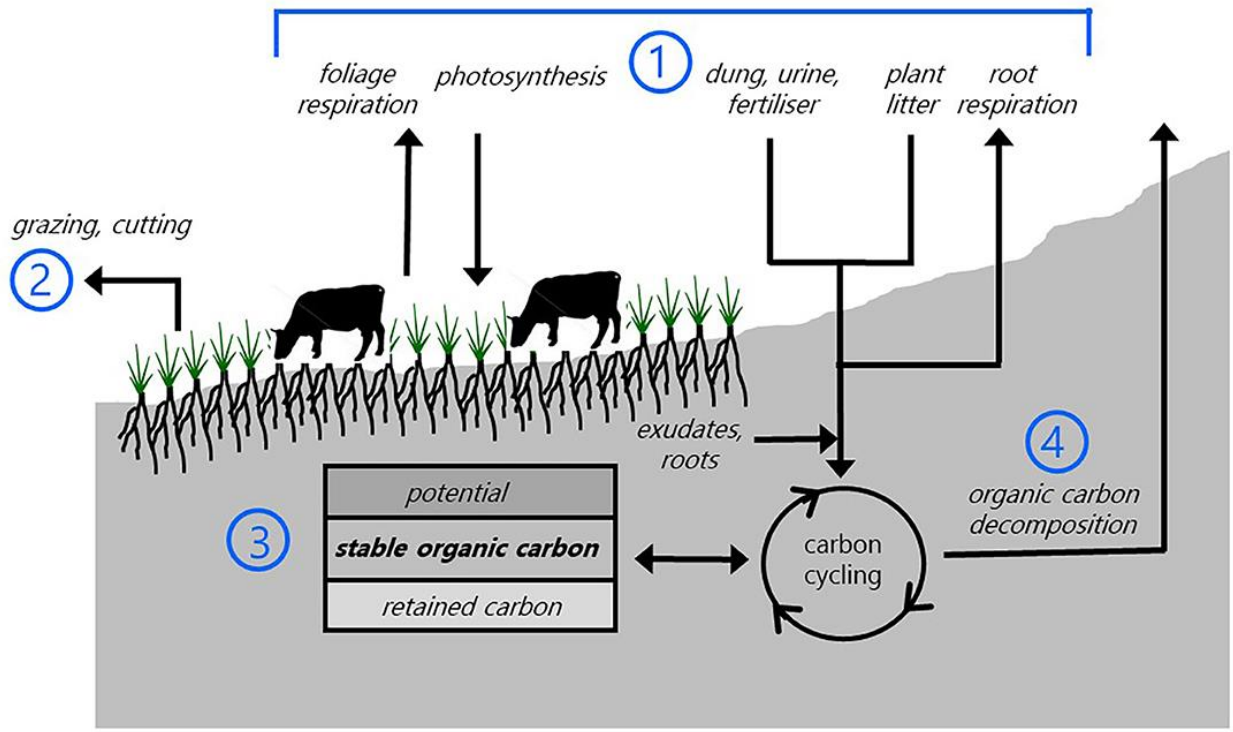


Figure 7. The management of grasslands to maximize soil carbon sequestration (Whitehead, 2020).

Loss of gaseous emissions, such as CO_2, CH_4, and N_2O, into the atmosphere can cause a dramatic rise in the buildup of GHGs (Liu et al., 2023). N_2O is around 300 times stronger than CO_2, while CH_4 is about 40 times more potent, when considering its ability to cause global warming (Chataut et al., 2023). Notably, compared to CO_2 emissions, N_2O emissions from grassland ecosystems are usually far lower, often spanning many orders of magnitude lower (Laubach et al., 2023). It must be acknowledged that the agricultural industry bears a heavy burden of global responsibility (Himu & Raihan, 2023; Raihan & Himu, 2023). It is responsible for approximately 25% of all GHG emissions on Earth, with systems for raising livestock being particularly influential in this regard (Raihan, 2023y; 2023z). The management of grasslands to maximize soil carbon sequestration is shown in Figure 7.

Obstacles and Prospects of SOC Sequestration

Soil carbon sequestration has its limits when it comes to reducing GHG emissions, as discussed by Moinet et al. (2023). Soil carbon sequestration has a lot of untapped potential, but the authors point out a few things that might make it hard to predict how effective it will be. A crucial component is soil carbon saturation, which occurs when the rate of soil carbon accumulation slows down to a quasi-equilibrium state. Longitudinal studies exhibit this saturation tendency, with the exception of certain instances such as peat formation. It is essential to take saturation effects into account while evaluating various management approaches for SOC increase. If this is not done, the potential for carbon sequestration may be overestimated. A total reduction of about 3000 Gt CO_2 emissions is necessary to keep the world's temperature rise to 1.5 ◦C by 2100, as stated in the Paris Agreement. According to Moinet et al. (2023), by 2100, soil carbon sequestration is expected to account for 4% to 1% of the world's emissions, at the very most. Aligning with recent estimates from other angles, this work gives a quantitative view of the function of SOC sequestration in reducing climate change. It also stresses the need for realistic evaluations. Another drawback is that, depending on factors like weather and soil microbes, grasslands may experience greater carbon loss than sequestration. The depletion of productive soil profile layers, which may take a long time to mix with the stored C, is another important limitation that can affect SOC sequestration. Restoring soil systems to their original C-storage equilibrium can take anywhere from a few years to several decades. The dynamics of SOC sequestration and its equilibrium constant in attaining a sustainable green environment in accordance with the UN's SDGs require additional research, nevertheless.

To lessen the impact of climate change on farming, it is essential to manage natural resources carefully and implement farming practices that increase soil carbon sequestration. The impact of shifting weather patterns on this industry is substantial (Raihan & Voumik, 2022a; 2022b). There is a direct correlation between soil carbon sequestration and a win-win strategy for dealing with climate change adaptation and mitigation. This method safeguards soil-based carbon stores from soil microbes that might discharge carbon into the environment by transferring CO_2 from the atmosphere into the soil. One way to restore soil and trap carbon from the air is to switch from traditional tillage to no-till farming methods and turn degraded or marginal lands into perpetual land use. Improved soil health, more sustainable ecosystems, more efficient use of water and nutrients, and substantial sequestration of atmospheric CO_2 are all benefits of no-till farming. The key to achieving these benefits is a combination of zero- or no-tillage and keeping crop residues in the field. SOC accumulation rates at different soil depths can be increased through crop rotation, which is an additional potentially useful technique for soil regeneration and carbon sequestration, especially in conservation agriculture systems. The stability of soil aggregates, water retention capacity, fertility condition of soil, and food security are all enhanced by agricultural management approaches that encourage carbon sequestration. Soil carbon sequestration should be considered as a means to mitigate climate change due to these additional benefits. There is a lack of knowledge on the

dynamics and security of soil carbon cycles across various regions of the world, despite the fact that agricultural methods have a huge potential for carbon sequestration. Predicting the broad adoption of carbon sequestration technologies in agriculture is problematic due to the varying patterns of land management. In spite of this ambiguity, knowing the full extent of soil carbon is crucial and shouldn't wait for a perfect grasp of sequestration capacity. Conservation tillage strategies seem to be more effective than other atmospheric drawdown approaches, and they can be improved upon soon. Soil quality and carbon sequestration are both improved by this approach, and it does so with little downsides.

Conclusion

Through the use of carbon inputs and the reduction of SOC losses, agricultural management practices have the potential to improve soil carbon sequestration. Methods for increasing carbon inputs include using cover crops, crop rotation, agroforestry, deep-rooting crops, or applying compost or biochar, which are external carbon sources. By keeping agricultural residues in the field and preventing soil erosion with practices like no-tillage and cover crops, farmers can reduce SOC losses. It is critical to weigh the benefits and drawbacks of various approaches, though. For instance, the accessibility of organic fertilizers such as compost, manure from farms, or biochar, as well as the additional CO_2 emissions that come with transporting them, are limitations. Although mineral fertilizers can help sequester carbon, the extra CO_2 emissions from processes like irrigation pumping and manufacturing can sometimes cancel each other out. We need long-term solutions that weigh the pros and cons of these activities. Downsides include more weeds, altered soil pH, decreased nutrient availability, and leaching from irrigation. Furthermore, the mineralization of SOM or denitrification of nitrogen-applied fertilizers' ammonia or nitrate contents are both accelerated by GHG emissions linked to soil activities. We need further studies and field trials with longer time periods to see how effective new management approaches are at sequestering carbon, such as applying inorganic carbon. In spite of these obstacles, SOC sequestration is essential for soil health, soil fertility, and ecosystem services through preserving soil productivity, reducing the effects of climate change, and providing ecosystem functions.

To maximize the potential for carbon sequestration, overcome limitations, and create effective strategies for preserving soil fertility and health while reducing the effects of climate change in agriculture, ongoing research and the adoption of sustainable agricultural practices are essential. The growing interest in soil carbon sequestration indicates that agricultural soils are likely to play an important role in stabilizing the atmospheric concentration of CO_2 and to do so by means that are consistent with sustainable and climate smart agriculture. Future research directions for climate change mitigation and agriculture sustainability through soil organic carbon involve expanding practices on a large scale, preserving areas with high carbon density, increasing soil organic carbon through modified management or land use in areas with low carbon density, and enhancing land management activities that maintain or enhance soil organic carbon. Additionally, forthcoming studies should prioritize enhancing climate resilience by means of carbon sequestration, monitoring, and maintenance in soils. Furthermore, it is imperative for future research to prioritize the augmentation of sustainable agricultural methods in order to enhance resilience and adaptability to climate change.

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References

Adamides, G. (2020). A review of climate-smart agriculture applications in Cyprus. *Atmosphere, 11*(9), 898.

Ahmad, S., Raihan, A., & Ridwan, M. (2024). Role of economy, technology, and renewable energy toward carbon neutrality in China. *Journal of Economy and Technology*. https://doi.org/10.1016/j.ject.2024.04.008

Akanmu, A. O., Babalola, O. O., Venturi, V., Ayilara, M. S., Adeleke, B. S., Amoo, A. E., ... & Glick, B. R. (2021). Plant disease management: leveraging on the plant-microbe-soil interface in the biorational use of organic amendments. *Frontiers in Plant Science, 12*, 700507.

Akter, S., Voumik, L. C., Rahman, M. H., Raihan, A., & Zimon, G. (2023). GDP, health expenditure, industrialization, education and environmental sustainability impact on child mortality: Evidence from G-7 countries. *Sustainable Environment,* 9(1), 2269746.

Ali, A. Z., Rahman, M. S., & Raihan, A. (2022). Soil carbon sequestration in agroforestry systems as a mitigation strategy of climate change: a case study from Dinajpur, Bangladesh. *Advances in Environmental and Engineering Research,* 3(4), 1-15.

Ameer, I., Kubar, K. A., Ali, Q., Ali, S., Khan, T., Shahzad, K., ... & Talpur, K. H. (2023). Land degradation resistance potential of a dry, semiarid region in relation to soil organic carbon stocks, carbon management index, and soil aggregate stability. *Land Degradation & Development*, *34*(3), 624-636.

Anghinoni, G., Anghinoni, F. B. G., Tormena, C. A., Braccini, A. L., de Carvalho Mendes, I., Zancanaro, L., & Lal, R. (2021). Conservation agriculture strengthen sustainability of Brazilian grain production and food security. *Land use policy, 108*, 105591.

Ariom, T. O., Dimon, E., Nambeye, E., Diouf, N. S., Adelusi, O. O., & Boudalia, S. (2022). Climate-smart agriculture in African countries: A Review of strategies and impacts on smallholder farmers. *Sustainability, 14*(18), 11370.

Arlauskienė, A., & Šarūnaitė, L. (2023). Cover Crop Yield, Nutrient Storage and Release under Different Cropping Technologies in the Sustainable Agrosystems. *Plants*, *12*(16), 2966.

Ayars, J. E., Fulton, A. L. A. N., & Taylor, B. (2015). Subsurface drip irrigation in California—Here to stay?. *Agricultural water management, 157,* 39-47.

Balasundram, S. K., Shamshiri, R. R., Sridhara, S., & Rizan, N. (2023). The Role of Digital Agriculture in Mitigating Climate Change and Ensuring Food Security: An Overview. *Sustainability*, *15*(6), 5325.

Begum, R. A., Raihan, A., & Said, M. N. M. (2020). Dynamic impacts of economic growth and forested area on carbon dioxide emissions in Malaysia. *Sustainability,* 12(22), 9375.

Bhattacharyya, R., Bhatia, A., Ghosh, B. N., Santra, P., Mandal, D., Kumar, G., ... & Chaudhari, S. K. (2023). Soil degradation and mitigation in agricultural lands in the Indian Anthropocene. *European Journal of Soil Science*, *74*(4), e13388.

Blanco-Canqui, H., Klocke, N. L., Schlegel, A. J., Stone, L. R., & Rice, C. W. (2010). Impacts of deficit irrigation on carbon sequestration and soil physical properties under no-till. *Soil Science Society of America Journal*, *74*(4), 1301-1309.

Bogale, A. A., Melash, A. A., & Percze, A. (2023). Symbiotic and Asymmetric Causality of the Soil Tillage System and Biochar Application on Soil Carbon Sequestration and Crop Production. *Soil Systems*, *7*(2), 48.

Çakmakçı, R., Salık, M. A., & Çakmakçı, S. (2023). Assessment and Principles of Environmentally Sustainable Food and Agriculture Systems. *Agriculture*, *13*(5), 1073.

Campos, R., Pires, G. F., & Costa, M. H. (2020). Soil carbon sequestration in rainfed and irrigated production systems in a new brazilian agricultural frontier. *Agriculture*, *10*(5), 156.

Chataut, G., Bhatta, B., Joshi, D., Subedi, K., & Kafle, K. (2023). Greenhouse gases emission from agricultural soil: A review. *Journal of Agriculture and Food Research*, *11*, 100533.

Cheng, H., Zhou, X., Dong, R., Wang, X., Liu, G., & Li, Q. (2023). Natural vegetation regeneration facilitated soil organic carbon sequestration and microbial community stability in the degraded karst ecosystem. *Catena*, *222*, 106856.

Csikós, N., & Tóth, G. (2023). Concepts of agricultural marginal lands and their utilisation: A review. *Agricultural Systems*, *204*, 103560.

Don, A., Seidel, F., Leifeld, J., Kätterer, T., Martin, M., Pellerin, S., ... & Chenu, C. (2024). Carbon sequestration in soils and climate change mitigation—Definitions and pitfalls. *Global Change Biology*, *30*(1), e16983.

Dong, L., & Huang, Z. (2023). Some evidence and new insights for feedback loops of human-nature interactions from a holistic Earth perspective. *Journal of Cleaner Production*, 139667.

Elkhlifi, Z., Iftikhar, J., Sarraf, M., Ali, B., Saleem, M. H., Ibranshahib, I., ... & Chen, Z. (2023). Potential role of biochar on capturing soil nutrients, carbon sequestration and managing environmental challenges: a review. *Sustainability*, *15*(3), 2527.

Elliott, S., Tucker, N. I., Shannon, D. P., & Tiansawat, P. (2023). The framework species method: harnessing natural regeneration to restore tropical forest ecosystems. *Philosophical Transactions of the Royal Society B*, *378*(1867), 20210073.

Engler, N., & Krarti, M. (2021). Review of energy efficiency in controlled environment agriculture. *Renewable and Sustainable Energy Reviews*, *141*, 110786.

Fajeriana, N., Ali, A., & Rini, R. P. (2024). Soil tillage and planting along the contour on sloping land to minimize the potential for erosion and surface runoff. *Sarhad Journal of Agriculture*, *40*(1), 82-93.

Fenner, R., & Cernev, T. (2021). The implications of the Covid-19 pandemic for delivering the Sustainable Development Goals. *Futures*, *128*, 102726.

Francaviglia, R., Almagro, M., & Vicente-Vicente, J. L. (2023). Conservation agriculture and soil organic carbon: principles, processes, practices and policy options. *Soil Systems*, *7*(1), 17.

Furtak, K., & Wolińska, A. (2023). The impact of extreme weather events as a consequence of climate change on the soil moisture and on the quality of the soil environment and agriculture–A review. *Catena*, *231*, 107378.

Gairhe, J. J., Adhikari, M., Ghimire, D., Khatri-Chhetri, A., & Panday, D. (2021). Intervention of climate-smart practices in wheat under rice-wheat cropping system in Nepal. *Climate*, *9*(2), 19.

Gawande, V., Saikanth, D. R. K., Sumithra, B. S., Aravind, S. A., Swamy, G. N., Chowdhury, M., & Singh, B. V. (2023). Potential of precision farming technologies for eco-friendly agriculture. *International Journal of Plant & Soil Science*, *35*(19), 101-112.

Ghimire, R., Shah, S. C., Dahal, K. R., Duxbury, J. M., & Lauren, J. G. (2008). Soil organic carbon sequestration by tillage and crop residue management in rice-wheat cropping system of Nepal. *Journal of the Institute of Agriculture and Animal Science*, *29*, 21-26.

Gholamahmadi, B., Jeffery, S., Gonzalez-Pelayo, O., Prats, S. A., Bastos, A. C., Keizer, J. J., & Verheijen, F. G. (2023). Biochar impacts on runoff and soil erosion by water: A systematic global scale meta-analysis. *Science of The Total Environment*, *871*, 161860.

Ghosh, S., Hossain, M. S., Voumik, L. C., Raihan, A., Ridzuan, A. R., & Esquivias, M. A. (2023). Unveiling the Spillover Effects of Democracy and Renewable Energy Consumption on the Environmental Quality of BRICS Countries: A New Insight from Different Quantile Regression Approaches. *Renewable Energy Focus*, 46, 222-235.

Gutierrez, S., Grados, D., Møller, A. B., de Carvalho Gomes, L., Beucher, A. M., Giannini-Kurina, F., ... & Greve, M. H. (2023). Unleashing the sequestration potential of soil organic carbon under climate and land use change scenarios in Danish agroecosystems. *Science of the Total Environment, 905*, 166921.

Haque, M. A., Rafii, M. Y., Yusoff, M. M., Ali, N. S., Yusuff, O., Datta, D. R., ... & Ikbal, M. F. (2021). Advanced breeding strategies and future perspectives of salinity tolerance in rice. *Agronomy, 11*(8), 1631.

Hartmann, M., & Six, J. (2023). Soil structure and microbiome functions in agroecosystems. *Nature Reviews Earth & Environment*, *4*(1), 4-18.

Harawa, R., Lehmann, J., Akinnifesi, F., Fernandes, E., & Kanyama-Phiri, G. (2006). Nitrogen dynamics in maize-based agroforestry systems as affected by landscape position in southern Malawi. *Nutrient Cycling in Agroecosystems*, *75*, 271-284.

Hati, K. M., Biswas, A. K., Somasundaram, J., Mohanty, M., Singh, R. K., Sinha, N. K., & Chaudhary, R. S. (2020). Soil organic carbon dynamics and carbon sequestration under conservation tillage in tropical vertisols. *Carbon management in tropical and sub-tropical terrestrial systems*, 201-212.

Himu, H. A., & Raihan, A. (2023). A review of the effects of intensive poultry production on the environment and human health. *Journal of Veterinary Science and Animal Husbandry, 11*(2), 203.

Ho, T. T., & Shimada, K. (2019). The effects of climate smart agriculture and climate change adaptation on the technical efficiency of rice farming—an empirical study in the Mekong Delta of Vietnam. *Agriculture, 9*(5), 99.

Holder, A. J., Clifton-Brown, J., Rowe, R., Robson, P., Elias, D., Dondini, M., ... & McCalmont, J. P. (2019). Measured and modelled effect of land-use change from temperate grassland to Miscanthus on soil carbon stocks after 12 years. *GCB Bioenergy*, *11*(10), 1173-1186.

Hondebrink, M. A., Cammeraat, L. H., & Cerdà, A. (2017). The impact of agricultural management on selected soil properties in citrus orchards in Eastern Spain: A comparison between conventional and organic citrus orchards with drip and flood irrigation. *Science of the Total Environment*, *581*, 153-160.

Imran, M. A., Ali, A., Ashfaq, M., Hassan, S., Culas, R., & Ma, C. (2018). Impact of Climate Smart Agriculture (CSA) practices on cotton production and livelihood of farmers in Punjab, Pakistan. *Sustainability, 10*(6), 2101.

Isfat, M., & Raihan, A. (2022). Current practices, challenges, and future directions of climate change adaptation in Bangladesh. *International Journal of Research Publication and Reviews,* 3(5), 3429-3437.

Jaafar, W. S. W. M., Maulud, K. N. A., Kamarulzaman, A. M. M., Raihan, A., Sah, S. M., Ahmad, A., Saad, S. N. M., Azmi, A. T. M., Syukri, N. K. A. J., & Khan, W. R. (2020). The influence of forest degradation on land surface temperature–a case study of Perak and Kedah, Malaysia. *Forests,* 11(6), 670.

Jakovac, C., Korys, K. A., Rodrigues, A. F., Ronix, A., Tubenchlak, F., Monteiro, L. M., ... & Latawiec, A. E. (2024). Meta-analysis of carbon stocks and biodiversity outcomes across Brazilian restored biomes. *Science of The Total Environment*, *906*, 167558.

Jat, H. S., Choudhary, M., Datta, A., Yadav, A. K., Meena, M. D., Devi, R., ... & Sharma, P. C. (2020). Temporal changes in soil microbial properties and nutrient dynamics under climate smart agriculture practices. *Soil and Tillage Research, 199*, 104595.

Jayara, A. S., Pandey, S., & Bhatt, M. K. (2023). Carbon sequestration as influenced by cropping practices: A review. *Agricultural Reviews*, *44*(4), 477-484.

Jayaraman, S., Dang, Y. P., Naorem, A., Page, K. L., & Dalal, R. C. (2021). Conservation agriculture as a system to enhance ecosystem services. *Agriculture*, *11*(8), 718.

Jubair, A. N. M., Rahman, M. S., Sarmin, I. J., & Raihan, A. (2023). Tree diversity and regeneration dynamics toward forest conservation and environmental sustainability: A case study from Nawabganj Sal Forest, Bangladesh. *Journal of Agriculture Sustainability and Environment*, 2(2), 1-22.

Kaczan, D., Arslan, A., & Lipper, L. (2013). Climate-smart agriculture? A review of current practice of agroforestry and conservation agriculture in Malawi and Zambia. ESA Working Paper No. 13-07. Food and Agriculture Organization (FAO).

Khan, N., Ma, J., Zhang, H., & Zhang, S. (2023b). Climate Change Impact on Sustainable Agricultural Growth: Insights from Rural Areas. *Atmosphere*, *14*(8), 1194.

Khan, Z., Yang, X. J., Fu, Y., Joseph, S., Khan, M. N., Khan, M. A., ... & Shen, H. (2023a). Engineered biochar improves nitrogen use efficiency via stabilizing soil water-stable macroaggregates and enhancing nitrogen transformation. *Biochar*, *5*(1), 52.

Khangura, R., Ferris, D., Wagg, C., & Bowyer, J. (2023). Regenerative Agriculture—A Literature Review on the Practices and Mechanisms Used to Improve Soil Health. *Sustainability*, *15*(3), 2338.

Khatri-Chhetri, A., Pant, A., Aggarwal, P. K., Vasireddy, V. V., & Yadav, A. (2019). Stakeholders prioritization of climate-smart agriculture interventions: Evaluation of a framework. *Agricultural systems*, *174*, 23-31.

Kroschewski, B., Richter, C., Baumecker, M., & Kautz, T. (2023). Effect of crop rotation and straw application in combination with mineral nitrogen fertilization on soil carbon sequestration in the Thyrow long-term experiment Thy_D5. *Plant and Soil*, *488*(1), 121-136.

Kudeyarov, V. N. (2023). Soil Respiration and Carbon Sequestration: A Review. *Eurasian Soil Science*, *56*(9), 1191-1200.

Kunmala, P., Jindaluang, W., & Darunsontaya, T. (2023). Distribution of Organic Carbon Fractions in Soil Aggregates and Their Contribution to Soil Aggregate Formation of Paddy Soils. *Communications in Soil Science and Plant Analysis*, *54*(10), 1350-1367.

Laubach, J., Hunt, J. E., Graham, S. L., Buxton, R. P., Rogers, G. N., Mudge, P. L., ... & Whitehead, D. (2023). Mitigation potential and trade-offs for nitrous oxide emissions and carbon balances of irrigated mixed-species and ryegrass-clover pastures. *Agricultural and Forest Meteorology*, *330*, 109310.

Lehtonen, H. S., Aakkula, J., Fronzek, S., Helin, J., Hildén, M., Huttunen, S., ... & Carter, T. R. (2021). Shared socioeconomic pathways for climate change research in Finland: co-developing extended SSP narratives for agriculture. *Regional Environmental Change*, *21*, 1-16.

Leng, Y., Liu, X., & Wang, X. (2023). Environmental regulation and high-quality agricultural development. *Plos one*, *18*(5), e0285687.

Lewis, J., & Rudnick, J. (2019). The policy enabling environment for climate smart agriculture: A case study of California. *Frontiers in Sustainable Food Systems*, *3*, 31.

Li, S., Xie, J., & Paudel, B. (2023). Do Ecological Restoration Projects Undermine Economic Performance? A Spatially Explicit Empirical Study in Loess Plateau, China. *Remote Sensing*, *15*(12), 3035.

Liu, C., Wang, Y., Chen, H., Sun, Q., Jiang, Q., & Wang, Z. (2023). High level of winter warming aggravates soil carbon, nitrogen loss and changes greenhouse gas emission characteristics in seasonal freeze-thaw farmland soil. *Science of The Total Environment*, *905*, 167180.

Loboguerrero, A. M., Campbell, B. M., Cooper, P. J., Hansen, J. W., Rosenstock, T., & Wollenberg, E. (2019). Food and earth systems: priorities for climate change adaptation and mitigation for agriculture and food systems. *Sustainability*, *11*(5), 1372.

Lockhart, S. R., Keller, C. K., Evans, R. D., Carpenter-Boggs, L. A., & Huggins, D. R. (2023). Soil CO2 in organic and no-till agroecosystems. *Agriculture, Ecosystems & Environment*, *349*, 108442.

Long, T. B., Blok, V., & Coninx, I. (2016). Barriers to the adoption and diffusion of technological innovations for climate-smart agriculture in Europe: evidence from the Netherlands, France, Switzerland and Italy. *Journal of cleaner production*, *112*, 9-21.

Longo, M., Delle Vedove, G., Grignani, C., Peressotti, A., Lazzaro, B., Cabrera, M., & Morari, F. (2023). How water table level influences C balance under different fertilization regimes. *Agricultural Water Management*, *289*, 108508.

Mäkipää, R., Abramoff, R., Adamczyk, B., Baldy, V., Biryol, C., Bosela, M., ... & Lehtonen, A. (2023). How does management affect soil C sequestration and greenhouse gas fluxes in boreal and temperate forests?–A review. *Forest Ecology and Management*, *529*, 120637.

Marvin, D. C., Sleeter, B. M., Cameron, D. R., Nelson, E., & Plantinga, A. J. (2023). Natural climate solutions provide robust carbon mitigation capacity under future climate change scenarios. *Scientific Reports*, *13*(1), 19008.

Meng, Y., Chen, H., Wang, B., Wu, Y., Wu, L., Bai, Y., & Chen, D. (2024). Soil biota associated with soil N cycling under multiple anthropogenic stressors in grasslands. *Applied Soil Ecology*, *193*, 105134.

Mengis, N., Paul, A., & Fernández-Méndez, M. (2023). Counting (on) blue carbon—Challenges and ways forward for carbon accounting of ecosystem-based carbon removal in marine environments. *PLOS Climate*, *2*(8), e0000148.

Mohanty, L. K., Singh, N. K., Raj, P., Prakash, A., Tiwari, A. K., Singh, V., & Sachan, P. (2024). Nurturing Crops, Enhancing Soil Health, and Sustaining Agricultural Prosperity Worldwide through Agronomy. *Journal of Experimental Agriculture International*, *46*(2), 46-67.

Moinet, G. Y., Hijbeek, R., van Vuuren, D. P., & Giller, K. E. (2023). Carbon for soils, not soils for carbon. *Global Change Biology*, *29*(9), 2384-2398.

Moradi, A., & Shabanian, N. (2023). Land-use change in the Zagros forests and its impact on soil carbon sequestration. *Environment, Development and Sustainability*, *25*(6), 5411-5426.

Mumah, E., Chen, Y., Hong, Y., & Okello, D. (2024). Machinery Adoption and Its Effect on Maize Productivity among Smallholder Farmers in Western Kenya: Evidence from the Chisel Harrow Tillage Practice. *Research on World Agricultural Economy*, *5*(1), 1-18.

Mupambwa, H. A., Hausiku, M. K., Nciizah, A. D., & Dube, E. (2019). The unique Namib desert-coastal region and its opportunities for climate smart agriculture: A review. *Cogent Food & Agriculture*, *5*(1), 1645258.

Navarro-Rosales, F., Fernández-Habas, J., Reyna-Bowen, L., Gómez, J. A., & Fernández-Rebollo, P. (2023). Subsoiling for planting trees in dehesa system: long-term effects on soil organic carbon. *Agroforestry Systems*, *97*(4), 699-710.

Neupane, A., Herndon, E. M., Whitman, T., Faiia, A. M., & Jagadamma, S. (2023). Manganese effects on plant residue decomposition and carbon distribution in soil fractions depend on soil nitrogen availability. *Soil Biology and Biochemistry*, *178*, 108964.

Ngaba, M. J. Y., Uwiragiye, Y., & Zhou, J. (2023). Patterns and controlling factors of soil carbon sequestration in nitrogen-limited and-rich forests in China—a meta-analysis. *PeerJ*, *11*, e14694.

Norderhaug, A., Clemmensen, K. E., Kardol, P., Thorhallsdottir, A. G., & Aslaksen, I. (2023). Carbon sequestration potential and the multiple functions of Nordic grasslands. *Climatic Change*, *176*(5), 55.

Nunes, L. J. (2023). The Rising Threat of Atmospheric CO2: A Review on the Causes, Impacts, and Mitigation Strategies. *Environments*, *10*(4), 66.

Pandao, M. R., Jejal, A. D., Shukla, E. P., Prabhumitrareddy, S., Rout, S., Baral, K., & Bhadani, M. (2023). Unlocking the Benefits of Carbon Sequestration for Enhancing Soil Health. *International Journal of Environment and Climate Change*, *13*(12), 1349-1359.

Patel, J. (2023). Cover Crops – The Sustainable Soil Health Approach. Retrieved from: https://www.linkedin.com/feed/update/urn:li:activity:6995352552502382592/ (Last Accessed: 12 February 2024).

Paul, C., Bartkowski, B., Dönmez, C., Don, A., Mayer, S., Steffens, M., ... & Helming, K. (2023). Carbon farming: Are soil carbon certificates a suitable tool for climate change mitigation?. *Journal of Environmental Management*, *330*, 117142.

Pereira, J. N., Mantovani, V. A., de Mello, C. R., Fornaro, A., & Vieira-Filho, M. (2023). Nitrogen atmospheric deposition driven by seasonal processes in a Brazilian region with agricultural background. *Environmental Science and Pollution Research*, *30*(13), 37174-37184.

Petrov, M., Nikolaeva, Z., & Dimitrov, A. (2023). The impact of anthropogenic activity on the global environment. *Science. Business. Society.*, *8*(2), 59-64.

Prangel, E., Kasari-Toussaint, L., Neuenkamp, L., Noreika, N., Karise, R., Marja, R., ... & Helm, A. (2023). Afforestation and abandonment of semi-natural grasslands lead to biodiversity loss and a decline in ecosystem services and functions. *Journal of Applied Ecology*, *60*(5), 825-836.

Puech, T., & Stark, F. (2023). Diversification of an integrated crop-livestock system: Agroecological and food production assessment at farm scale. *Agriculture, Ecosystems & Environment*, *344*, 108300.

Quintarelli, V., Radicetti, E., Allevato, E., Stazi, S. R., Haider, G., Abideen, Z., ... & Mancinelli, R. (2022). Cover crops for sustainable cropping systems: a review. *Agriculture*, *12*(12), 2076.

Raihan, A. (2023a). A comprehensive review of artificial intelligence and machine learning applications in energy consumption and production. *Journal of Technology Innovations and Energy*, 2(4), 1-26.

Raihan, A. (2023b). A concise review of technologies for converting forest biomass to bioenergy. *Journal of Technology Innovations and Energy*, 2(3), 10-36.

Raihan, A. (2023c). A Comprehensive Review of the Recent Advancement in Integrating Deep Learning with Geographic Information Systems. *Research Briefs on Information and Communication Technology Evolution*, *9*, 98-115.

Raihan, A. (2023d). Artificial intelligence and machine learning applications in forest management and biodiversity conservation. *Natural Resources Conservation and Research*, 6(2), 3825.

Raihan, A. (2023e). A review on the role of green vegetation in improving urban environmental quality. Eco Cities, 4(2), 2387.

Raihan, A. (2023f). A review of agroforestry as a sustainable and resilient agriculture. *Journal of Agriculture Sustainability and Environment*, 2(1), 49-72.

Raihan, A. (2023g). A review of tropical blue carbon ecosystems for climate change mitigation. *Journal of Environmental Science and Economics*, *2*(4), 14-36.

Raihan, A. (2023h). Sustainable development in Europe: A review of the forestry sector's social, environmental, and economic dynamics. *Global Sustainability Research*, 2(3), 72-92.

Raihan, A. (2023i). A review on the integrative approach for economic valuation of forest ecosystem services. *Journal of Environmental Science and Economics*, 2(3), 1-18.

Raihan, A. (2023j). Nexus between Greenhouse gas emissions and its determinants: the role of renewable energy and technological innovations towards green development in South Korea. *Innovation and Green Development*, 2, 100066.

Raihan, A. (2023k). An Overview of the Implications of Artificial Intelligence (AI) in Sixth Generation (6G) Communication Network. *Research Briefs on Information and Communication Technology Evolution, 9*, 120-146.

Raihan, A. (2023l). Nexus between economy, technology, and ecological footprint in China. *Journal of Economy and Technology*, 1, 94-107.

Raihan, A. (2023m). Nexus between economic growth, natural resources rents, trade globalization, financial development, and carbon emissions toward environmental sustainability in Uruguay. *Electronic Journal of Education, Social Economics and Technology*, 4(2), 55-65.

Raihan, A. (2023n). Economy-energy-environment nexus: the role of information and communication technology towards green development in Malaysia. *Innovation and Green Development*, 2, 100085.

Raihan, A. (2023o). Energy, economy, and environment nexus: New evidence from China. *Energy Technologies and Environment, 1*(1), 68-80.

Raihan, A. (2023p). An overview of the energy segment of Indonesia: present situation, prospects, and forthcoming advancements in renewable energy technology. *Journal of Technology Innovations and Energy*, 2(3), 37-63

Raihan, A. (2023q). Exploring Environmental Kuznets Curve and Pollution Haven Hypothesis in Bangladesh: The Impact of Foreign Direct Investment. *Journal of Environmental Science and Economics*, 2(1), 25-36.

Raihan, A. (2023r). Green energy and technological innovation towards a low-carbon economy in Bangladesh. *Green and Low-Carbon Economy*. https://doi.org/10.47852/bonviewGLCE32021340

Raihan, A. (2023s). The influences of renewable energy, globalization, technological innovations, and forests on emission reduction in Colombia. *Innovation and Green Development*, 2, 100071.

Raihan, A. (2023t). The contribution of economic development, renewable energy, technical advancements, and forestry to Uruguay's objective of becoming carbon neutral by 2030. *Carbon Research*, 2, 20.

Raihan, A. (2023u). A review of the global climate change impacts, adaptation strategies, and mitigation options in the socio-economic and environmental sectors. *Journal of Environmental Science and Economics*, 2(3), 36-58.

Raihan, A. (2023v). Toward sustainable and green development in Chile: dynamic influences of carbon emission reduction variables. *Innovation and Green Development*, 2, 100038.

Raihan, A. (2023w). An econometric evaluation of the effects of economic growth, energy use, and agricultural value added on carbon dioxide emissions in Vietnam. *Asia-Pacific Journal of Regional Science*, 7, 665-696.

Raihan, A. (2023x). The dynamic nexus between economic growth, renewable energy use, urbanization, industrialization, tourism, agricultural productivity, forest area, and carbon dioxide emissions in the Philippines. *Energy Nexus*, 9, 100180.

Raihan, A. (2023y). An econometric assessment of the relationship between meat consumption and greenhouse gas emissions in the United States. *Environmental Processes*, 10(2), 32.

Raihan, A. (2023z). The influence of meat consumption on greenhouse gas emissions in Argentina. *Resources, Conservation & Recycling Advances*, 19, 200183.

Raihan, A. (2024a). A review of the digitalization of the small and medium enterprises (SMEs) toward sustainability. *Global Sustainability Research*, 3(2), 1-16.

Raihan, A. (2024b). A Systematic Review of Geographic Information Systems (GIS) in Agriculture for Evidence-Based Decision Making and Sustainability. *Global Sustainability Research*, 3(1), 1-24.

Raihan, A. (2024c). The interrelationship amid carbon emissions, tourism, economy, and energy use in Brazil. *Carbon Research*, 3, 11.

Raihan, A. (2024d). Influences of foreign direct investment and carbon emission on economic growth in Vietnam. *Journal of Environmental Science and Economics*, 3(1), 1-17.

Raihan, A. (2024e). Energy, economy, financial development, and ecological footprint in Singapore. *Energy Economics Letters*, 11(1), 29-40.

Raihan, A. (2024f). The influences of economic progress, natural resources, and capitalization on financial development in the United States. *Innovation and Green Development*, 3(2), 100146.

Raihan, A. (2024g). The influence of tourism on the road to achieving carbon neutrality and environmental sustainability in Malaysia: the role of renewable energy. *Sustainability Analytics and Modeling, 4*, 100028.

Raihan, A. (2024h). The potential of agroforestry in South Asian countries towards achieving the climate goals. *Asian Journal of Forestry 8*(1), 1-17.

Raihan, A., & Bari, A. B. M. M. (2024). Energy-economy-environment nexus in China: The role of renewable energies toward carbon neutrality. *Innovation and Green Development*, 3(3), 100139.

Raihan, A., Begum, R. A., & Said, M. N. M. (2021b). A meta-analysis of the economic value of forest carbon stock. *Geografia–Malaysian Journal of Society and Space*, 17(4), 321-338.

Raihan, A., Begum, R. A., Said, M. N. M., & Abdullah, S. M. S. (2018). Climate change mitigation options in the forestry sector of Malaysia. *Journal Kejuruteraan*, 1, 89-98.

Raihan, A., Begum, R. A., Said, M. N. M., & Abdullah, S. M. S. (2019). A review of emission reduction potential and cost savings through forest carbon sequestration. *Asian Journal of Water, Environment and Pollution*, 16(3), 1-7.

Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2021a). Assessment of carbon stock in forest biomass and emission reduction potential in Malaysia. *Forests*, 12(10), 1294.

Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2022b). Relationship between economic growth, renewable energy use, technological innovation, and carbon emission toward achieving Malaysia's Paris agreement. *Environment Systems and Decisions*, 42, 586-607.

Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2022h). Dynamic impacts of energy use, agricultural land expansion, and deforestation on CO_2 emissions in Malaysia. *Environmental and Ecological Statistics*, 29, 477-507.

Raihan, A., & Bijoy, T. R. (2023). A review of the industrial use and global sustainability of Cannabis sativa. *Global Sustainability Research*, 2(4), 1-29.

Raihan, A., Farhana, S., Muhtasim, D. A., Hasan, M. A. U., Paul, A., & Faruk, O. (2022c). The nexus between carbon emission, energy use, and health expenditure: empirical evidence from Bangladesh. *Carbon Research*, 1(1), 30.

Raihan, A., & Himu, H. A. (2023). Global impact of COVID-19 on the sustainability of livestock production. *Global Sustainability Research*, 2(2), 1-11.

Raihan, A., Ibrahim, S., & Muhtasim, D. A. (2023i). Dynamic impacts of economic growth, energy use, tourism, and agricultural productivity on carbon dioxide emissions in Egypt. *World Development Sustainability*, 2, 100059.

Raihan, A., Muhtasim, D. A., Farhana, S., Hasan, M. A. U., Paul, A., & Faruk, O. (2022d). Toward environmental sustainability: Nexus between tourism, economic growth, energy use and carbon emissions in Singapore. *Global Sustainability Research*, 1(2), 53-65.

Raihan, A., Muhtasim, D. A., Farhana, S., Hasan, M. A. U., Pavel, M. I., Faruk, O., Rahman, M., & Mahmood, A. (2022i). Nexus between economic growth, energy use, urbanization, agricultural productivity, and carbon dioxide emissions: New insights from Bangladesh. *Energy Nexus*, 8, 100144.

Raihan, A., Muhtasim, D. A., Farhana, S., Hasan, M. A. U., Pavel, M. I., Faruk, O., Rahman, M., & Mahmood, A. (2023j). An econometric analysis of Greenhouse gas emissions from different agricultural factors in Bangladesh. *Energy Nexus*, 9, 100179.

Raihan, A., Muhtasim, D. A., Farhana, S., Rahman, M., Hasan, M. A. U., Paul, A., & Faruk, O. (2023k). Dynamic linkages between environmental factors and carbon emissions in Thailand. *Environmental Processes*, 10, 5.

Raihan, A., Muhtasim, D. A., Farhana, S., Pavel, M. I., Faruk, O., & Mahmood, A. (2022a). Nexus between carbon emissions, economic growth, renewable energy use, urbanization, industrialization, technological innovation, and forest area towards achieving environmental sustainability in Bangladesh. *Energy and Climate Change*, 3, 100080.

Raihan, A., Muhtasim, D. A., Khan, M. N. A., Pavel, M. I., & Faruk, O. (2022e). Nexus between carbon emissions, economic growth, renewable energy use, and technological innovation towards achieving environmental sustainability in Bangladesh. *Cleaner Energy Systems*, 3, 100032.

Raihan, A., Muhtasim, D. A., Pavel, M. I., Faruk, O., & Rahman, M. (2022f). Dynamic impacts of economic growth, renewable energy use, urbanization, and tourism on carbon dioxide emissions in Argentina. *Environmental Processes*, 9, 38.

Raihan, A., Muhtasim, D. A., Pavel, M. I., Faruk, O., & Rahman, M. (2022j). An econometric analysis of the potential emission reduction components in Indonesia. *Cleaner Production Letters*, 3, 100008.

Raihan, A., Pavel, M. I., Muhtasim, D. A., Farhana, S., Faruk, O., & Paul, A. (2023a). The role of renewable energy use, technological innovation, and forest cover toward green development: Evidence from Indonesia. *Innovation and Green Development*, 2(1), 100035.

Raihan, A., Pereira, J. J., Begum, R. A., & Rasiah, R. (2023b). The economic impact of water supply disruption from the Selangor River, Malaysia. *Blue-Green Systems*, *5*(2), 102-120.

Raihan, A., Rashid, M., Voumik, L. C., Akter, S., & Esquivias, M. A. (2023c). The dynamic impacts of economic growth, financial globalization, fossil fuel energy, renewable energy, and urbanization on load capacity factor in Mexico. *Sustainability*, 15(18), 13462.

Raihan, A., Ridwan, M., Tanchangya, T., Rahman, J., & Ahmad, S. (2023d). Environmental Effects of China's Nuclear Energy within the Framework of Environmental Kuznets Curve and Pollution Haven Hypothesis. *Journal of Environmental and Energy Economics*, 2(1), 1-12.

Raihan, A., & Said, M. N. M. (2022). Cost–benefit analysis of climate change mitigation measures in the forestry sector of Peninsular Malaysia. *Earth Systems and Environment*, 6(2), 405-419.

Raihan, A., Tanchangya, T., Rahman, J., & Ridwan, M. (2024c). The Influence of Agriculture, Renewable Energy, International Trade, and Economic Growth on India's Environmental Sustainability. *Journal of Environmental and Energy Economics*, 3(1), 37-53.

Raihan, A., Tanchangya, T., Rahman, J., Ridwan, M., & Ahmad, S. (2022g). The influence of Information and Communication Technologies, Renewable Energies and Urbanization toward Environmental Sustainability in China. *Journal of Environmental and Energy Economics*, 1(1), 11–23.

Raihan, A., & Tuspekova, A. (2022a). Role of economic growth, renewable energy, and technological innovation to achieve environmental sustainability in Kazakhstan. *Current Research in Environmental Sustainability*, 4, 100165.

Raihan, A., & Tuspekova, A. (2022b). The nexus between economic growth, energy use, urbanization, tourism, and carbon dioxide emissions: New insights from Singapore. *Sustainability Analytics and Modeling*, 2, 100009.

Raihan, A., & Tuspekova, A. (2022c). Dynamic impacts of economic growth, renewable energy use, urbanization, industrialization, tourism, agriculture, and forests on carbon emissions in Turkey. *Carbon Research,* 1(1), 20.

Raihan, A., & Tuspekova, A. (2022d). Towards sustainability: dynamic nexus between carbon emission and its determining factors in Mexico. *Energy Nexus,* 8, 100148.

Raihan, A., & Tuspekova, A. (2022e). Dynamic impacts of economic growth, energy use, urbanization, tourism, agricultural value-added, and forested area on carbon dioxide emissions in Brazil. *Journal of Environmental Studies and Sciences,* 12(4), 794-814.

Raihan, A., & Tuspekova, A. (2022f). Dynamic impacts of economic growth, energy use, urbanization, agricultural productivity, and forested area on carbon emissions: new insights from Kazakhstan. *World Development Sustainability,* 1, 100019.

Raihan, A., & Tuspekova, A. (2022g). Nexus between emission reduction factors and anthropogenic carbon emissions in India. *Anthropocene Science,* 1(2), 295-310.

Raihan, A., & Tuspekova, A. (2022h). Nexus between economic growth, energy use, agricultural productivity, and carbon dioxide emissions: new evidence from Nepal. *Energy Nexus,* 7, 100113.

Raihan, A., & Tuspekova, A. (2022i). The nexus between economic growth, renewable energy use, agricultural land expansion, and carbon emissions: new insights from Peru. *Energy Nexus,* 6, 100067.

Raihan, A., & Tuspekova, A. (2022j). Nexus between energy use, industrialization, forest area, and carbon dioxide emissions: new insights from Russia. *Journal of Environmental Science and Economics,* 1(4), 1-11.

Raihan, A., & Tuspekova, A. (2022k). Toward a sustainable environment: Nexus between economic growth, renewable energy use, forested area, and carbon emissions in Malaysia. *Resources, Conservation & Recycling Advances,* 15, 200096.

Raihan, A., & Tuspekova, A. (2023a). The role of renewable energy and technological innovations toward achieving Iceland's goal of carbon neutrality by 2040. *Journal of Technology Innovations and Energy*, 2(1), 22-37.

Raihan, A., & Tuspekova, A. (2023b). Towards net zero emissions by 2050: the role of renewable energy, technological innovations, and forests in New Zealand. *Journal of Environmental Science and Economics*, 2(1), 1-16.

Raihan, A., & Voumik, L. C. (2022a). Carbon emission dynamics in India due to financial development, renewable energy utilization, technological innovation, economic growth, and urbanization. *Journal of Environmental Science and Economics*, 1(4), 36-50.

Raihan, A., & Voumik, L. C. (2022b). Carbon emission reduction potential of renewable energy, remittance, and technological innovation: empirical evidence from China. *Journal of Technology Innovations and Energy*, 1(4), 25-36.

Raihan, A., Voumik, L. C., Akter, S., Ridzuan, A. R., Fahlevi, M., Aljuaid, M., & Saniuk, S. (2024a). Taking flight: Exploring the relationship between air transport and Malaysian economic growth. *Journal of Air Transport Management*, 115, 102540.

Raihan, A., Voumik, L.C., Esquivias, M.A., Ridzuan, A.R., Yusoff, N.Y.M., Fadzilah, A.H.H., & Malayaranjan, S. (2023e). Energy trails of tourism: analyzing the relationship between tourist arrivals and energy consumption in Malaysia. *GeoJournal of Tourism and Geosites*, 51, 1786–1795.

Raihan, A., Voumik, L. C., Mohajan, B., Rahman, M. S., Zaman, M. R. (2023l). Economy-energy-environment nexus: the potential of agricultural value-added toward achieving China's dream of carbon neutrality. *Carbon Research,* 2, 43.

Raihan, A., Voumik, L. C., Rahman, M. H., & Esquivias, M. A. (2023f). Unraveling the interplay between globalization, financial development, economic growth, greenhouse gases, human capital, and renewable energy uptake in Indonesia: multiple econometric approaches. *Environmental Science and Pollution Research*, 30, 119117-119133.

Raihan, A., Voumik, L. C., Ridwan, M., Ridzuan, A. R., Jaaffar, A. H., Yusof, N. Y. M. (2023g). From growth to green: navigating the complexities of economic development, energy sources, health spending, and carbon emissions in Malaysia. Energy Reports, 10, 4318-4331.

Raihan, A., Voumik, L. C., Yusma, N., & Ridzuan, A. R. (2023h). The nexus between international tourist arrivals and energy use towards sustainable tourism in Malaysia. *Frontiers in Environmental Science*, 11, 575.

Raihan, A., Zimon, G., Alam, M. M., Khan, M. R., & Sadowska, B. (2024b). Nexus between Nuclear Energy, Economic Growth, and Greenhouse Gas Emissions in India. *International Journal of Energy Economics and Policy*, 14(2), 172-182.

Ramesh, T., Bolan, N. S., Kirkham, M. B., Wijesekara, H., Kanchikerimath, M., Rao, C. S., ... & Freeman II, O. W. (2019). Soil organic carbon dynamics: Impact of land use changes and management practices: A review. *Advances in agronomy*, *156*, 1-107.

Rattan, L. A. L. (2023). Carbon farming by recarbonization of agroecosystems. *Pedosphere*, *33*(5), 676-679.

Reichenbach, M., Fiener, P., Hoyt, A., Trumbore, S., Six, J., & Doetterl, S. (2023). Soil carbon stocks in stable tropical landforms are dominated by geochemical controls and not by land use. *Global Change Biology*, *29*(9), 2591-2607.

Ren, Z., Han, X., Feng, H., Wang, L., Ma, G., Li, J., ... & Wang, C. (2024). Long-term conservation tillage improves soil stoichiometry balance and crop productivity based on a 17-year experiment in a semi-arid area of northern China. *Science of the Total Environment*, *908*, 168283.

Ridwan, M., Raihan, A., Ahmad, S., Karmakar, S., & Paul, P. (2023). Environmental Sustainability in France: The Role of Alternative and Nuclear Energy, Natural Resources, and Government Spending. *Journal of Environmental and Energy Economics*, 2(2), 1-16.

Rodrigues, C. I. D., Brito, L. M., & Nunes, L. J. (2023). Soil carbon sequestration in the context of climate change mitigation: A review. *Soil Systems*, *7*(3), 64.

Roy, P., Pal, S. C., Chakrabortty, R., Saha, A., & Chowdhuri, I. (2023). A systematic review on climate change and geo-environmental factors induced land degradation: Processes, policy-practice gap and its management strategies. *Geological Journal*, *58*(9), 3487-3514.

Ruehr, S., Keenan, T. F., Williams, C., Zhou, Y., Lu, X., Bastos, A., ... & Terrer, C. (2023). Evidence and attribution of the enhanced land carbon sink. *Nature Reviews Earth & Environment*, *4*(8), 518-534.

Saarikoski, H., Huttunen, S., & Mela, H. (2023). Deliberating just transition: lessons from a citizens' jury on carbon-neutral transport. *Sustainability: Science, Practice and Policy*, *19*(1), 2261341.

Scavo, A., Fontanazza, S., Restuccia, A., Pesce, G. R., Abbate, C., & Mauromicale, G. (2022). The role of cover crops in improving soil fertility and plant nutritional status in temperate climates. A review. *Agronomy for Sustainable Development*, *42*(5), 93.

Seitz, D., Fischer, L. M., Dechow, R., Wiesmeier, M., & Don, A. (2023). The potential of cover crops to increase soil organic carbon storage in German croplands. *Plant and soil*, *488*(1), 157-173.

Shah, S. T., Basit, A., Mohamed, H. I., Ullah, I., Sajid, M., & Sohrab, A. (2023). Use of mulches in various tillage conditions reduces the greenhouse gas emission—an overview. *Gesunde Pflanzen*, *75*(3), 455-477.

Sierra, C. A., Ahrens, B., Bolinder, M. A., Braakhekke, M. C., von Fromm, S., Kätterer, T., ... & Wang, G. (2024). Carbon sequestration in the subsoil and the time required to stabilize carbon for climate change mitigation. *Global Change Biology*, *30*(1), e17153.

Singh, A., Ghimire, R., & Acharya, P. (2024). Soil profile carbon sequestration and nutrient responses varied with cover crops in irrigated forage rotations. *Soil and Tillage Research*, *238*, 106020.

Stoner, S., Trumbore, S. E., González-Pérez, J. A., Schrumpf, M., Sierra, C. A., Hoyt, A. M., ... & Doetterl, S. (2023). Relating mineral–organic matter stabilization mechanisms to carbon quality and age distributions using ramped thermal analysis. *Philosophical Transactions of the Royal Society A*, *381*(2261), 20230139.

Subramanian, A., Nagarajan, A. M., Vinod, S., Chakraborty, S., Sivagami, K., Theodore, T., ... & Mangesh, V. L. (2023). Long-term impacts of climate change on coastal and transitional eco-systems in India: an overview of its current status, future projections, solutions, and policies. *RSC advances*, *13*(18), 12204-12228.

Sultana, T., Hossain, M. S., Voumik, L. C., & Raihan, A. (2023). Democracy, green energy, trade, and environmental progress in South Asia: Advanced quantile regression perspective. *Heliyon*, 9(10), e20488.

Sultana, T., Hossain, M. S., Voumik, L. C., & Raihan, A. (2023). Does globalization escalate the carbon emissions? Empirical evidence from selected next-11 countries. *Energy Reports*, 10, 86-98.

Sünnemann, M., Beugnon, R., Breitkreuz, C., Buscot, F., Cesarz, S., Jones, A., ... & Eisenhauer, N. (2023). Climate change and cropland management compromise soil integrity and multifunctionality. *Communications Earth & Environment*, *4*(1), 394.

Tadesse, M., Simane, B., Abera, W., Tamene, L., Ambaw, G., Recha, J. W., ... & Solomon, D. (2021). The effect of climate-smart agriculture on soil fertility, crop yield, and soil carbon in southern Ethiopia. *Sustainability*, *13*(8), 4515.

Tan, S. S., & Kuebbing, S. E. (2023). A synthesis of the effect of regenerative agriculture on soil carbon sequestration in Southeast Asian croplands. *Agriculture, Ecosystems & Environment*, *349*, 108450.

Thapa, V. R., Ghimire, R., Adhikari, K. P., & Lamichhane, S. (2023). Soil organic carbon sequestration potential of conservation agriculture in arid and semi-arid regions: A review. *Journal of Arid Environments*, *217*, 105028.

Tian, D., Xiang, Y., Seabloom, E., Wang, J., Jia, X., Li, T., ... & Niu, S. (2023). Soil carbon sequestration benefits of active versus natural restoration vary with initial carbon content and soil layer. *Communications Earth & Environment*, *4*(1), 83.

Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., & Baumecker, M. (2013). Irrigation, soil organic carbon and N 2 O emissions. A review. *Agronomy for Sustainable Development*, *33*, 733-749.

Vaidya, S., Hoffmann, M., Holz, M., Macagga, R., Monzon, O., Thalmann, M., ... & Augustin, J. (2023). Similar strong impact of N fertilizer form and soil erosion state on N2O emissions from croplands. *Geoderma*, *429*, 116243.

Vechi, N. T., Mellqvist, J., Samuelsson, J., Offerle, B., & Scheutz, C. (2023). Ammonia and methane emissions from dairy concentrated animal feeding operations in California, using mobile optical remote sensing. *Atmospheric Environment*, *293*, 119448.

Voumik, L. C., Islam, M. J., & Raihan, A. (2022). Electricity production sources and CO_2 emission in OECD countries: static and dynamic panel analysis. *Global Sustainability Research*, 1(2), 12-21.

Voumik, L. C., Mimi, M. B., & Raihan, A. (2023a). Nexus between urbanization, industrialization, natural resources rent, and anthropogenic carbon emissions in South Asia: CS-ARDL approach. *Anthropocene Science*, 2(1), 48-61.

Voumik, L. C., Rahman, M. H., Rahman, M. M., Ridwan, M., Akter, S., & Raihan, A. (2023b). Toward a sustainable future: Examining the interconnectedness among Foreign Direct Investment (FDI), urbanization, trade openness, economic growth, and energy usage in Australia. Regional Sustainability, 4, 405-415.

Voumik, L. C., Ridwan, M., Rahman, M. H., & Raihan, A. (2023c). An Investigation into the Primary Causes of Carbon Dioxide Releases in Kenya: Does Renewable Energy Matter to Reduce Carbon Emission?. *Renewable Energy Focus*, 47, 100491.

Wang, J., Yu, G., Han, L., Yao, Y., Sun, M., & Yan, Z. (2024). Ecosystem carbon exchange across China's coastal wetlands: Spatial patterns, mechanisms, and magnitudes. *Agricultural and Forest Meteorology*, *345*, 109859.

Wang, Y., Wu, P., Qiao, Y., Li, Y., Liu, S., Gao, C., ... & Wang, T. (2023). The potential for soil C sequestration and N fixation under different planting patterns depends on the carbon and nitrogen content and stability of soil aggregates. *Science of the Total Environment*, *897*, 165430.

Wani, O. A., Kumar, S. S., Hussain, N., Wani, A. I. A., Subhash, B. A. B. U., Parvej, A. L. A. M., ... & Mansoor, S. (2023). Multi-scale processes influencing global carbon storage and land-carbon-climate nexus: A critical review. *Pedosphere*, *33*(2), 250-267.

Waring, E. R., Pederson, C., Lagzdins, A., Clifford, C., & Helmers, M. J. (2024). Water and soil quality respond to no-tillage and cover crops differently through 10 years of implementation. *Agriculture, Ecosystems & Environment*, *360*, 108791.

Whitehead, D. (2020). Management of grazed landscapes to increase soil carbon stocks in temperate, dryland grasslands. Front Sustain Food Syst 4.

Wiltshire, S., & Beckage, B. (2022). Soil carbon sequestration through regenerative agriculture in the US state of Vermont. *PLOS Climate*, *1*(4), e0000021.

Xiao, L., You, Z., Zhang, H., Xie, Z., Zhao, R., & Greenwood, P. (2023). Effects of conservation practices on global wind erosion control: Evidence from experimental data. *Land Degradation & Development*, *34*(14), 4386-4398.

Yin, L., Tao, F., Chen, Y., Wang, Y., Ciais, P., & Smith, P. (2023). Novel cropping-system strategies in China can increase plant protein with higher economic value but lower greenhouse gas emissions and water use. *One Earth*, *6*(5), 560-572.

You, Y., Tian, H., Pan, S., Shi, H., Lu, C., Batchelor, W. D., ... & Reilly, J. (2024). Net greenhouse gas balance in US croplands: How can soils be part of the climate solution?. *Global Change Biology*, *30*(1), e17109.

Zhang, X., Wang, J., Feng, X., Yang, H., Li, Y., Yakov, K., ... & Li, F. M. (2023). Effects of tillage on soil organic carbon and crop yield under straw return. *Agriculture, Ecosystems & Environment*, *354*, 108543.

Zhao, H., Di, L., Guo, L., Zhang, C., & Lin, L. (2023). An Automated Data-Driven Irrigation Scheduling Approach Using Model Simulated Soil Moisture and Evapotranspiration. *Sustainability*, *15*(17), 12908.

Zilberman, D., Lipper, L., McCarthy, N., & Gordon, B. (2018). Innovation in response to climate change. *Climate smart agriculture: building resilience to climate change*, 49-74.

Zuo, W., Gu, B., Zou, X., Peng, K., Shan, Y., Yi, S., ... & Bai, Y. (2023). Soil organic carbon sequestration in croplands can make remarkable contributions to China's carbon neutrality. *Journal of Cleaner Production*, *382*, 135268.

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https://doi.org/10.56556/jase.v2i2.877

RESEARCH ARTICLE

Intra and Interspecific Relation of Tree Species Aspects of Seed Biometry, Phenology, Seed Dispersion, and Germination

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Abstract

Bangladesh, with its dense population and diverse ecological landscape, embodies a unique environmental tapestry. This study explores the intricate interplay between tree phenology, seed dispersal seed germination, and biometric characteristics within the context of Bangladesh's rich biodiversity. Through field research conducted from 2020 to 2023 in the Chittagong division, we investigated species such as *Artocarpus chama*, *Avicennia officinalis*, *Terminalia arjuna*, *Terminalia bellirica*, and *Terminalia chebula*. The findings reveal significant variations in seed morphology, phenology, germination, and ecological roles among these species. Furthermore, through dendrogram analysis and principal component analysis (PCA), we elucidate the underlying patterns and relationships governing biometric variability. These insights provide valuable contributions to our understanding of ecological processes and inform conservation strategies aimed at preserving Bangladesh's forest tree biodiversity.

Keywords: Seed biometry; Phenology; Seed dispersion; Seed quality; Germination

Introduction

Bangladesh, a country marked by its dense population and rich biodiversity, presents a unique environmental canvas. With an astounding density of 1,119 people per square kilometer (Miah et al., 2023), it covers approximately 11% of its total land area with forests, comprising three distinct types: evergreen, mixed evergreen, and deciduous. This diversity in forest types contributes to the nation's extensive biodiversity, boasting around 500 timber species among its flora (Reza & Kamrul, 2012; Uddin et al., 2020). Such ecological richness plays a pivotal role in the global effort to combat warming, offering a natural buffer against climate change (Islam et al., 2022). However, this biodiversity is under threat, with an increasing number of species becoming critically endangered (Rahman et al., 2018). The causes of species degradation in Bangladesh are multifaceted, involving both abiotic and biotic factors that influence species distribution. These factors are intertwined with the ecological processes (Crouzeilles et al., 2016) that sustain the country's rich biodiversity. For instance, phenology, the study of periodic plant and animal life cycle events, seed size, types, and dispersal rates are crucial for understanding seed germination and the natural regeneration of species (Lima et al., 2020). These elements are essential for the maintenance and restoration of ecological balance within the forests (Islam et al., 2022).

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The challenge of preserving Bangladesh's biodiversity is significant, given the pressures of human population density and the consequent habitat destruction (Roy et al., 2015). Conservation efforts must prioritize the understanding of ecological interactions, such as the relationships between species and their physical environment, and how these are affected by human activity. Protecting the natural habitats, promoting sustainable land use practices, and fostering a deeper understanding of the ecological importance of biodiversity are critical steps toward mitigating the effects of global warming and ensuring the survival of critically endangered species (Hossain et al., 2020). The path forward involves a comprehensive approach that integrates conservation, education, and sustainable development to safeguard the natural heritage of Bangladesh for future generations (Islam et al., 2022).

Artocarpus chama, a species within the genus Artocarpus, is a remarkable deciduous tree known for its straight bole and significant stature (Krupa et al., 2022), reaching heights of 30-40 meters with a diameter at breast height (DBH) of 1-1.5 meters (Roy et al., 2015). This tree exemplifies the diversity and utility found within its family, contributing not only to the ecological framework of its native habitats but also offering benefits to wildlife, particularly birds that find its fruits edible (Kumar et al., 2017).

Preferring shaded environments, *Artocarpus chama* thrives in moist conditions, indicative of its adaptation to specific ecological niches that favor moisture and reduced direct sunlight. This preference suggests that the tree plays a crucial role in its ecosystem, likely contributing to the structure and function of the forest layers by providing canopy coverage or acting as an understory component in more densely forested areas (Jagtap & Bapat, 2010). The fruit of *Artocarpus chama* serves as a food source for a variety of bird species, facilitating seed dispersal through ornithochory (seed dispersal by birds) (Lima et al., 2020). This ecological interaction highlights the tree's role in its ecosystem, promoting biodiversity through its contribution to the diet of birds and the subsequent dispersal of its seeds, which is crucial for the regeneration of forests and the maintenance of healthy ecological systems (Getzner & Islam, 2020). Conservation of *Artocarpus chama* and its habitat is essential for preserving the biodiversity of the regions it inhabits (Islam et al., 2022). Understanding the ecological requirements and the role of this tree species in its natural environment helps inform conservation strategies (Mengist & Soromessa, 2019). Protecting the moist and shaded habitats preferred by *Artocarpus chama* ensures not only the survival of this species but also the myriad forms of life that depend on it, directly or indirectly, for sustenance and habitat (Ashrafuzzaman et al., 2021).

Avicennia officinalis, a vital mangrove species, typically reaches a height of 10-13 meters with a diameter at breast height (DBH) of 18-25 cm. This light-demanding tree thrives in the unique intertidal zones of mangrove forests (Mehta et al., 2021), requiring regular inundation by tidal waters to sustain its growth and physiological processes. The species is adapted to saline environments, showcasing remarkable resilience to the challenging conditions characteristic of mangrove ecosystems. Its roots are equipped with specialized pneumatophores, which facilitate oxygen intake in waterlogged soils, demonstrating a fascinating adaptation to its habitat. The presence of *Avicennia officinalis* is crucial for maintaining the ecological balance of mangrove forests, providing essential services such as coastline stabilization, carbon sequestration, and serving as a nursery for various marine species (Mitra et al., 2023). Conservation efforts for these mangrove habitats are essential to ensure the survival of *Avicennia officinalis* and the myriad of life forms that depend on this ecosystem for their survival (Sultana et al., 2021).

Terminalia arjuna, a member of the Combretaceae family, is an evergreen tree distinguished by its extensive use in traditional medicine and it’s ecological significance (Getzner and Islam, 2020). Noted for its shade-bearing capacity(Hasnat et al.,2016), it thrives in various environmental conditions (Amalraj & Gopi, 2017; Basha et al., 2017;Crouzeilles et al.,2016), contributing to the biodiversity of the areas it inhabits. Its broad, dense canopy provides essential habitat and protection for numerous species, while its striking appearance and robust stature add aesthetic value to landscapes (Roy et al., 2015). *Terminalia arjuna* plays a pivotal role in ecological balance, supporting a range of organisms and processes within its ecosystem, making it a valuable component of its native habitats.

Terminalia bellirica, a deciduous and light-demanding tree, holds significant value beyond its ecological role known for its large stature and distinctive fruit (Saxena et al., 2013; Das et al.,2020), it is widely utilized in traditional practices, particularly in the production of dyes and inks. This usage stems from the rich tannins and pigments found within its fruit and bark, offering a natural source for these substances. The tree's contributions to local ecosystems (Islam et al., 2022), combined with its utility in crafts and traditional industries, underscore its importance in both natural and human-made environments. Its cultivation and sustainable harvesting are key to preserving the balance between its ecological importance and cultural uses. *Terminalia chebula*, a member of the Combretaceae family, reaches an impressive height of up to 30 meters with a diameter at breast height (DBH) of around 130 cm. This substantial tree is renowned for its medicinal properties and slow seedling growth (Basha et al., 2017; Das et al., 2020; Sairkar et al., 2017; Saxena et al., 2013), which underscores its need for conservation and mindful cultivation. The slow development from seedling to mature tree highlights the importance of patience and long-term planning in the conservation of this species. *Terminalia chebula*'s significant ecological and medicinal values make it a key species within its native habitats, contributing to biodiversity and offering benefits ranging from healthcare to ecosystem stability (Hossain et al., 2020; Islam et al., 2022). The purpose of this study is to develop an understanding of the processes governing tree phenology, seed dispersal, and seed biometry. Investigating seed traits such as length, width, thickness, and volume offers insights into how these characteristics influence seed dispersal, germination rates, and seedling survival (Hasnat et al., 2016; Lima et al., 2020; Matin et al., 2006; Nguyen et al., 2019). This study aims to examine the phenological diversity and biometric variations of selected tree species. By analyzing critical phases like seed dispersal, flowering, and fruiting times, and using statistical methods including t-tests, Euclidean distance in Ward's method, and Principal Component Analysis (PCA), the research seeks to identify significant differences and similarities among the species, enhancing our understanding of their biological and ecological diversity.

Methods and materials

The study, conducted from 2020 to 2023, took place in the Chittagong division of Bangladesh, a region known for its diverse geological and biological habitats. This area is particularly rich in species such as *Artocarpus chama*, *Terminalia arjuna*, *Terminalia bellirrica*, and *Terminalia chebula*, all found within the geographical boundaries of Chittagong (22° 22' 0.001" N, 91° 47' 60" E) at an altitude of 29 meters (Roy et al., 2015). The average temperature and rainfall in this area are 26°C and 3000mm respectively. *Avicennia officinalis* specimens were collected from the Sundarbans.

Biometric analysis of the selected species was conducted at the IFESCU seed laboratory at the University of Chittagong. The university campus features both natural and artificial forest habitats that provide an ideal environment for seed storage and germination practices. In April 2022, the area experienced its highest recorded temperature of 39°C and a maximum rainfall of 3200mm (Alam et al., 2023; Roy et al., 2015). The selected species—*A. chama*, *T. arjuna*, *T. bellirrica*, and *T. chebula* - are widely found and distributed across the Chattogram, Bandarban, and Rangamati districts. These areas are characterized by hilly tertiary mountain ranges and contain virgin forests and seed orchards. To ensure effective seed harvesting, monitoring was conducted across 10 representative reproductive stages up to the year 2022. The species were classified into groups based on germination % (high, mid, low), leaf deciduousness (deciduous, evergreen, and semi-evergreen) and seed dispersal syndromes, including zoochoric and barochoric dispersal mechanisms, as detailed in Table 1.

Table 1: List of five forest tree species included in this study with Phenology and Dispersion Syndrome.

Species	Family	Phenology	Seed dispersal	Germination%	Flowering	Fruiting
Artocarpaus chama	Moracceae	DT	Z	L	March	July
Avicennia officinalis	Avicenniaceae	EG	Z	M	February	August
Terminalia arjuna	Combretaceae	EG	B	H	April	February
Terminalia bellirrica	Combretaceae	DT	B	H	March	November
Terminalia chebula	Combretaceae	DT	B	H	April	November

Note: Leaf phenology is represented as Deciduous Tree (DT) and Evergreen (EG), while seed dispersal is categorized as Zoochronic (Z) and Barochoric (gravity) (B), germination% also categories into high=H(+80%), mid=M(+50%), low=L(+20%).

Among the selected plus trees, three individuals were chosen from the 10 monitored, in a randomized manner for seed collection. Ripe seeds were harvested manually from these selected representative plus trees. The seeds were then extracted from the fruits in the seed lab and dried for one day in sunlight. Following this, biometric variables were measured for ten seeds from each species. Seed matrix measurements were taken from base to apex for length (cm), width (cm), and thickness (cm), measured at the seed's midline. These measurements were made using a digital caliper with a precision of 0.01 cm. Data analysis was conducted in two main ways: firstly, a simple arithmetic mean was calculated for each parameter (length, width, thickness, and calculated volume in cubic centimeters (L×W×T)) (Pereira & Alberto, 2017). Additionally, a univariate statistical analysis was performed to ascertain the biometric variable (bioV) from the seed matrix, including the minimum, maximum, mean, standard error, and coefficient of variance (CV%) (Do Nascimento et al., 2019).

Statistical Analysis

The similarity of biometric variables measured among and between the species was assessed using t-tests, with the results visualized in box plot graphs. To standardize the averages of biometric variables for each seed matrix, data were analyzed to understand cluster formation using Euclidean distance in Ward's method (Ukpatu et al., 2015), determining if the species were grouped accordingly. Furthermore, Principal Component Analysis (PCA) was conducted to identify the biometric variables that contributed to species grouping (Janekovi & Novak, 2012; Udoinyang, 2015). Data management was performed using Excel, while all statistical analyses were executed using R version 4.2.2. These analyses enabled the identification of significant differences and similarities in biometric variables, providing insights into the grouping patterns and relationships among the species. By using robust statistical methods, the study ensured accurate classification and understanding of the species' biometric characteristics, contributing to a deeper knowledge of their biological and ecological diversity.

Results

A univariate analysis statistical analysis of species

Phenological diversity, as detailed in Table 1, provides insights into the timings of seed dispersal, flowering, and fruiting across months. Initial standard errors are also presented, indicating data reliability, where lower values suggest greater accuracy. Elucidates that seeds from species such as *A. officinalis*, *T. arjuna*, and *T. chebula* have unique shapes, leading to significantly larger standard errors, as revealed in Table 2. These species demonstrate low coefficients of variance in length, width, and thickness, whereas *A. chama*'s seed volume shows a higher coefficient of variance at 106.07%. Relationship between parameters (length, width, thickness, and volume) are assessed, with Figure 1 displaying the results of t-tests. These tests reveal statistical significance ($P<0.05$) for length and width in *A. officinalis*, *T. arjuna*, *T. bellirrica*, and *T. chebula*, indicating noteworthy differences in these dimensions. Despite belonging to the same family, *A. officinalis* and *T. arjuna* exhibit different seed dispersal syndromes, namely zoochoric and barochoric, respectively. Figure 1 and Table 2 highlight the variations in seed volumes among species. *A. officinalis*, *T. arjuna*, *T. bellirrica*, and *T. chebula* all show higher volumes, with *T. arjuna* standing out for its superior germination percentages (60-70%) in both forest and conventional soils.

Table 2: A univariate analysis statistics of biometric parameters evaluated, verifying differences within and between species.

Species	BioV	N	Min	Max	Mean	SE	CV (%)
Artocarpaus chama Buch.-Ham ex Wall.	L	10	1.32	1.54	1.43	0.16	10.88
	W	10	0.57	0.9	0.74	0.23	31.75
	T	10	0.07	0.49	0.28	0.30	106.07
	V	10	0.06	0.27	0.17	0.15	88.28
Avicennia officinalis L.	L	10	2.8	3.71	3.26	0.64	19.77
	W	10	2.6	2.92	2.76	0.23	8.20
	T	10	0.52	1.88	1.20	0.96	80.14
	V	10	4.51	10.57	7.54	4.29	56.84
Terminalia arjuna (Roxbo.ex DC)	L	10	3.51	5.99	4.75	1.75	36.92
	W	10	2.1	2.9	2.50	0.57	22.63
	T	10	1.53	2.38	1.96	0.60	30.74
	V	10	12.81	23.35	18.08	7.46	41.23
Terminalia bellirrica (Gaertn.) Roxb.	L	10	2.33	3.43	2.88	0.78	27.01
	W	10	2.02	2.38	2.20	0.25	11.57
	T	10	1.53	1.69	1.61	0.11	7.03
	V	10	8.06	10.21	9.14	1.52	16.61
Terminalia chebula Retz	L	10	3.3	4.77	4.04	1.04	25.76
	W	10	1.95	2.31	2.13	0.25	11.95
	T	10	1.12	1.84	1.48	0.51	34.40
	V	10	7.97	12.12	10.05	2.93	29.14

Note: Biometric Variables (BioV) include Length (L), Width (W), Thickness (T), and Volume (V). Number of Seeds (N), Minimum (Min), Maximum (Max), Standard Error (SE), and Coefficient of Variation (CV %) are recorded for Length (cm), Width (cm), Thickness (cm), and Volume (cm^3).

The smaller dimensions of A. chama seeds have been found to affect both the percentage and timing of germination. A higher mass or volume generally correlates with higher germination percentages but inversely affects the germination time. Furthermore, A. chama's smaller seed size facilitates a higher rate of dispersal compared to T. arjuna, despite their distinct phonologies. Within the Combretaceae family, T. arjuna is notable

for its unique flowering and fruiting periods, spanning from March-April and November to February, respectively. Research indicates that the thickness of A. chama's seed coating layers plays a crucial role in nutrient and water permeability. These findings underscore the interconnectedness of biometric characteristics, demonstrating that larger seed volumes not only contribute to higher germination percentages but also enhance nutrient and water absorption.

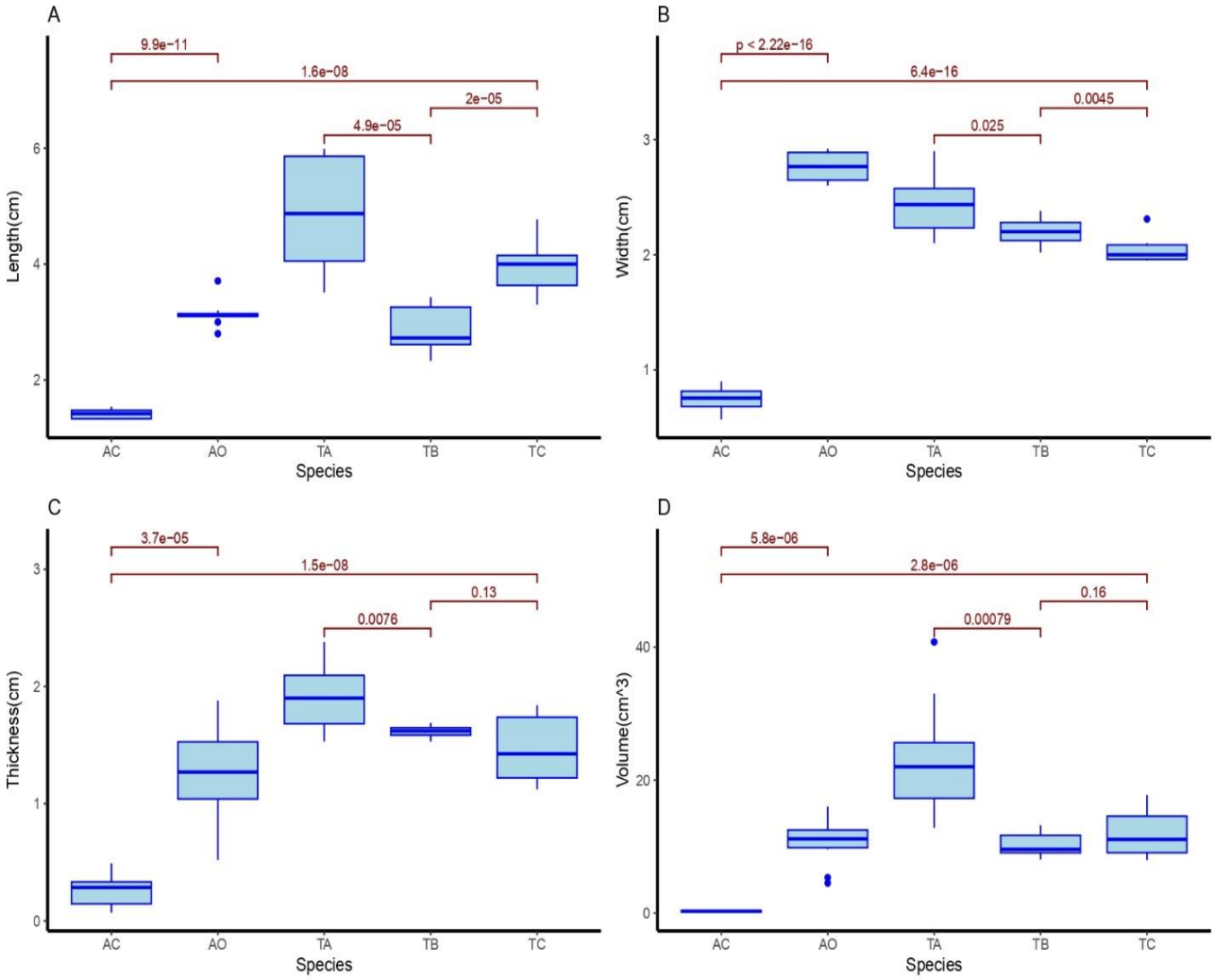


Figure 1: Box plot (t-test) displaying the values of length, width, thickness (cm), and volume (cm^3) for five tree species: *Artocarpus chama* (AC), *Avicennia officinalis* (AO), *Terminalia arjuna* (TA), *Terminalia bellirica* (TB), and *Terminalia chebula* (TC).

Similarity of biometric Variable in species Intra and interspecific analysis

Constructed using Euclidean-agglomerative-complete clustering, the dendrogram, featuring 50 observations for each biometric variable, is meticulously annotated with phenology and seed dispersal color information (Figure 2). This dendrogram divides into two main branches, encompassing a total of 50 members, and reaches a height of 7.66. Its distinctive structure uncovers specific patterns, notably that leaves numbered 1, 3, 6, 7, 8, and 9 distinctly

represent the Combretaceae family. Conversely, leaves numbered 41, 42, 44, 46, 47, and 49, alongside leaves 43, 45, 48, and 50, are indicative of the Moraceae family. This hierarchical arrangement effectively unveils the inherent relationships among the biometric variables, highlighting the distinctive characteristics of these plant families. The dendrogram's visual representation is instrumental in discerning these patterns, thereby facilitating a comprehensive understanding of the complex interplay between phenology, seed dispersal color, and the biometric variables across the diverse plant specimens. This enhanced insight aids significantly in advancing the study of plant biology by illuminating the connections between physical traits and their evolutionary and ecological implications.

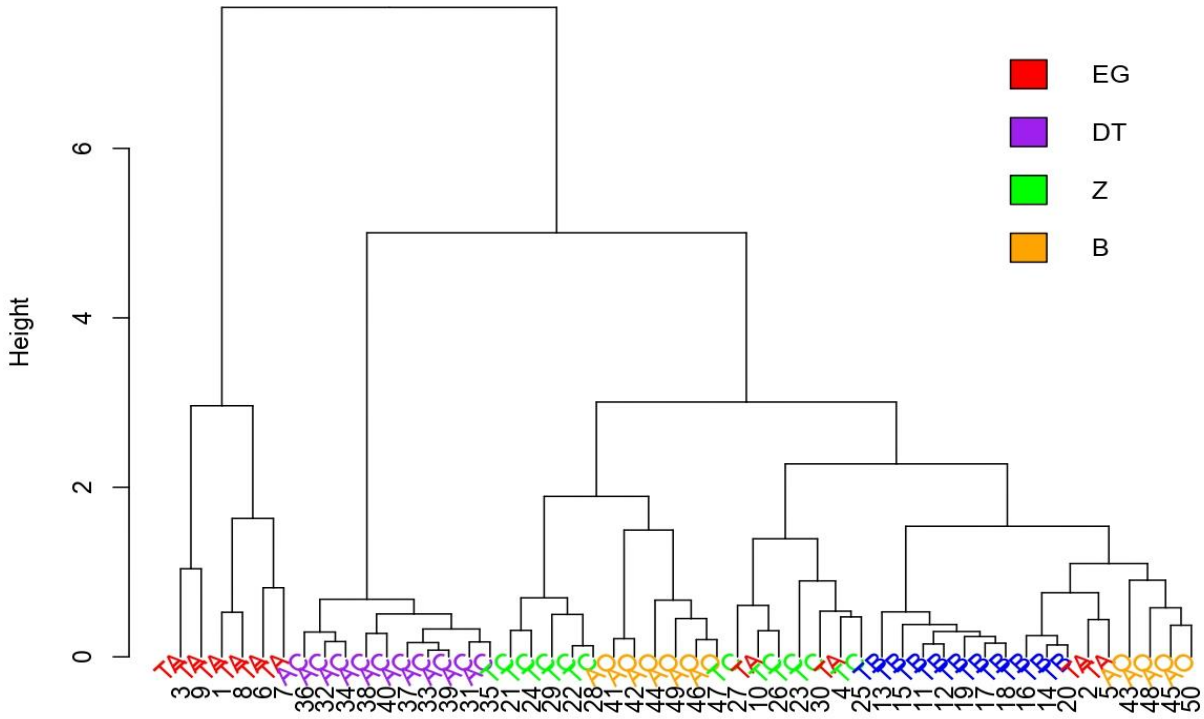


Figure 2: Dendrogram depicting intra- and interspecific similarity based on biometric variables (length, width, thickness, volume) of forest species seeds, with n=10 for each species, totaling N=50 for each biometric variable. Species include *Artocarpus chama* (AC), *Avicennia officinalis* (AO), *Terminalia arjuna* (TA), *Terminalia bellirica* (TB), and *Terminalia chebula* (TC). Cophenetic coefficient = 0.7541.

PCA of Biometric variable

Within the framework of dimension reduction, the principal components exhibit a progressive decline from PCA1 through PCA4, highlighting the essence of data simplification in complex analysis. Remarkably, PCA1 and PCA2 cumulatively account for a significant 92.5% of the variance among components, illustrating the primary axes potency in capturing the bulk of the data's variability. The PCA plot offers a lucid illustration of how PCA1, contributing 82.84%, and PCA2, adding another 10.17%, delineate the intricacies of seed dispersion and phenology within the cluster groups (Figure 3). It's within this graphical representation that the distinction of *A. chama*'s data

from others becomes markedly apparent, underscoring the unique characteristics of this specimen in comparison to its counterparts. Delving into the specifics, the standard deviations associated with PCA1 through PCA4 (n=4) stand at 1.82, 0.63, 0.45, and 0.27, respectively. These figures reflect the decreasing influence of each successive principal component on the dataset's variance. Furthermore, the contributions to PCA1, characterized by values of -0.5 for length, -0.4 for width, -0.5 for thickness, and -0.5 for volume, underscore the uniform influence of these biometric parameters in shaping the primary component. Conversely, the contributions to PCA2 are more varied, with -0.4 from length, +0.8 from width, +0.04 from thickness, and -0.3 from volume, indicating differential impacts on this secondary axis. This meticulous analysis sheds light on the pivotal elements steering the principal components and elucidates their consequential effects on the overarching biometric traits of the specimens. Such insights are instrumental in comprehending the multidimensional aspects of biometric variability, thereby enhancing our understanding of the intrinsic and extrinsic factors that define the biological and ecological identities of these plant species. Through this lens, the principal component analysis not only simplifies complex data but also reveals the meaningful patterns and relationships hidden within, offering a rich narrative on the dynamics of seed dispersion, germination and phenology in relation to biometric characteristics.

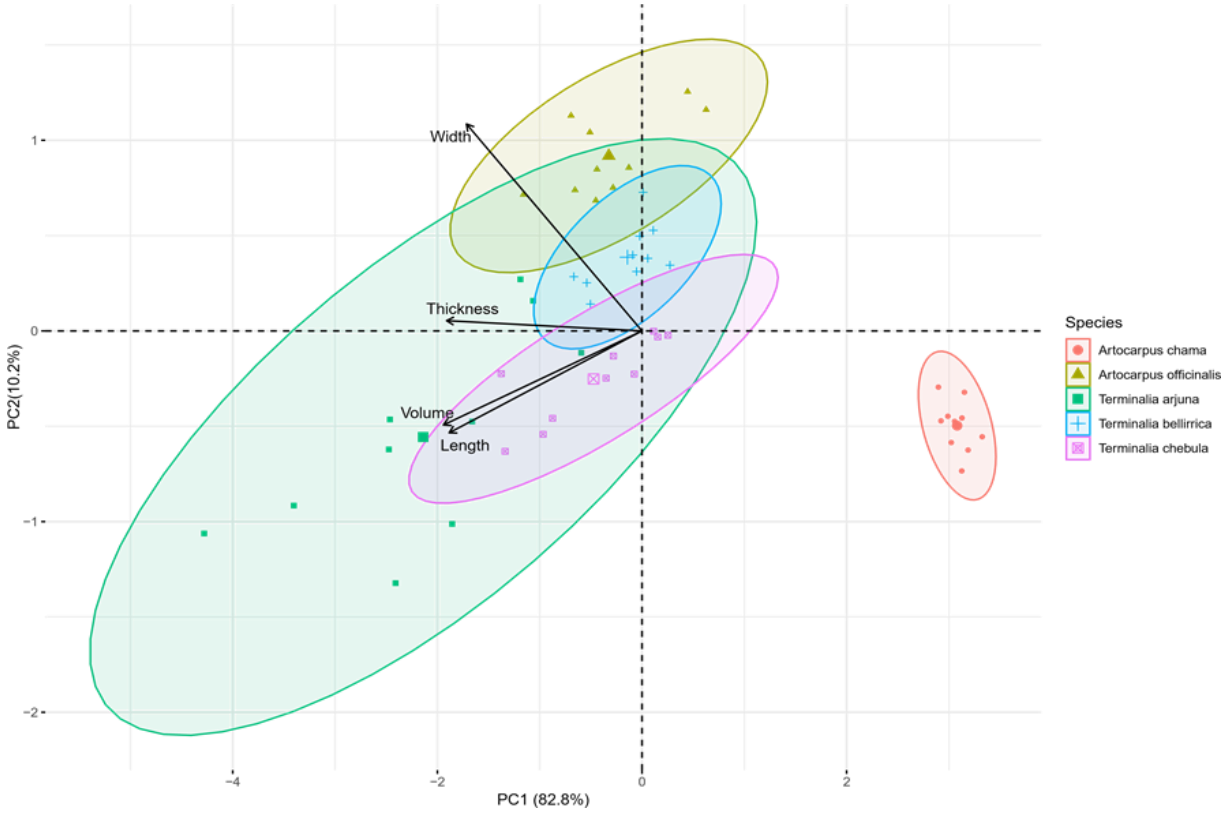


Figure 3: Principal Component Analysis depicting the distances between biometric variable matrices based on characteristics of *Artocarpus chama* (AC), *Avicennia officinalis* (AO), *Terminalia arjuna* (TA), *Terminalia bellirica* (TB), and *Terminalia chebula* (TC). The left figure illustrates the variation explained by each component, presented as percentages, while the right figure focuses on PCA1 and PCA2, detailing their contributions.

Discussion and implementation

The influence of seed size on germination, seed dispersal, and seedling growth in *T. bellirica*, *T. chebula*, *A. officinalis*, and *A. chama* is profound and multifaceted. In *T. bellirica*, larger seeds significantly enhance seed dispersal and afforestation efforts (Chowdhury et al., 2024; Wright et al., 2007). Seeds averaging 2.77 cm in length exhibit a 45% germination rate, underscoring the vital correlation between seed size and germination success (Hossain et al., 2013,2020; Khan & Shankar, 2014). This finding sets the stage for further observations across different species. Similarly, *T. chebula* demonstrates a direct relationship between seed size and germination rates, seed dispersal efficiency, and seedling growth robustness (Westoby, 1998). This pattern highlights the critical role of seed dimensions in species survival and expansion, suggesting that larger seeds tend to have advantageous outcomes in terms of germination and establishment (Chowdhury et al., 2024).In mangrove ecosystems, the seed sizes of *A. officinalis* are markedly influenced by pollinators, plant diversity, and seed establishment efficacy (Mehta et al., 2021). This interplay emphasizes the ecological significance of seed size in mangrove forests, where larger seeds generally exhibit greater success in rooting and proliferating (Westoby et al., 2002; Yang et al., 2018).

For *A. chama*, seed mass emerges as a pivotal factor for germination success. Seeds weighing between 300-350 mg achieve over 90% germination rates, fostering extensive seed dispersal and enhancing plant resilience (Khan & Shankar, 2014). Seedlings from larger and heavier seeds display superior resilience, crucial for the continued growth and spread of these species in their natural habitats (Hossain et al., 2014; Ashrafuzzaman et al.,2021). The broader implications of this study suggest that seed size not only affects immediate germination and seedling viability but also has long-term impacts on the ecological success and sustainability of these species. For instance, larger seeds often contain more resources, which support the initial stages of seedling development, giving them a competitive edge in nutrient-poor environments. This advantage can lead to higher survival rates and greater ability to withstand environmental stresses, such as drought or poor soil conditions (Hasnat et al., 2016).Furthermore, understanding the relationship between seed size and plant performance can inform conservation strategies(Zuffo et al., 2017). For endangered or threatened species, selecting larger seeds for propagation could improve the chances of successful restoration efforts. In managed forests and plantations, utilizing seeds with optimal size characteristics can enhance overall forest health and productivity.

However, the study also points out the limitations, such as the need for larger sample sizes and more extensive field surveys to validate the findings. Future research could explore the genetic basis of seed size variation and its ecological implications across a broader range of species and environments. Integrating molecular techniques with traditional biometric analyses could offer deeper insights into how seed size influences plant fitness and ecosystem dynamics. In conclusion, this research underscores the multifaceted role of seed size in plant ecology, providing crucial insights that can enhance both theoretical understanding and practical applications in forestry, conservation, and ecological restoration.

Conclusion

This study explores phenological diversity by examining key phrases such as seed dispersal, flowering, and fruiting times. Standard errors in Table 2 highlight species-specific variations, with *A. officinalis*, *T. arjuna*, and *T. chebula* distinguished by their unique seed shapes, underscoring nature's complexity. While biometric measurements show low variance in length, width, and thickness, *A. chama* stands out with significant seed volume variation, suggesting diverse adaptability and dispersal strategies compared to *T. arjuna* (Khan & Shankar, 2014). A dendrogram visually separates the Combretaceae and Moraceae families, revealing their hierarchical relationships. Principal component analysis (PCA) further clarifies species differentiation, particularly for *A. chama*. This comprehensive study offers

deep insights into plant phenology, seed dispersal, and the intricate interplay between genetic and environmental factors, enriching our understanding of biological diversity and adaptability.

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Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request, included within the article and its supplementary materials, etc. This statement ensures transparency and reproducibility of the research findings.

Manuscript Originality: I confirm that this manuscript is original, has not been published before, and is not currently under consideration for publication by any other journal. All the authors have approved the manuscript and agree with its submission to Journal of Agriculture Sustainability and Environment.

References

Alam, E., Hridoy, A. E. E., Tusher, S. M. S. H., Islam, A. R. M. T., & Islam, M. K. (2023). Climate change in Bangladesh: Temperature and rainfall climatology of Bangladesh for 1949-2013 and its implication on rice yield. *PLoS ONE*, *18*(10 October), 1–26. https://doi.org/10.1371/journal.pone.0292668

Amalraj, A., & Gopi, S. (2017). Medicinal properties of Terminalia arjuna (Roxb.) Wight & Arn.: A review. *Journal of Traditional and Complementary Medicine*, *7*(1), 65–78.
https://doi.org/10.1016/j.jtcme.2016.02.003

Ashrafuzzaman, M., Khatun, M. M., Tunazzina, N. A., & Golam Sarwar, A. K. M. (2021). Conservation of minor fruit genetic resources at the Botanical Garden, Bangladesh Agricultural University. *International Journal of Minor Fruits, Medicinal and Aromatic Plants*, *7*(1), 1–18.
https://doi.org/10.53552/ijmfmap.2021.v07i01.001

Basha, S. J., Reddy, V. J., Rani, Y. S., Koshma, M., & Hanumanthu, G. (2017). A review on Terminalia chebula. *International Journal of Pharmacological Research*, *7*(10), 187–191.

Chowdhury, M.I.H., Rakib, M.H., Das, C., Hossain, M.Z. Tree Species Germination: A Comprehensive Meta-Analysis and its Implications for Pre-Sowing Treatment in Bangladesh. Journal of Soil, Plant and Environment. (2024). 3(1), 24–29, DOI: 10.56946/jspae.v3i1.397

Crouzeilles, R., Curran, M., Ferreira, M. S., Lindenmayer, D. B., Grelle, C. E. V., & Rey Benayas, J. M. (2016). A global meta-Analysis on the ecological drivers of forest restoration success. *Nature Communications*, *7*(May), 1–8. https://doi.org/10.1038/ncomms11666

Das, G., Kim, D. Y., Fan, C., Gutiérrez-Grijalva, E. P., Heredia, J. B., Nissapatorn, V., Mitsuwan, W., Pereira, M. L., Nawaz, M., Siyadatpanah, A., Norouzi, R., Sawicka, B., Shin, H. S., & Patra, J. K. (2020). Plants of the Genus Terminalia: An Insight on Its Biological Potentials, Pre-Clinical and Clinical Studies. *Frontiers in Pharmacology*, *11*(October), 1–30.
https://doi.org/10.3389/fphar.2020.561248

Do Nascimento, C. R., Chagas, E. A., Smiderle, O. J., de Andrade Souza, A., & Cardoso Chagas, P. (2019). Biometry and vigor of seeds of Myrciaria dubia (Kunth) McVaugh. *Advances in Horticultural Science*, *33*(3), 359–364. https://doi.org/10.13128/ahs-23992

Getzner, M., & Islam, M. S. (2020). Ecosystem services of mangrove forests: Results of a meta-analysis of economic values. *International Journal of Environmental Research and Public Health*, *17*(16), 1–13. https://doi.org/10.3390/ijerph17165830

Hasnat, G. N. T., Hossain, M. K., & Hossain, M. A. (2016). Flowering, fruiting and seed maturity of common plantation tree species in Bangladesh. *Journal of Bioscience and Agriculture Research*, *7*(1), 583–589. https://doi.org/10.18801/jbar.070116.70

Hossain, A., Ferdous, J., Rahman, M. A., Azad, A. K., & Shukor, N. A. A. (2014). Towards the propagation of a critically endangered tree species Anisoptera scaphula. *Dendrobiology*, *71*(October), 137–148. https://doi.org/10.12657/denbio.071.014

Hossain, A., Uddin, M. S., & Rahman, M. M. (2013). Enhancing seed germination and seedling growth attributes of a medicinal tree species Terminalia chebula through depulping of fruits and soaking the seeds in water. *Journal of Food, Agriculture & Environment* Vol.11 (3&4): 2573-2578.

Hossain, M. K., Alim, A., Hossen, S., Hossain, A., & Rahman, A. (2020). Diversity and conservation status of tree species in Hazarikhil Wildlife Sanctuary (HWS) of Chittagong, Bangladesh. *Geology, Ecology, and Landscapes*, *4*(4), 298–305. https://doi.org/10.1080/24749508.2019.1694131

Islam, I., Cui, S., Hoque, M. Z., Abdullah, H. M., Tonny, K. F., Ahmed, M., Ferdush, J., Xu, L., & Ding, S. (2022). Dynamics of Tree outside Forest Land Cover Development and Ecosystem Carbon Storage Change in Eastern Coastal Zone, Bangladesh. *Land*, *11*(1). https://doi.org/10.3390/land11010076

Jagtap, U. B., & Bapat, V. A. (2010). Artocarpus: A review of its traditional uses, phytochemistry and pharmacology. *Journal of Ethnopharmacology*, *129*(2), 142–166.
https://doi.org/10.1016/j.jep.2010.03.031

Janekovi, F., & Novak, T. (2012). PCA – A Powerful Method for Analyze Ecological Niches. *Principal Component Analysis - Multidisciplinary Applications*, *February 2012*. https://doi.org/10.5772/38538

Khan, M. L., & Shankar, U. (2014). Seed Mass , Germination and Seedling Growth in Artocarpus chama. *International Journal of Ecology and Environmental Sciences ·*, *30(4)*(December 2004), 369–376.

Krupa, S., Tasmiya, S., & Rohini. (2022). A Review on the Distribution, Nutritional Status and Biological Activity of Various Parts of Artocarpus heterophyllus Lam. *Asian Journal of Applied Science and Technology*, *06*(04), 01–20. https://doi.org/10.38177/ajast.2022.6401

Kumar, H., Lal, S. B., Wani, A. M., Umrao, R., Khare, N., & Kerketta, N. S. (2017). Seed Size Correlates with Germination Traits in Terminalia arjuna Genotypes. *International Journal of Current Microbiology and Applied Sciences*, *6*(8), 2896–2903. https://doi.org/10.20546/ijcmas.2017.608.346

Lima, T. M., Amaral, E. S., Gaiotto, F. A., Anjos, L. dos, Dalmolin, Â. C., Santos, A. S., & Mielke, M. S. (2020). Fruit and seed biometry of Carpotroche brasiliensis (RB) A. Gray (Achariaceae), a tropical tree with great potential to provide natural forest products. *Australian Journal of Crop Science*, *14*(11), 1826–1833. https://doi.org/10.21475/ajcs.20.14.11.p2596

Matin, M. A., Islam, M. S., & Azad, M. S. (2006). Seed Germination, Seedling Growth and Rooting of Branch

Cuttings of Dalbergia Sissoo Roxb. *Khulna University Studies*, 83–87.
https://doi.org/10.53808/kus.si.frcc.2006.83-87-ls

Mehta, B., Nagar, B., Patel, B., Chaklashiya, P., Shah, M., Verma, P., & Shah, M. B. (2021). A review on a Lesser Known Indian Mangrove: Avicennia officinalis L. (Family: Acanthaceae). *International Journal of Green Pharmacy*, *15*(1), 1–10.

Mengist, W., & Soromessa, T. (2019). Assessment of forest ecosystem service research trends and methodological approaches at global level: a meta-analysis. *Environmental Systems Research*, *8*(1). https://doi.org/10.1186/s40068-019-0150-4

Miah, M. D., Hasnat, G. N. T., Nath, B., Saeem, M. G. U., & Rahman, M. M. (2023). Spatial and Temporal Changes in the Urban Green Spaces and Land Surface Temperature in the Chittagong City Corporation of Bangladesh Between 2000 and 2020. *Forestist*, *73*(2), 171–182.
https://doi.org/10.5152/forestist.2022.22013

Mitra, S., Naskar, N., Lahiri, S., & Chaudhuri, P. (2023). A study on phytochemical profiling of Avicennia marina mangrove leaves collected from Indian Sundarbans. *Sustainable Chemistry for the Environment*, *4*(August), 100041. https://doi.org/10.1016/j.scenv.2023.100041

Nguyen, T. T., Arndt, S. K., & Baker, P. J. (2019). Leaf physiological responses to drought stress and community assembly in an Asian Savanna. *Forests*, *10*(12), 15–17. https://doi.org/10.3390/f10121119

Rahman, M., Parvin, W., Sultana, N., & Tarek, S. (2018). Ex-situ conservation of threatened forest tree species for sustainable use of forest genetic resources in Bangladesh. *Journal of Biodiversity Conservation and Bioresource Management*, *4*(2), 89–98. https://doi.org/10.3329/jbcbm.v4i2.39855

Roy, M., Biswas, B., & Ghosh, S. (2015). Trend Analysis of Climate Change in Chittagong Station in Bangladesh. *International Letters of Natural Sciences*, *47*(1), 42–53.
https://doi.org/10.18052/www.scipress.com/ilns.47.42

Sairkar, P. K., Chouhan, S., Sen, A., Sharma, R., & Singh, R. K. (2017). Genetic drift in six cultivated populations of Terminalia arjuna. *Journal of Applied Biology & Biotechnology*, *5*(04), 48–56. https://doi.org/10.7324/jabb.2017.50408

Saxena, V., Mishra, G., Saxena, A., & Vishwakarma, K. K. (2013). A comparative study on quantitative estimation of tannins in Terminalia chebula, Terminalia belerica, Terminalia arjuna and Saraca indica using spectrophotometer. *Asian Journal of Pharmaceutical and Clinical Research*, *6*(SUPPL.3), 148–149.

Sultana, N., Limon, S. H., Rahman, M. S., Akther, A., Salekin, S., Meason, D. F., & Bloomberg, M. (2021). Germination and growth responses to water stress of three agroforestry tree species from Bangladesh. *Environmental Challenges*, *5*(August), 100256. https://doi.org/10.1016/j.envc.2021.100256

Uddin, M., Chowdhury, F. I., & Hossain, M. K. (2020). Assessment of tree species diversity, composition and structure of Medha Kachhapia National Park, Cox's Bazar, Bangladesh. *Asian Journal of Forestry*, *4*(1). https://doi.org/10.13057/asianjfor/r040104

Udoinyang, E. . & U. J. (2015). Application of Principal Component Analysis (PCA) for the Characterization of the Water Quality of Okoro River Estuary, South Eastern Nigeria. *International Journal of Geology, Agriculture and Environmental Sciences*, *3*(December), 25–32.

Ukpatu, J., Udoinyang, E., & Udoh, J. P. (2015). The Use of Agglomerative Hierarchical Cluster Analysis for the Assessment of Mangrove Water Quality of Okoro River Estuary , Southeastern Nigeria. *International Journal of Geology, Agriculture and Environmental Sciences*, *3*(December), 17–24.

Westoby, M., Falster, D. S., Moles, A. T., Vesk, P. A., & Wright, I. J. (2002). Plant ecological strategies: some leading dimensions of variation between species. Annual Review of Ecology and Systematics, 33(1), 125-159. doi: 10.1146/annurev.ecolsys.33.010802.150452

Westoby, M. (1998). A leaf-height-seed (LHS) plant ecology strategy scheme. Plant and soil, 199(2), 213-227. doi: 10.1023/A:1004327224729

Wright, I. J., Ackerly, D. D., Bongers, F., Harms, K. E., Ibarra-Manriquez, G., Martinez-Ramos, M., ... Wright, S. J. (2007). Relationships among ecologically important dimensions of plant trait variation in seven neotropical forests. Annals of Botany, 99, 1003-1015. doi: 10.1093/aob/mcl066

Yang, X., Yan, C., Zhao, Q., Holyoak, M., Fortuna, M. A., Bascompte, J., … Zhang, Z. (2018). Ecological succession drives the structural change of seed-rodent interaction networks in fragmented forests. Forest Ecology and Management, 419-420, 42-50. doi: 10.1016/j.foreco.2018.03.023

Zuffo, A. M., Steiner, F., Zoz, T., Zuffo Júnior, J. M., Douradinho, G. Z., Oliveira, C. P., & Bortolazzo, G. (2017). Atributos biométricos de frutos e sementes de Peltophorumdubium (Spreng.) Taub. Revista de Ciências Agrárias, 40(1), 61-68. doi: 10.19084/RCA16123

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REVIEW ARTICLE

Enhancing Soil Carbon Sequestration and Land Restoration through Tropical Forest Management

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Abstract
Soil has a high capacity for absorbing carbon dioxide (CO_2). The significance of soil organic carbon (SOC) in tropical regions is often overlooked, despite its crucial role. This study investigates the potential of forest management to enhance the sequestration of SOC and rehabilitate degraded tropical ecosystems. Sequestering soil organic carbon has the potential to improve soil fertility while also mitigating land degradation and reducing greenhouse gas (GHG) emissions. The improvement of soil structure, aggregation, infiltration, faunal mobility, and nutrient cycling (specifically carbon, nitrogen, phosphorus, and sulfur) is observed. Managing forest ecosystems enhances carbon sequestration, mitigates climate change, and rehabilitates degraded land. By integrating organic residue management with nitrogen-fixing plants, afforestation or reforestation of marginal or degraded lands can effectively increase carbon storage in both biomass and soil. This approach also promotes soil health, improves food productivity, restores land quality, and contributes to the reduction of GHG emissions. The sequestration of carbon promotes the biological, physical, and chemical fertility of the soil, hence enhancing soil health.

Keywords: Tropical forest; Climate change; Forest management; Soil carbon; Soil fertility

Introduction

Between 1990 and 2015, the total area of land used for forestry decreased by 33%, from 4128 million hectares to 3999 million hectares. Tropical regions comprise 45 percent, or 728 million hectares, of the world's woods, with the boreal, temperate, and subtropical regions following suit (FAO, 2020). However, studies indicate that tropical deforestation is mostly attributed to agricultural and industrial activities (Raihan, 2023a), with a particular focus on South America and Africa (FAO, 2020). Africa saw a net loss of 3.9 million hectares of forests between 2010 and 2020. According to the FAO (2020), South America has a total of 1 million hectares. Pan et al. (2011) discovered that the carbon absorption capacity of forests is similar to that of the land in terms of absorbing carbon dioxide released from burning fossil fuels. Forests contain 80% of the carbon stored above the ground and 70% of the carbon stored in the soil (Raihan et al., 2021a).

Effective forest management is crucial for the processes of carbon sequestration, soil rejuvenation, and reduction of greenhouse gas emissions (Ontl et al., 2020; Raihan et al., 2022a). Managing forest ecosystems entails understanding the dynamics, size, and chemical composition of their pools. Forest management and carbon sequestration are influenced by various factors such as silviculture (the selection of tree species and rotation periods), gaps (the quantity of trees planted at once), turbulence (including pest influxes, wind pitch, and wildfires), air contamination, and water management (Raihan et al., 2019). A study conducted by Biber et al. (2020) used modeling techniques to forecast the extension of forests in 10 European landscapes over the next century. The study examined how forest management practices in Europe impact ecosystem services such as carbon sequestration, biodiversity, and sustainable timber production. The study concluded that it is important to take into account storms and droughts that are caused by climate change. Within the eastern region of the United States, the Community Land Model 4.5 places a high importance on conserving forested areas. This is achieved by taking into account factors such as susceptibility to drought and fire, and by comparing the relative importance of preserving biodiversity. This approach differs from the one used in the western region (Buotte et al., 2020). Preserved temperate forests in the western US, which have a moderate to high capacity for storing carbon, are estimated to have a mitigation capacity equivalent to 27-32 percent of the global capacity previously observed in boreal and temperate forests. This capacity is sufficient to absorb fossil fuel emissions for around 8 years, according to Buotte et al. (2020).

According to the US forest inventory, there are 1.4 trillion plants in over 130,000 federal forestlands. This shows that planting trees can increase the ability to store carbon and decrease CO_2 emissions (Domke et al., 2020). Tropical trees sequester carbon both below and above ground (Raihan and Tuspekova, 2023). The ecosystem in question has the highest carbon storage capacity, with a value of 91 tha^{-1}, and also exhibits the highest wood production, with a value of 121 m^3ha^{-1}. According to Pan et al. (2011), boreal forest soils that are rich in carbon do not have them. Tropical forests have the highest carbon concentration, allowing them to accumulate and retain the most carbon (Raihan et al., 2018; Raihan, 2023b). Figure 1 illustrates the simplified global carbon cycle in tropical forest habitats. Their capacity to capture and store atmospheric carbon has shown the most significant growth in the recent two periods, making them crucial for mitigating climate change (Fernández-Martnez et al., 2019). The capacity was examined by MACC-II and Jena CarboScope atmospheric inversion models, as well as 10 dynamic universal plants models. The findings indicate that the ability of ecosystems to absorb carbon dioxide may serve as a countermeasure against global warming and climate change (Raihan et al., 2022b). Hence, effective forest management has a crucial role in carbon sequestration, the regeneration of degraded woodlands and other areas, the mitigation of climate change, the preservation of natural forests, and the conservation of biodiversity (Raihan and Tuspekova, 2022a).

The FAO (2020) anticipated that by 2020, the world forest carbon stock would reach 662 gigatonnes (or 163 tonnes per hectare). Forest soils comprise 50% of the organic carbon found in terrestrial ecosystems (Mayer et al., 2020; Raihan and Said, 2022). Tropical forest soils possess a carbon (C) content that is three times more than that found in the atmosphere or plants. The biogeochemical cycles of carbon (C), water, and other components in forests have an impact on the Earth's climate on a global scale (Malhi et al., 2020). Forest ecosystems require adaptability and resilience in order to endure the impacts of climate change (Begum et al., 2020; Raihan and Tuspekova, 2022b; Raihan et al., 2023a). Tropical forests are concerned that climate change may lead to increased aridity. However, over the past twenty years, they have significantly enhanced their capacity to capture atmospheric carbon, hence boosting their effectiveness in addressing climate change (Fernández-Martnez et al., 2019; Raihan et al., 2022c). Malhi et al. (2020) found that land-use alteration, which encompasses the loss of habitats and excessive exploitation, has a greater impact on ecosystems compared to climate change.

The combination of increasing population, declining soil fertility, and food shortages leads to land degradation, which exacerbates the impact of climate change on forest ecosystems in tropical regions (Jaafar et al., 2020; Raihan and Tuspekova, 2022c; Raihan et al., 2023b). The United Nations and other global initiatives, such as the "Bonn Challenge" and the "UN-Decade on Ecosystem Restoration" (2021-2030), have long been advocating for the separation of land dilapidation and the achievement of the UN Sustainable Development Goals (SDGs). Soil deterioration can occur naturally or as a result of human activities. There are four main types of soil deterioration: chemical, biological, physical, and ecological. Chemical deterioration includes processes such as

salinization, acidification, leaching, pollution, and nutrient depletion. Biological deterioration involves a decrease in soil organic material, damage to soil biodiversity, and a decline in the ability of soil to store carbon. Physical deterioration includes compaction, runoff and erosion, and desertification. Ecological deterioration disrupts nutrient cycling, perturbs the hydrological cycle, and leads to a decline in the efficiency of input use.

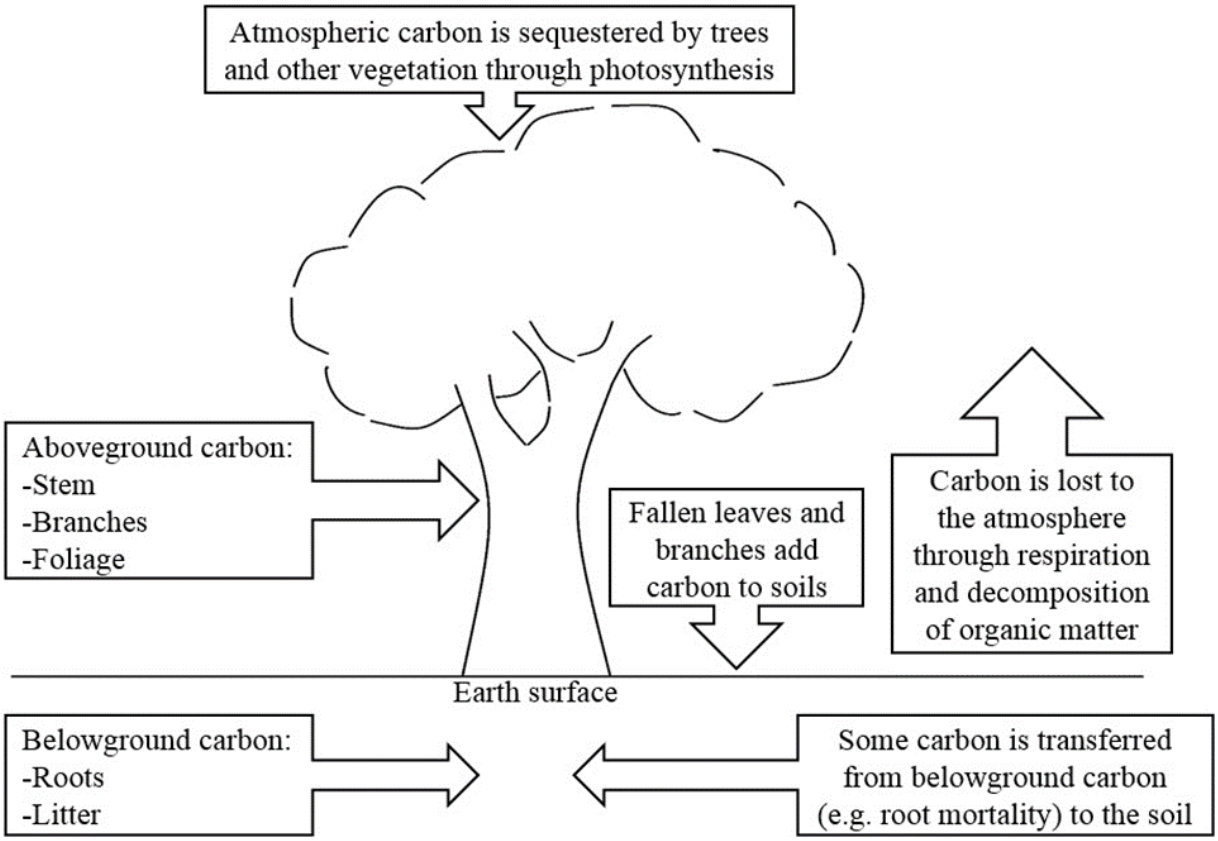


Figure 1. Carbon sequestration in forests.

Implementing forest management practices and engaging in tree planting activities on degraded land have been shown to enhance the accumulation of carbon in the soil and contribute to the preservation of ecosystem carbon pools (Raihan and Tuspekova, 2022d). Research on SOC has shown a significant growth over the past two decades (Mayer et al., 2020; Ali et al., 2022). The majority of publications and articles focus on the topic of soil organic carbon (SOC) and its role in several areas such as nutrient cycling, soil fertility, crop production, climate change, and land restoration (Lal, 2013). The "4 per 10000 Initiative," alternatively referred to as Soils for Food Security and Climate Change, was introduced during the 21st Conference of the Parties (COP) of the UNFCCC, garnering global interest in soil (Soussana et al., 2019). Climate change and land degradation pose significant threats to agriculture, forestry, food production, and sustainability (Raihan and Tuspekova, 2022e). Hence, the 22nd Conference of the Parties (COP) placed emphasis on the utilization of fertilizers and the management of manure as means to achieve sustainable and resilient agriculture.

Nevertheless, soil organic matter (SOM) functions as a storage for nutrients and is frequently employed as an indicator for evaluating soil fertility, as well as the chemical, physical, and biological characteristics of soil health. Soil organic carbon (SOC) accounts for 50-99% of the total quantity of soil organic matter (SOM). The SOM pool exhibits a notable level of stability and maintains an average residence length of several decades. Hence, it is possible that the process of appropriately assessing changes in SOC may require a duration beyond 2 years. However, changes in the ability of SOM to be broken down by natural processes or in the amount of microbes present can be readily seen over a shorter period of time. Soils have a vital role in storing carbon, acting as both a supplier and absorber of carbon (Raihan et al., 2022d). The variables that affect this

phenomenon encompass climate, soil texture, soil acidity, vegetation cover, biomass inputs, management approaches, as well as soil depth, starting carbon levels, and soil type (Marin-Spiotta and Sharma, 2013; Akpa et al., 2016).

The quality of soil organic matter (SOM) is enhanced by the accumulation of soil organic carbon (SOC), especially when it is protected by small soil particles (Eclesia et al., 2012; Sang, 2013). The decrease in soil organic matter (SOM) quality is ascribed to the heightened process of carbon mineralization caused by climate changes, management methods, or soil-related factors (Bonfatti et al., 2015; Cook et al., 2016). Soil carbon sequestration can improve soil fertility, boost agricultural output, and reduce climate change by reducing greenhouse gas emissions (Paustian et al., 2016; Raihan, 2024a). The storage of soil organic carbon (SOC) is essential for effectively managing, reducing, and stopping land degradation (Raihan, 2023c). Shimamoto et al. (2018) performed a comprehensive worldwide meta-analysis on the recovery of ecosystem services in tropical forests. The researchers discovered that restoration initiatives were especially successful in improving the preservation of biodiversity in previously damaged grazing land, as well as in augmenting carbon storage in previously depleted agricultural areas. The authors proposed that the most suitable method involves enhancing the recovery of ecosystem services in deteriorated tropical forests.

Research on soil organic carbon (SOC) should give priority to monitoring and assessing places where decomposition is happening rapidly, such as tropical forest ecosystems that are suffering land degradation worsened by high amounts of organic matter and climate change (FAO, 2020; Raihan and Tuspekova, 2022f). Carbon sequestration is an essential aspect of sustainable soil management, which plays a critical role in restoring and maintaining soil health, as well as reducing climate change and rehabilitating land (FAO, 2020; Raihan et al., 2023c). Hence, the main objective of this study is to concentrate on the management of soil organic carbon (SOC) in tropical forest ecosystems, which are now facing the highest level of endangerment among all forest ecosystems. The objective of this research is to tackle both the mitigation of climate change and the prevention/restoration of land degradation.

Planting trees on agricultural, grassland, or city-edge property can have an impact on both the environment and the economy. The introduction of nitrogen-fixing species and the management of organic wastes enhance the sequestration of soil organic carbon (SOC) and the cycling of nutrients, hence promoting the growth and development of forest ecosystems. The study of tropical soil organic carbon (SOC) levels and characteristics has been insufficient, despite their capacity to enhance carbon sequestration and prevent land degradation by influencing nitrogen (N) and phosphorus (P) levels. This study investigates the impact of the quantity and quality of soil organic carbon (SOC) on land rehabilitation in tropical forest ecosystems. The study specifically examines the influence of SOC coupled with nitrogen or phosphorus cycles, carbon stocks, and stable versus labile carbon forms. Restoring and planting trees in marginal and degraded tropical forest habitats can enhance soil fertility, mitigate climate change, and combat land degradation.

Methodology

A comprehensive literature analysis was conducted to investigate the connections between land restoration, soil organic carbon (SOC), and other components in tropical forest ecosystems, as well as soil carbon management and storage. This has demonstrated the importance of forest management in relation to the amount and quality of carbon sequestered and land restored in tropical ecosystems. Figure 2 clearly demonstrates that the review followed the principles of systematic review methodology. By breaking down the research questions into their individual concepts, it is feasible to create a list of search terms that would enable a comprehensive and representative literature search on the subject of managing soil carbon and its connection to climate change and land restoration in tropical forest ecosystems. The classification of databases has been considered, including synonyms, singular and plural models, broader phrases, alternate spellings, and more specific terms.

This study conducted a systematic literature review to examine the potential connections between climate change adaptation and resilience in tropical forest ecosystems, the interaction between soil organic carbon (SOC) and other nutrient cycling processes, and the links to land restoration. The retrieved publications and papers were assessed using a set of encoded criteria for the inclusion and exclusion of primary research papers. This project involved conducting primary assessments to evaluate the management of social-ecological systems

in the context of mitigating climate change or repairing degraded land in tropical regions. The secondary literature on forests in the tropics, both qualitative and quantitative, is also examined.

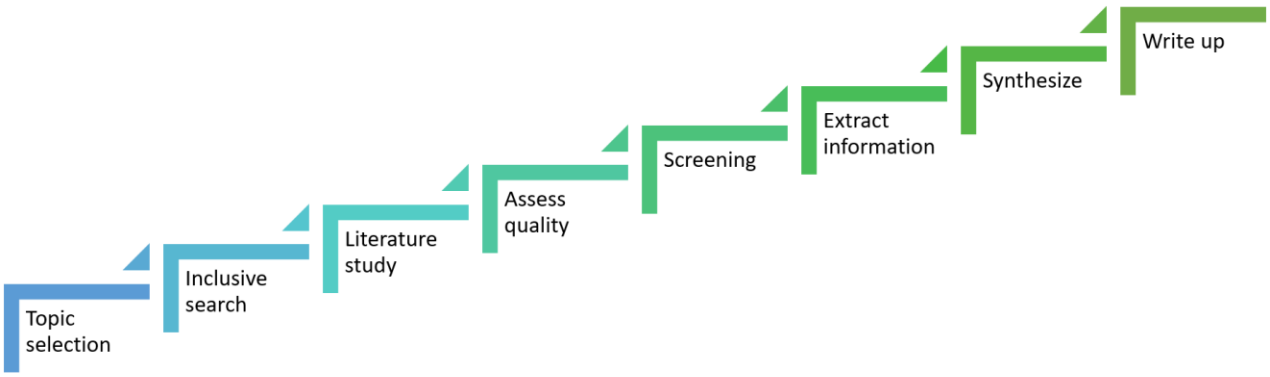


Figure 2. The procedure of systematic review conducted by the study.

Following an extensive examination of the pertinent literature, a total of 86 publications published from 1990 to 2022 were selected for further scrutiny. The papers were sourced from the academic aggregators Google Scholar, Scopus, and Web of Science (WOS). This work presents an overview of the connections between carbon sequestration and land degradation repair in tropical forests over a long period of time. The goal is to establish a model for future forest research and management that considers both of these processes. This study exclusively utilized research articles published in peer-reviewed journals to ensure the credibility and reliability of the findings. These findings serve as a basis for future research and management efforts in tropical forests, with a focus on carbon sequestration and the restoration of land degradation. Subsequently, these articles underwent evaluation to ascertain whether their main subject matter aligned with that of the present inquiry.
Although a specific instrument for quality assessment was not used, the review ensured that the evidence extracted from the research papers (that met the inclusion criteria) was relevant and accurate by evaluating the research methodology and questions, sources of information, and the selection of the evaluation criteria.

Results and Discussion

Enhancing soil carbon through tropical forest management

Due to their crucial role in the overall carbon cycle and the numerous benefits they provide to ecosystems, such as carbon sequestration in biomass and soil, forests necessitate meticulous management to enhance carbon sequestration and improve soil health (Raihan, 2023d). Fernandez-Martinez et al. (2019) state that tropical forest ecosystems have demonstrated enhanced capacity to trap carbon during the previous two decades. The sequestration of carbon (C) in tropical forests can occur depending on the management practices employed. Table 1 provides a summary of carbon sequestration in various tropical forests. The rate of soil organic carbon (SOC) sequestration is influenced by various elements such as tree species, soil type, environmental conditions, climate, and geographic considerations. This topic has been extensively studied and documented by Mayer et al. (2020). Carbon sequestration in biomass and soil is a frequent outcome of managing forest ecosystems through afforestation and reforestation. However, the effectiveness of these activities relies heavily on soil conditions, in addition to the parameters mentioned earlier (Dou et al., 2016; Raihan, 2023e).

Table 1. Sequestration of carbon in some tropical forests.

Location	Forest type	Sequestrated C	Sources
Panama	Teak plantation	3-41 Mg Cha^{-1}	Derwisch et al. (2009)
Colombia	Mixed forest	122-141 Mg Cha^{-1}	Saatchi et al. (2011)
Venezuela	Mixed forest	118-139 Mg Cha^{-1}	Saatchi et al. (2011)
Bolivia	Mixed forest	84-94 Mg Cha^{-1}	Saatchi et al. (2011)
Myanmar	Mixed forest	146-157 Mg Cha^{-1}	Saatchi et al. (2011)
Papua New Guinea	Mixed forest	147-153 Mg Cha^{-1}	Saatchi et al. (2011)
Vietnam	*A. mangium* and Eucalypt plantation	11.5 $tCha^{-1}yr^{-1}$	Sang et al. (2013)
Indonesia	Production forest	46.32 t C ha^{-1}	Situmorang et al. (2016)
Cameroon	Mixed forest	318 t C ha^{-1}	Zapfack et al. (2016)
India	All types of forests	3979 million tons	Indian State of Forest (2017)
Brazil	Eucalypt and *A. mangium* plantation	C accretion	Pereira et al. (2018)
Ghana	Plantation forests	56-70 Mg Cha^{-1}	Brown et al. (2020)
Nepal	Community forests	301 tha^{-1}	Joshi et al. (2020)
Peru	Agroforestry	106 Mg Cha^{-1}	Aragón et al. (2021)
Thailand	Teak plantation	45-82 Mg Cha^{-1}	Chayaporn et al. (2021)
Costa Rica	Natural forest	18210 tons	Paniagua-Ramirez et al. (2021)
Malaysia	All types of forests	157.5 tC ha^{-1}	Raihan et al. (2021b)
Congo	Peatland	634 Mg Cha^{-1}	Crezee et al. (2022)

The afforestation of huge uncultivated regions in central China with woodland, shrubland, and agricultural plants has led to an improvement in soil carbon storage, particularly in macroaggregates (>2000 m), as reported by Dou et al. (2016). Compared to pure acacia and eucalypt stands, which had soil carbon levels of 16.7 and 15.9 tha^{-1} respectively, the mixed-species stands consisting of 50% acacia and 50% eucalypt showed a rise in soil carbon stocks to 17.8 ± 0.7 tha^{-1} after afforestation of natural tropical savannas. The carbon stock in *A. mangium* plantations in Malaysia showed an increase from year 1 (74.9 tha^{-1}) to years 3 (89.9 tha^{-1}) and 5 (138.9 tha^{-1}) by 15 tha^{-1} and 64 tha^{-1}, respectively, despite the soil type being loamy siliceous with low fertility (Lee et al., 2015). Camacho et al. (2009) provided a framework for the long-term storage of carbon (C) in the Makiling forest reserve and the Philippines. The authors suggested the implementation of reforestation, particularly focusing on fast-growing and high-timber species, as a means to enhance the process of carbon sequestration. Reforestation and afforestation strategies, such as using fast-growing natural fertilizer substitutes (NFS) or nitrogen-fixing bacteria, or leaving organic residues on the field after wood harvesting, can further increase soil organic carbon (SOC) stocks in coarse-textured soils that have a high rate of SOC decomposition (Dubliez et al., 2018; Mayer et al., 2020). The reason for this is that the addition of new organic residues or organic matter rich in nitrogen changes the activity of microorganisms and/or the composition of bacteria (Bini et al., 2018; Pereira et al., 2018). Soil microorganisms showed higher levels of carbon and nitrogen buildup after 27 months in the combination plantation of acacia and eucalyptus compared to pure or treated stands. Plants that engage in nitrogen fixation can enhance soil fertility and carbon sequestration in tropical forest plantations through their interactions with organisms and nutrient availability (Bini et al., 2018; Raihan and Bijoy, 2023).

The climate mitigation capability of secondary spontaneously regenerated forest and managed forest plantations of 42 to 47 years old *Aucoumea klaineana*, *Tarrietia utilis*, *Cedrela odorata*, and *Terminalia ivorensis* in Ghana's moist and wet zones differed significantly (Brown et al., 2020). Natural forests remain highly effective for carbon sequestration and storage (Raihan, 2023f). A study conducted to promote the development of forest management practices for enhancing carbon sequestration in forest soils discovered a total of 23.48 million metric tons of carbon, with a carbon sequestration capacity of 4 metric tons per hectare per year (Chinade et al., 2015). The Malaysian forest ecosystem does not take into consideration soil carbon (C), which makes up 36-46% of it (Chinade et al., 2015). The Soil Organic Carbon (SOC) has been examined in several contexts, including the Forest Survey of India in 2017 and a study conducted by Joshi et al. in 2020. The SOC pool,

which is the largest, increased from 3,968 million tons in 2015 to 3,979 million tons in 2017. The aboveground C stock also increased from 2,220 million tons in 2015 to 2,238 million tons in 2017. However, the belowground C stock decreased from 695 million tons in 2015 to 699 million tons in 2017. Joshi et al. (2020) assessed the process of soil organic carbon (SOC) sequestration in both damaged and undisturbed community forests located in Nepal's Terai area near the city of Kanchanpur. The undisturbed community forests stored 54.21 ± 3.59 tha^{-1} of soil organic carbon (SOC) and had a total carbon stock of 301.08 ± 27.07 tha^{-1}. In contrast, the degraded community forests stored only 42.55 ± 3.10 tha^{-1} of SOC and had a total carbon stock of 152.68 ± 22.95 tha^{-1}. A recent investigation on forest management in a 35-year-old teak plantation located in western Thailand highlighted the plantation's capacity to sequester carbon in its aboveground biomass, hence mitigating the effects of climate change (Chayaporn et al., 2021). The study conducted by Satakhun et al. (2019) determined that the yearly CO_2 sequestration rate in a Thai rubber tree plantation (*Hevea brasiliensis* Müll.Arg.) ranged from 28 to 43 tons CO_2 $ha^{-1}yr^{-1}$, with an average of 36.7 tons CO_2 $ha^{-1}yr^{-1}$. These measurements were obtained using the eddy covariance method to assess the net ecosystem exchange. The study found that for every kilogram of natural-rubber latex extracted from these plants, 24.9 kilos of carbon dioxide were retained in the soil.

However, it is important to note that SOC sequestration does not exclusively occur as a consequence of forest ecosystem management. An inhibiting factor for the sequestration of SOC in forest ecosystems is their mature age. A study conducted at the San Luis Campus (Monteverde) in Costa Rica has revealed that secondary forests have a greater capacity to sequester carbon (C) through tree growth compared to primary forests (Paniagua-Ramirez et al., 2021). According to Cook et al. (2016), the soil carbon reserves in Brazil were reduced throughout a vast geographical gradient due to three short eucalypt plantation cycles lasting only 6-8 years, after decades of agricultural output and grazing. The capacity of forest ecosystems to rehabilitate degraded lands and alleviate climate change may be hindered by factors that either enhance or impede carbon sequestration (Malhi et al., 2020; Raihan, 2023g). The soil, weather, and plants are all constituent factors that have a significant effect. In their study, Sayer et al. (2019) discovered that the accumulation of litter over a period of 15 years in a fully developed lowland tropical forest in Panama did not result in an increase in carbon stocks. The storage of soil organic carbon (SOC) in humid tropics is contingent upon the stability of soil minerals. According to Epron et al. (2015), a sand-based eucalypt plantation in the Congolese coastal plains had a decrease in carbon accretion after three rotations, 21 years after it was planted. After 7 years, carbon accumulation was noticed at the end of the initial phase of eucalyptus and acacia plantings along a section of the Congolese coastline. However, the proportion of carbon in particulate organic matter reduced by 5% after two years into the second rotation. The presence of high nitrogen content in the fresh organic waste from the plantation, along with the low capacity of sandy soils to retain carbon, is expected to result in an increase in soil organic matter turnover (Epron et al., 2015).

Accelerated breakdown rates hinder the process of carbon sequestration. The occurrence of this phenomenon is attributed to environmental factors such as drought and extended dry seasons, as well as management practices such as leaving organic residues on the field after wood collection. Additionally, reforestation efforts have also been identified as a contributing factor (Epron et al., 2015; Akpa et al., 2016; Raihan, 2023h). Marin-Spiotta and Sharma (2013) examined soil carbon data from 510 sites where tropical afforestation and reforestation took place in 32 different nations and territories. The study concluded that soil carbon variability in successional and forest plantation ecosystems is primarily influenced by climatic change, rather than land use or forest age. This study revealed that there was no correlation between the age of tropical forest plantings and the amount of carbon reserves in the soil. In their study, Campo et al. (2016) examined the soils of Mexico's tropical forests and compared them under varying precipitation patterns. They proposed the hypothesis that soils experiencing prolonged drought periods may contain a greater amount of resilient biopolymers, leading to the accumulation of organic matter through selective preservation. The possible diversion of SOC could result in the destruction of forest ecosystems, which may take several decades to recover. Research conducted by Cook et al. (2014) in Southeast Brazil revealed that it took over twenty years for the soil SOC stores of native forests to recover to their original levels after being transformed from mature forests to forest plantations and grasslands. Saynes et al. (2005) discovered that the restoration of soil carbon and nitrogen processes in primary and secondary seasonally dry tropical forests in central Mexico took 60 years to fully occur during secondary succession.

Researchers observed a change in soil organic carbon (SOC) levels at 27 places in South America (Brazil, Argentina, and Uruguay) thirty years after establishing a plantation or pasture, according to Eclesia et al. (2012).
Tropical forest ecosystems have numerous barriers that hinder their ability to absorb carbon, support land restoration, and mitigate climate change (Raihan, 2023i). Possible factors contributing to this phenomenon include the disparity in knowledge and inaccuracies in measurement in certain domains, as well as the impact of socioeconomic impacts, which are interconnected with social, economic, environmental, and political contexts. The forests in Kalimantan, which have been damaged and are at risk due to palm oil plantations and peatland fires, have the potential to store between 0.8 and 1.1 PgC (petagrams of carbon), as determined by emission assessments using lidar or a random forest map (Ferraz et al., 2018). The scientists concluded that the damaged forests in Kalimantan have a significantly higher capacity for storing carbon than the second-growth forests in South America (35.33 Mg Cha^{-1}).

SOC and land degradation restoration in tropical forests

Nutrients such as nitrogen and phosphorus have the potential to influence both the overall quantity and duration of soil organic carbon (SOC) that is stored. The availability of nitrogen is connected to the storage of carbon dioxide (Liu et al., 2018). Multiple studies on the dynamics of soil carbon indicate that nitrogen deposition can increase the storage of carbon in the soil through different methods. These mechanisms encompass the reduction of plant litter and soil organic matter breakdown, the inhibition of soil respiration, and the alteration of microbial enzymatic activity (Lu et al., 2021). The process of nitrogen fixation allows for the accumulation of carbon in mixed-species plantations, which has been associated with elevated rates of carbon sequestration (Bauters et al., 2015; Dubliez et al., 2018). Raised soil nitrogen (N) levels can enhance the accumulation of soil organic carbon (SOC) by promoting plant development both below and above ground (Fornara et al., 2013). Nitrogen-fixing plants have the potential to improve the long-term stability of soil organic matter by causing changes in living organisms through the addition of nitrogen-rich plant material (Bini et al., 2018; Pereira et al., 2018). Cusack et al. (2010) discovered that the addition of nitrogen improved the storage of soil organic carbon (SOC) in two tropical forest soils in Puerto Rico. While nitrogen deposition and climate change are acknowledged as worldwide factors that impact the stability of sequestered soil organic carbon (SOC) in tropical forest ecosystems, the authors assert that there is still much to be comprehended.
The sequestration of soil organic carbon (SOC) occurs concurrently with phosphorus (P), which is a crucial element for the growth of plants, the increase of timber production, and the agricultural output. Phosphorus availability is connected to soil organic carbon (SOC) mineralization in tropical forests, even though phosphorus is a restricting factor in many of these ecosystems (Bachega et al., 2016). The lack of phosphorus in the litter of *A. mangium*, a natural substitute for fertilizer, led to a stoichiometric imbalance (N:P) which caused hunger or inhibition of decomposers, as well as reduced microbial biomass and activity (Santos et al., 2017). Microbial communities have low C:N:P ratios in comparison to the soil and the material they decompose, which means they need significant amounts of nitrogen (N) and phosphorus (P). Bacteria have a limited capacity to hold nitrogen and phosphorus, and once this capacity is reached, they start to release these elements (Schleuss et al., 2020). The availability of nitrogen (N) in the soil is limited, while there is a significant demand for phosphorus (P) (Schleuss et al., 2020). Typically, diverse species stands with Sensitive kinds show synergistic effects in the accumulation of P and C, as opposed to monoculture plantations.
The presence of animals and microbes in the soil also impacts the superiority of sequestered SOC (Bini et al., 2018; Pereira et al., 2018; Santos et al., 2017). The decomposition of litter in monocultures was controlled by water-soluble components and the concentration of lignin. However, in tropical forests, the activity of decomposers was restricted by the availability of energy or phosphorus (P). An alteration in the composition of soil microorganisms and bacteria is linked to heightened microbial activity in litter and soil, suggesting enhanced efficiency in the process of nitrogen cycling (Bini et al., 2018). The study conducted in Puerto Rico by Cusack et al. (2010) found that the cycling of carbon in two nitrogen-rich tropical forest soils was influenced by the composition of the microbial community, the capacities of enzymes, and the chemistry of soil carbon. The text demonstrates the role of microorganisms in enhancing the storage of soil organic carbon (SOC) and its

connection to essential nutrients such as nitrogen and phosphorus. The soil processes in tropical forests provide stable, less mineralized carbon, which plays a crucial role in mitigating climate change and facilitating land restoration (Baccini et al., 2017; Raihan, 2023j). Figure 3 illustrates the connection between established sequestered soil organic carbon (SOC) and extra nutrients, which contribute to the maintenance of SOC sequestration and its associated co-benefits.

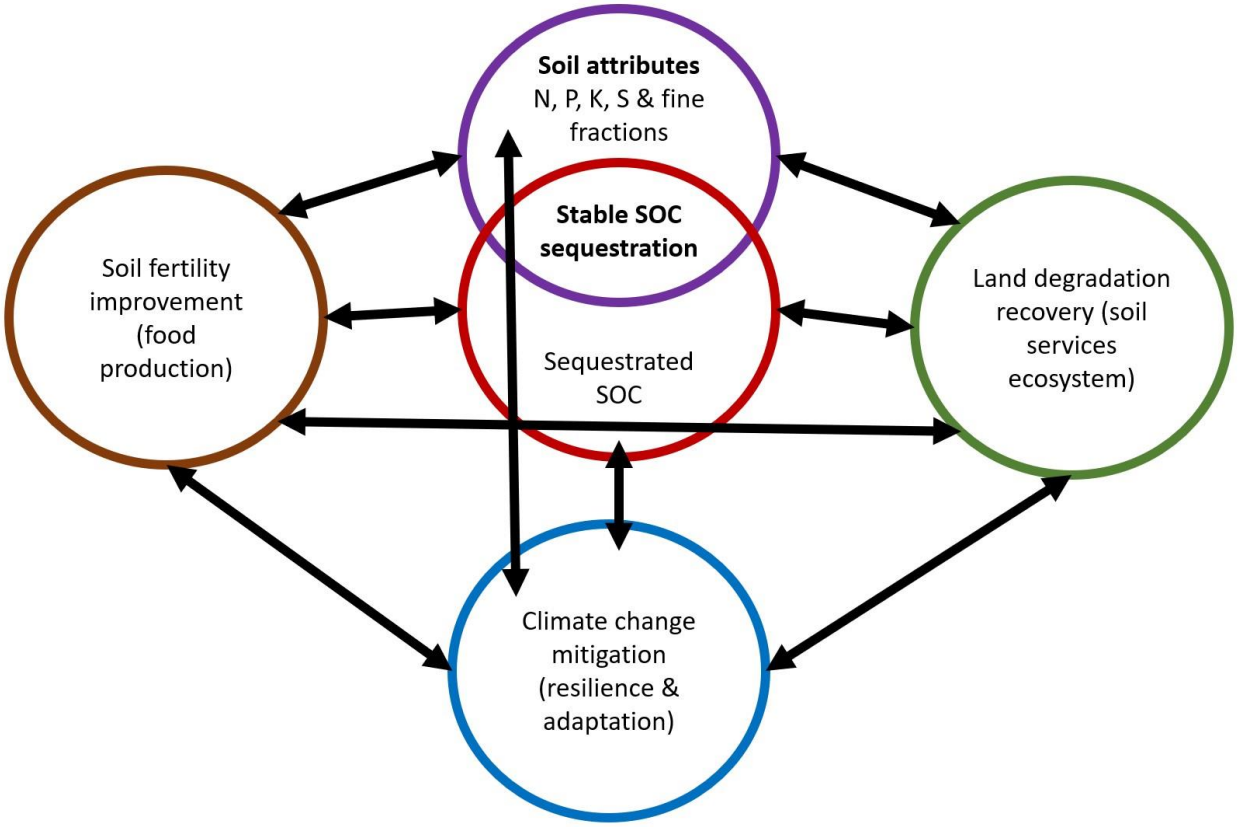


Figure 3. Conceptual framework of stable SOC sequestration and its co-benefits.

The stable segregation of SOC (soil organic carbon) and its subsidies on land restitution are enhanced by the dynamics of other nutrients such as nitrogen (N), phosphorus (P), and sulfur (S). The relationship between carbon (C) and nitrogen (N), phosphorus (P), and sulfur (S) is important for enhancing the physical properties of clusters and the chemical disposal of N, P, and S. Additionally, this relationship helps convert volatile carbon from agricultural and animal waste into stable soil organic matter (SOM) (Lal, 2013). The availability of inorganic nutrients such as nitrogen (N), phosphorus (P), and sulfur (S) is crucial for the storage of carbon (C) in the deeper layers of the soil organic matter (SOM) community. This holds true independent of the type of soil or the response of carbon. McDonald et al. (2018) demonstrated strong correlations among decomposition proportions, photosynthesis, and the soil's capacity to retain carbon, nitrogen, and phosphorus. This addresses a part of the second point raised in the review by demonstrating a connection between the quality of the sequestered SOC (its association with other N, P nutrients), land recovery, and the long-term benefits in tropical forest ecosystems.

Brazilian forests that have undergone degradation have been transformed into regions that trap carbon through the assistance of legume plants, nitrogen-fixing microorganisms, and arbuscular mycorrhizal fungus (Macedo et al., 2008). The scientists found that after 13 years of planting legume trees, there was a 23 Mg ha^{-1} increase in soil carbon stock and a 1.7 Mg ha^{-1} increase in nitrogen stock in the deforested region, assuming it had the same carbon stocks as the restored area (Macedo et al., 2008). Natural fertilizer substitutes (NFS) are commonly employed to enhance the chemical fertility of agriculturally inappropriate or marginal soils (Raihan, 2024b).

The objective can be achieved by enhancing the nitrogen (N) levels and carbon (C) status, as demonstrated by Wang et al. (2010) and Chen et al. (2011). The study conducted by Wang et al. (2010) found that the use of *Acacia mangium* and *A. auriculiformis* in the restoration of southern Chinese soils improved the processes of carbon and nitrogen cycling. In their study, Chen et al. (2011) found that *Acacia crassicarpa* stands in Guangdong Province, Southern China, had larger carbon sinks and higher stocks of soil organic carbon (SOC) compared to *Eucalyptus urophylla* stands. The carbon sink for *Acacia crassicarpa* stands was measured at 330±76 C m^{-2} yr^{-1}, while for *Eucalyptus urophylla* stands it was 1960±178 g C m^{-2} yr^{-1}. A comparison of *A. mangium* and *E. urophylla* plantations, as well as the resulting woodlands and meadows, across different soil and climate conditions in Vietnam, shows a positive relationship between aboveground biomass production and levels of soil carbon, nitrogen, and phosphorus (Sang et al., 2013; Raihan, 2023k). In Malaysia, Ahmed et al. (2010) discovered that the concentrations of total carbon (C) and phosphorus (P) increased progressively from ages 0 to 6, 12, and 17. Studies have shown that restored forests with native plants are capable of absorbing carbon and phosphorus.

Unforeseen circumstances can hinder the use of NFS plants for carbon sequestration and land restoration. The presence of clay in the soil, the amount of rainfall received annually, and the average temperature all influence the amount of carbon stored in the soil of eucalypt plantations in Brazil. This relationship may also hold true for other species, as suggested by Cook et al. (2014) who found that the soil organic carbon (SOC) stock decreases as eucalypt planting age increases in tropical and subtropical areas. They observed a decline from an average of 29 Mg ha^{-1} to 0.87 Mg $ha^{-1}yr^{-1}$ over a depth of 0-30 cm beneath eucalypt plantations aged 18-26 years. The findings of this study demonstrate that the sequestration of soil organic carbon (SOC) is a direct effect of managing organic deposits or introducing NFS in the restoration or refurbishment of degraded lands or forests.

Conclusions

This review examined forest management techniques that enhance the sequestration of soil organic carbon (SOC) and the restoration of land, with the goal of improving the state of SOC stored in tropical forest ecosystems. The study also explored the influence of soil biota on the interactions between SOC and other nutrients. However, SOC sequestration may not always occur since it is influenced by factors such as edaphic conditions, land-use history, climate, ecosystem characteristics, and intrinsic features. This is due to the possibility of SOC becoming sequestered within a system. Effective carbon sequestration management is crucial for the restoration of degraded lands in tropical ecosystems, the mitigation of climate change impacts, and the preservation of soil health. Soil biota plays a crucial role in the sequestration of carbon and has important interactions with other components of soil, such as nitrogen, phosphorus, and sulfur. Managing forest ecosystems, whether through planting or allowing natural growth, involves implementing specific methods such as initiating National Forest Systems and overseeing organic deposits. These methods generally enhance the sequestration of soil organic carbon (SOC) and can lead to long-term benefits in terms of mitigating climate change and restoring land. These benefits can be attained by effectively managing forest ecosystems, which involves maintaining a proper balance of carbon, as well as ensuring a strong connection to nitrogen, phosphorus, and soil components.

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Authors contribution: Asif Raihan contributed to the study's conception and design. Material preparation, methodology development, reviewing literature, extracting information, synthesize, and manuscript writing were performed by Asif Raihan, Md. Shoaibur Rahman, Samanta Islam, Pramila Paul, and Sourav Karmakar. The first draft of the manuscript was written by Asif Raihan and Md. Shoaibur Rahman commented on previous versions of the manuscript. All authors read and approved the final manuscript.

References

Ahmed, O. H., Hasbullah, N. A., & Ab Majid, N. M. (2010). Accumulation of soil carbon and phosphorus contents of a rehabilitated forest. *The Scientific World Journal*, *10*, 1988-1995.

Akpa, S. I., Odeh, I. O., Bishop, T. F., Hartemink, A. E., & Amapu, I. Y. (2016). Total soil organic carbon and carbon sequestration potential in Nigeria. *Geoderma*, *271*, 202-215.

Ali, A., Rahman, S., & Raihan, A. (2022). Soil carbon sequestration in agroforestry systems as a mitigation strategy of climate change: a case study from Dinajpur, Bangladesh. *Advances in Environmental and Engineering Research*, *3*(4), 1-15.

Aragón, S., Salinas, N., Nina-Quispe, A., Qquellon, V. H., Paucar, G. R., Huaman, W., ... & Roman-Cuesta, R. M. (2021). Aboveground biomass in secondary montane forests in Peru: Slow carbon recovery in agroforestry legacies. *Global Ecology and Conservation*, *28*, e01696.

Baccini, A., Walker, W., Carvalho, L., Farina, M., Sulla-Menashe, D., & Houghton, R. A. (2017). Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science*, *358*(6360), 230-234.

Bachega, L. R., Bouillet, J. P., de Cássia Piccolo, M., Saint-André, L., Bouvet, J. M., Nouvellon, Y., ... & Laclau, J. P. (2016). Decomposition of Eucalyptus grandis and Acacia mangium leaves and fine roots in tropical conditions did not meet the Home Field Advantage hypothesis. *Forest Ecology and Management*, *359*, 33-43.

Bauters, M., Ampoorter, E., Huygens, D., Kearsley, E., De Haulleville, T., Sellan, G., ... & Verheyen, K. (2015). Functional identity explains carbon sequestration in a 77-year-old experimental tropical plantation. *Ecosphere*, *6*(10), 1-11.

Begum, R. A., Raihan, A., & Said, M. N. M. (2020). Dynamic impacts of economic growth and forested area on carbon dioxide emissions in Malaysia. *Sustainability*, *12*(22), 9375.

Biber, P., Felton, A., Nieuwenhuis, M., Lindbladh, M., Black, K., Bahýl', J., ... & Tuček, J. (2020). Forest biodiversity, carbon sequestration, and wood production: modeling synergies and trade-offs for ten forest landscapes across Europe. *Frontiers in Ecology and Evolution*, *8*, 547696.

Bini, D., Santos, C. A. D., Silva, M. C. P. D., Bonfim, J. A., & Cardoso, E. J. B. N. (2018). Intercropping Acacia mangium stimulates AMF colonization and soil phosphatase activity in Eucalyptus grandis. *Scientia Agricola*, *75*, 102-110.

Bond, W. J., Stevens, N., Midgley, G. F., & Lehmann, C. E. (2019). The trouble with trees: afforestation plans for Africa. *Trends in ecology & evolution*, *34*(11), 963-965.

Bonfatti, B. R., Hartemink, A. E., Giasson, E., Tornquist, C. G., & Adhikari, K. (2016). Digital mapping of soil carbon in a viticultural region of Southern Brazil. *Geoderma*, *261*, 204-221.

Brown, H. C., Berninger, F. A., Larjavaara, M., & Appiah, M. (2020). Above-ground carbon stocks and timber value of old timber plantations, secondary and primary forests in southern Ghana. *Forest ecology and management*, *472*, 118236.

Buotte, P. C., Law, B. E., Ripple, W. J., & Berner, L. T. (2020). Carbon sequestration and biodiversity co-benefits of preserving forests in the western United States. *Ecological Applications*, *30*(2), e02039.

Camacho, L. D., Camacho, S. C., & Youn, Y. C. (2009). Carbon sequestration benefits of the Makiling forest reserve, Philippines. *Forest Science and Technology*, *5*(1), 23-30.

Campo, J., & Merino, A. (2016). Variations in soil carbon sequestration and their determinants along a precipitation gradient in seasonally dry tropical forest ecosystems. *Global Change Biology*, *22*(5), 1942-1956.

Crezee, B., Dargie, G. C., Ewango, C. E., Mitchard, E. T., Emba B, O., Kanyama T, J., ... & Lewis, S. L. (2022). Mapping peat thickness and carbon stocks of the central Congo Basin using field data. *Nature Geoscience*, *15*(8), 639-644.

Chayaporn, P., Sasaki, N., Venkatappa, M., & Abe, I. (2021). Assessment of the overall carbon storage in a teak plantation in Kanchanaburi province, Thailand–Implications for carbon-based incentives. *Cleaner Environmental Systems*, *2*, 100023.

Chen, D., Zhang, C., Wu, J., Zhou, L., Lin, Y., & Fu, S. (2011). Subtropical plantations are large carbon sinks: evidence from two monoculture plantations in South China. *Agricultural and Forest Meteorology*, *151*(9), 1214-1225.

Chinade, A. A., Siwar, C., Ismail, S. M., & Isahak, A. (2015). A review on carbon sequestration in Malaysian forest soils: Opportunities and barriers. *International Journal of Soil Science*, *10*(1), 17.

Cook, R. L., Binkley, D., Mendes, J. C. T., & Stape, J. L. (2014). Soil carbon stocks and forest biomass following conversion of pasture to broadleaf and conifer plantations in southeastern Brazil. *Forest Ecology and Management*, *324*, 37-45.

Cook, R. L., Binkley, D., & Stape, J. L. (2016). Eucalyptus plantation effects on soil carbon after 20 years and three rotations in Brazil. *Forest Ecology and Management*, *359*, 92-98.

Cusack, D. F., Torn, M. S., McDOWELL, W. H., & Silver, W. L. (2010). The response of heterotrophic activity and carbon cycling to nitrogen additions and warming in two tropical soils. *Global Change Biology*, *16*(9), 2555-2572.

Derwisch, S., Schwendenmann, L., Olschewski, R., & Hölscher, D. (2009). Estimation and economic evaluation of aboveground carbon storage of Tectona grandis plantations in Western Panama. *New Forests*, *37*, 227-240.

Domke, G. M., Oswalt, S. N., Walters, B. F., & Morin, R. S. (2020). Tree planting has the potential to increase carbon sequestration capacity of forests in the United States. *Proceedings of the national academy of sciences*, *117*(40), 24649-24651.

Dou, X., Xu, X., Shu, X., Zhang, Q., & Cheng, X. (2016). Shifts in soil organic carbon and nitrogen dynamics for afforestation in central China. *Ecological Engineering*, *87*, 263-270.

Dubiez, E., Freycon, V., Marien, J. N., Peltier, R., & Harmand, J. M. (2019). Long term impact of Acacia auriculiformis woodlots growing in rotation with cassava and maize on the carbon and nutrient contents of savannah sandy soils in the humid tropics (Democratic Republic of Congo). *Agroforestry Systems*, *93*, 1167-1178.

Eclesia, R. P., Jobbagy, E. G., Jackson, R. B., Biganzoli, F., & Piñeiro, G. (2012). Shifts in soil organic carbon for plantation and pasture establishment in native forests and grasslands of South America. *Global Change Biology*, *18*(10), 3237-3251.

Epron, D., Mouanda, C., Mareschal, L., & Koutika, L. S. (2015). Impacts of organic residue management on the soil C dynamics in a tropical eucalypt plantation on a nutrient-poor sandy soil after three rotations. *Soil Biology and Biochemistry*, *85*, 183-189.

FAO. (2020). Global Forest Resources Assessment 2020. FAO, Rome, Italy, 2020. http://www.fao.org/forest-resourcesassessment/2020 (Accessed: 11 February 2023).

Fernández-Martínez, M., Sardans, J., Chevallier, F., Ciais, P., Obersteiner, M., Vicca, S., ... & Peñuelas, J. (2019). Global trends in carbon sinks and their relationships with CO_2 and temperature. *Nature climate change*, *9*(1), 73-79.

Ferraz, A., Saatchi, S., Xu, L., Hagen, S., Chave, J., Yu, Y., ... & Ganguly, S. (2018). Carbon storage potential in degraded forests of Kalimantan, Indonesia. *Environmental Research Letters*, *13*(9), 095001.

Forest Survey of India. (2017). Carbon stock in India's Forests. Indian State Forest Report, 8, 120-127.

F Fornara, D. A., Banin, L., & Crawley, M. J. (2013). Multi-nutrient vs. nitrogen-only effects on carbon sequestration in grassland soils. *Global Change Biology*, *19*(12), 3848-3857.

Jaafar, W. S. W. M., Maulud, K. N. A., Kamarulzaman, A. M. M., Raihan, A., Sah, S. M., Ahmad, A., Saad, S. N. M., Azmi, A. T. M., Syukri, N. K. A. J., & Khan, W. R. (2020). The influence of forest degradation on land surface temperature–a case study of Perak and Kedah, Malaysia. *Forests, 11*(6), 670.

Joshi, R., Singh, H., Chhetri, R., & Yadav, K. (2020). Assessment of carbon sequestration potential in degraded and non-Degraded community forests in Terai Region of Nepal. *Journal of forest and environmental science*, *36*(2), 113-121.

Lal, R. (2013). Soil carbon management and climate change. *Carbon Management*, *4*(4), 439-462.

Lee, K. L., Ong, K. H., King, P. J. H., Chubo, J. K., & Su, D. S. A. (2015). Stand productivity, carbon content, and soil nutrients in different stand ages of Acacia mangium in Sarawak, Malaysia. *Turkish Journal of Agriculture and Forestry*, *39*(1), 154-161.

Lu, X., Vitousek, P. M., Mao, Q., Gilliam, F. S., Luo, Y., Turner, B. L., ... & Mo, J. (2021). Nitrogen deposition accelerates soil carbon sequestration in tropical forests. *Proceedings of the National Academy of Sciences*, *118*(16), e2020790118.

Liu, J., Yang, Z., Dang, P., Zhu, H., Gao, Y., Ha, V. N., & Zhao, Z. (2018). Response of soil microbial community dynamics to Robinia pseudoacacia L. afforestation in the loess plateau: a chronosequence approach. *Plant and Soil*, *423*, 327-338.

Macedo, M. O., Resende, A. S., Garcia, P. C., Boddey, R. M., Jantalia, C. P., Urquiaga, S., ... & Franco, A. A. (2008). Changes in soil C and N stocks and nutrient dynamics 13 years after recovery of degraded land using leguminous nitrogen-fixing trees. *Forest Ecology and Management*, *255*(5-6), 1516-1524.

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M. G., Field, C. B., & Knowlton, N. (2020). Climate change and ecosystems: Threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B*, *375*(1794), 20190104.

Marín-Spiotta, E., & Sharma, S. (2013). Carbon storage in successional and plantation forest soils: a tropical analysis. *Global Ecology and Biogeography*, *22*(1), 105-117.

Mayer, M., Prescott, C. E., Abaker, W. E., Augusto, L., Cécillon, L., Ferreira, G. W., ... & Vesterdal, L. (2020). Tamm Review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. *Forest Ecology and Management*, *466*, 118127.

McDonald, C. A., Delgado-Baquerizo, M., Reay, D. S., Hicks, L. C., & Singh, B. K. (2018). Soil nutrients and soil carbon storage: modulators and mechanisms. In *Soil carbon storage* (pp. 167-205). Academic Press.

Ontl, T. A., Janowiak, M. K., Swanston, C. W., Daley, J., Handler, S., Cornett, M., ... & Patch, N. (2020). Forest management for carbon sequestration and climate adaptation. *Journal of Forestry*, *118*(1), 86-101.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., ... & Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *Science*, *333*(6045), 988-993.

Paniagua-Ramirez, A., Krupinska, O., Jagdeo, V., & Cooper, W. J. (2021). Carbon storage estimation in a secondary tropical forest at CIEE Sustainability Center, Monteverde, Costa Rica. *Scientific reports*, *11*(1), 23464.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49-57.

Pereira, A. P., Zagatto, M. R., Brandani, C. B., Mescolotti, D. D. L., Cotta, S. R., Gonçalves, J. L., & Cardoso, E. J. (2018). Acacia changes microbial indicators and increases C and N in soil organic fractions in intercropped Eucalyptus plantations. *Frontiers in microbiology*, *9*, 655.

Raihan, A. (2023a). The dynamic nexus between economic growth, renewable energy use, urbanization, industrialization, tourism, agricultural productivity, forest area, and carbon dioxide emissions in the Philippines. *Energy Nexus*, *9*, 100180.

Raihan, A. (2023b). Toward sustainable and green development in Chile: dynamic influences of carbon emission reduction variables. *Innovation and Green Development*, *2*(2), 100038.

Raihan, A. (2023c). Artificial intelligence and machine learning applications in forest management and biodiversity conservation. *Natural Resources Conservation and Research, 6*(2), 3825.

Raihan, A. (2023d). A review of tropical blue carbon ecosystems for climate change mitigation. Journal of *Environmental Science and Economics, 2*(4), 14-36.
Raihan, A. (2023e). Sustainable development in Europe: A review of the forestry sector's social, environmental, and economic dynamics. *Global Sustainability Research, 2*(3), 72-92.
Raihan, A. (2023f). A review of the global climate change impacts, adaptation strategies, and mitigation options in the socio-economic and environmental sectors. *Journal of Environmental Science and Economics, 2*(3), 36-58.
Raihan, A. (2023g). The influences of renewable energy, globalization, technological innovations, and forests on emission reduction in Colombia. *Innovation and Green Development, 2*, 100071.
Raihan, A. (2023h). A concise review of technologies for converting forest biomass to bioenergy. *Journal of Technology Innovations and Energy, 2*(3), 10-36.
Raihan, A. (2023i). A review on the integrative approach for economic valuation of forest ecosystem services. *Journal of Environmental Science and Economics, 2*(3), 1-18.
Raihan, A. (2023j). The contribution of economic development, renewable energy, technical advancements, and forestry to Uruguay's objective of becoming carbon neutral by 2030. *Carbon Research, 2*, 20.
Raihan, A. (2023k). An econometric evaluation of the effects of economic growth, energy use, and agricultural value added on carbon dioxide emissions in Vietnam. *Asia-Pacific Journal of Regional Science, 7*, 665-696.
Raihan, A. (2024a). The potential of agroforestry in South Asian countries towards achieving the climate goals. *Asian Journal of Forestry 8*(1), 1-17.
Raihan, A. (2024b). A Systematic Review of Geographic Information Systems (GIS) in Agriculture for Evidence-Based Decision Making and Sustainability. *Global Sustainability Research, 3*(1), 1-24.
Raihan, A., Begum, R. A., Said, M. N. M., & Abdullah, S. M. S. (2018). Climate change mitigation options in the forestry sector of Malaysia. *J. Kejuruter*, *1*(6), 89-98.
Raihan, A., Begum, R. A., Mohd Said, M. N., & Abdullah, S. M. S. (2019). A review of emission reduction potential and cost savings through forest carbon sequestration. *Asian Journal of Water, Environment and Pollution*, *16*(3), 1-7.
Raihan, A., Begum, R. A., & Said, M. N. M. (2021a). A meta-analysis of the economic value of forest carbon stock. *Geografia–Malaysian Journal of Society and Space*, *17*(4), 321-338.
Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2021b). Assessment of carbon stock in forest biomass and emission reduction potential in Malaysia. *Forests*, *12*(10), 1294.
Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2022a). Dynamic impacts of energy use, agricultural land expansion, and deforestation on CO_2 emissions in Malaysia. *Environmental and Ecological Statistics*, *29*(3), 477-507.
Raihan, A., Begum, R. A., Said, M. N. M., & Pereira, J. J. (2022b). Relationship between economic growth, renewable energy use, technological innovation, and carbon emission toward achieving Malaysia's Paris agreement. *Environment Systems and Decisions*, *42*(4), 586-607.
Raihan, A., & Bijoy, T. R. (2023). A review of the industrial use and global sustainability of Cannabis sativa. *Global Sustainability Research*, *2*(4), 1-29.
Raihan, A., Muhtasim, D. A., Farhana, S., Hasan, M. A. U., Pavel, M. I., Faruk, O., ... & Mahmood, A. (2023a). An econometric analysis of Greenhouse gas emissions from different agricultural factors in Bangladesh. *Energy Nexus*, *9*, 100179.
Raihan, A., Muhtasim, D. A., Farhana, S., Pavel, M. I., Faruk, O., Rahman, M., & Mahmood, A. (2022c). Nexus between carbon emissions, economic growth, renewable energy use, urbanization, industrialization, technological innovation, and forest area towards achieving environmental sustainability in Bangladesh. *Energy and Climate Change*, *3*, 100080.
Raihan, A., Muhtasim, D. A., Farhana, S., Rahman, M., Hasan, M. A. U., Paul, A., & Faruk, O. (2023b). Dynamic linkages between environmental factors and carbon emissions in Thailand. *Environmental Processes*, *10*(1), 5.
Raihan, A., Muhtasim, D. A., Pavel, M. I., Faruk, O., & Rahman, M. (2022d). An econometric analysis of the potential emission reduction components in Indonesia. *Cleaner Production Letters*, *3*, 100008.

Raihan, A., Pavel, M. I., Muhtasim, D. A., Farhana, S., Faruk, O., & Paul, A. (2023c). The role of renewable energy use, technological innovation, and forest cover toward green development: Evidence from Indonesia. *Innovation and Green Development*, *2*(1), 100035.

Raihan, A., & Said, M. N. M. (2022). Cost–benefit analysis of climate change mitigation measures in the forestry sector of Peninsular Malaysia. *Earth Systems and Environment*, *6*(2), 405-419.

Raihan, A., & Tuspekova, A. (2022a). Dynamic impacts of economic growth, energy use, urbanization, tourism, agricultural value-added, and forested area on carbon dioxide emissions in Brazil. *Journal of Environmental Studies and Sciences*, *12*(4), 794-814.

Raihan, A., & Tuspekova, A. (2022b). Nexus between energy use, industrialization, forest area, and carbon dioxide emissions: New insights from Russia. *Journal of Environmental Science and Economics*, *1*(4), 1-11.

Raihan, A., & Tuspekova, A. (2022c). Toward a sustainable environment: Nexus between economic growth, renewable energy use, forested area, and carbon emissions in Malaysia. *Resources, Conservation & Recycling Advances*, *15*, 200096.

Raihan, A., & Tuspekova, A. (2022d). Dynamic impacts of economic growth, energy use, urbanization, agricultural productivity, and forested area on carbon emissions: New insights from Kazakhstan. *World Development Sustainability*, *1*, 100019.

Raihan, A., & Tuspekova, A. (2022e). Dynamic impacts of economic growth, renewable energy use, urbanization, industrialization, tourism, agriculture, and forests on carbon emissions in Turkey. *Carbon Research*, *1*(1), 20.

Raihan, A., & Tuspekova, A. (2022f). Nexus between emission reduction factors and anthropogenic carbon emissions in India. *Anthropocene Science*, *1*(2), 295-310.

Raihan, A., & Tuspekova, A. (2023). Towards net zero emissions by 2050: the role of renewable energy, technological innovations, and forests in New Zealand. *Journal of Environmental Science and Economics*, *2*(1), 1-16.

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T., Salas, W., ... & Morel, A. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the national academy of sciences*, *108*(24), 9899-9904.

Sang, P. M., Lamb, D., Bonner, M., & Schmidt, S. (2013). Carbon sequestration and soil fertility of tropical tree plantations and secondary forest established on degraded land. *Plant and Soil*, *362*, 187-200.

Santos, F. M., Balieiro, F. D. C., Fontes, M. A., & Chaer, G. M. (2018). Understanding the enhanced litter decomposition of mixed-species plantations of Eucalyptus and Acacia mangium. *Plant and soil*, *423*, 141-155.

Satakhun, D., Chayawat, C., Sathornkich, J., Phattaralerphong, J., Chantuma, P., Thaler, P., ... & Kasemsap, P. (2019). Carbon sequestration potential of rubber-tree plantation in Thailand. In *IOP Conference Series: Materials Science and Engineering,* 526(1), 012036.

Sang, P. M., Lamb, D., Bonner, M., & Schmidt, S. (2013). Carbon sequestration and soil fertility of tropical tree plantations and secondary forest established on degraded land. *Plant and Soil*, *362*, 187-200.

Sayer, E. J., Lopez-Sangil, L., Crawford, J. A., Bréchet, L. M., Birkett, A. J., Baxendale, C., ... & Schmidt, M. W. (2019). Tropical forest soil carbon stocks do not increase despite 15 years of doubled litter inputs. *Scientific Reports*, *9*(1), 18030.

Saynes, V., Hidalgo, C., Etchevers, J. D., & Campo, J. E. (2005). Soil C and N dynamics in primary and secondary seasonally dry tropical forests in Mexico. *Applied Soil Ecology*, *29*(3), 282-289.

Schleuss, P. M., Widdig, M., Heintz-Buschart, A., Kirkman, K., & Spohn, M. (2020). Interactions of nitrogen and phosphorus cycling promote P acquisition and explain synergistic plant-growth responses. *Ecology*, *101*(5), e03003.

Situmorang, J. P., & Sugianto, S. (2016). Estimation of carbon stock stands using EVI and NDVI vegetation index in production forest of Lembah Seulawah sub-district, Aceh Indonesia. *Aceh International Journal of Science and Technology*, *5*(3), 126-139.

Shimamoto, C. Y., Padial, A. A., da Rosa, C. M., & Marques, M. C. (2018). Restoration of ecosystem services in tropical forests: A global meta-analysis. *PloS one*, *13*(12), e0208523.

Soussana, J. F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., ... & Lal, R. (2019). Matching policy and science: Rationale for the '4 per 1000-soils for food security and climate'initiative. *Soil and Tillage Research*, *188*, 3-15.

Wang, F., Li, Z., Xia, H., Zou, B., Li, N., Liu, J., & Zhu, W. (2010). Effects of nitrogen-fixing and non-nitrogen-fixing tree species on soil properties and nitrogen transformation during forest restoration in southern China. *Soil Science & Plant Nutrition*, *56*(2), 297-306.

Zapfack, L., Noiha, N. V., & Tabue, M. R. B. (2016). Economic estimation of carbon storage and sequestration as ecosystem services of protected areas: a case study of Lobeke National Park. *Journal of Tropical Forest Science*, 406-415.

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RESARCH ARTICLE

The effect of silicon-based preparation on the amount of humus and essential nutrients in the soil

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Abstract
In today's changing climate, increasing agricultural land use and soil productivity, as well as ensuring the availability of soil organic matter and soil essential nutrients, is becoming increasingly difficult. Farmers can increase crop yields by directly applying many commercial products and various pesticides to the soil, but this is only for this period. Due to the negative impact of such preparations on the basic properties of the soil, they can lead to the destruction of the soil structure in subsequent years. For long-term use of soil, it is very important that the fertilizers or preparations used are environmentally friendly and scientifically based. Today, to improve the relationship between soil and plant, many silicon-containing preparations are processed into the soil. This study examined the effect of silicon-containing Aminosid-Si and other Aminosid-Aton, Bionitrogen preparations on the amount of humus in the soil, the total content of N, P, K and $N\text{-}NH_4$, $N\text{-}NH_3$, P_2O_5 and K_2O has been studied. Studies have been conducted comparing the effects of silicon-containing preparations with the effects of other preparations. Because of the study, positive results were recorded for the preparation of Aminosid-Si.

Keywords: Soil; Silicon; Silicon fertilizer; Humus; gross and mobile nitrogen; phosphorus

Introduction

Soil is a non-renewable dynamic natural resource that is essential to life. As a substrate for growing plants, soil is important. In support of a wide range of animal and human activities. The soil is a supply of nutrients and water that is suitable for the needs of plants in their growth. Soil can also serve as a medium for decomposition and immobilization of materials added to the surface (in addition to the above-mentioned plant and animal debris), such as fertilizers and pesticides and wastes such as sewage sludge, animal waste and slurries, and composted waste (Urra et al. 2019) The soil is a multifaceted and ever-changing system where the interactions of biological, chemical, and physical elements lead to the conversion of materials. This process can potentially make harmful substances less hazardous while also immobilizing certain elements due to the interplay between added materials and the organic and inorganic components of the soil (Li et al. 2022). The breakdown of the potentially hazardous materials into less hazardous forms may be made possible by this immobilization (Tang et al. 2020).

These interactions and transformations may be long term, over decades, medium term over months or years, short term between individual events such as rainstorms, or almost instantaneous (Nemerow et al. 2009). Typically, the soil is composed of a series of vertical layers or horizons that are distinguished by differences in their physical, chemical, or biological properties (Adewara et al. 2024). Understanding the agrochemical properties of soil, or its nutritional components, is crucial when assessing the soil's nutritional value (Luo et al. 2023). Today, many studies are focusing on the presence of silicon in soil and its forms available to plants. Silicon (Si), next to oxygen, the most abundant element on the Earth's surface as well as in the soil, is useful for plants according to their growth and development in various environmental conditions. (Liang et al. 2005; Rasoolizadeh et al. 2018). Normally, Si is presented in various forms in the soil and in abundance especially the quartz, silicates, biogenic SiO_2 (e.g diatoms and phytoliths) and silica gel (Liang et al. 2005; Sommer et al. 2006). The extractable forms of Si in the soil include amorphous, active, and water soluble Si (Khan et al. 2021). Water-soluble forms of Si can be directly available to plants, while the remaining Si is first converted to a water-soluble form under favorable conditions and then readily available to plants. (Ali et al. 2020). Si as silicic acid ranges from 0.1 to 0.6 mM in the soil, which is roughly two times higher than the concentration of phosphorus in the soil solution (Epstein 1999). It has been reported that Si is not on the list of essential elements, but it is involved in growth and development processes and has extensive functions in plant metabolism, especially in graminaceous and cyperaceae species (Epstein 1999; Liang et al. 2005). Nevertheless, numerous environmental and soil factors have a substantial impact on the bioavailability of Si in the soil and its subsequent transportation to plants (Hao et al. 2020). The occurrence of abundant rainfall causes the leaching of silicon (Si) and the subsequent decrease in soil pH, which in turn adversely affects the biological silicon pools present in the soil. Consequently, this leads to a reduction in the availability of bioactive silicon for plants (Schaller et al. 2021). Additionally, poor soil management techniques and excessive crop harvesting rates negatively affect the silicon concentration in the soil solution, resulting in heightened stress levels in plants (Puppe 2020; Schaller et al. 2021). The positive roles of Si vary with different types of biotic and abiotic stresses (Epstein 1999). According to (Epstein 1999; Sommer et al. 2006) modified definition, an element is deemed essential if it satisfies either one or both of the following criteria: (i) the element plays an active role in the formation of molecular structures involved in metabolic processes in plants, and (ii) the absence of the element in a plant leads to abnormalities in growth and development when compared to plants with lower deficits. Consequently, it can be anticipated that Si will be recognized as an essential element for higher plants in the near future. (Pavlovic et al. 2021).

The monomeric or monosilicic (H_4SiO_4) nature of silicon in the soil solution allows for easy absorption by the root system and subsequent translocation to the aboveground parts of plants, leading to accumulation (Imtiaz et al. 2016). The soil characteristics can be modified by enhancing air and water regimes, improving nutrient contents such as nitrogen, phosphorus, and potassium, raising soil pH, mitigating the toxicity of heavy metals by enhancing soil physical and chemical properties, and facilitating the formation of new silicate complexes (Matichenkov & Bocharnikova 2001). The absorption of Si by the plant root system enhances the plant's well-being by diminishing the uptake and movement of heavy metals from the roots to the shoots. Additionally, it activates the antioxidant system, facilitates chelation, compartmentalization, and regulates the gene expression of heavy metal transporters. (Hou et al. 2023). Similarly, Si plays a role in mitigating heavy metals toxicity, stimulating soil phosphorus (P) activity, and enhancing the uptake of P by plant roots alongside other necessary nutrients. (Kim et al. 2014). Furthermore, the health of soils is closely linked to soil physical and chemical properties, soil ecological functions, and soil fertility, all of which are influenced by soil bacterial communities (Kleytsova et al. 2022). Incorporating silicon or silicon-based fertilizers into the soil can bring about alterations in the bacterial community structure and the physicochemical properties of the soil. These modifications may influence the restriction, immobilization, and transformation of pollutants like cadmium (Ma et al. 2011). Soil

salinity is a significant constraint that hinders plant growth and decreases yield in arid and semi-arid regions. Nevertheless, the adverse effects of salt stress can be alleviated through the use of silicon (Zhu et al. 2004). Previous studies have shown the beneficial impact of silicon on various plant species, including cucumber, wheat, tomato, rice, barley, and maize, when cultivated in saline conditions (Zhu et al. 2004)

Silicon effectively enhances plant growth characteristics and biomass by enhancing the physicochemical properties of the soil in relation to soil nutrients and minerals (Korndörfer & Lepsch 2001). Upon Si addition, a significant reduction in the soil available N and P which directly reflects more uptake of N and P by plants due to Si application (Campos & Da Silva 2023). In addition, the presence of P competing with Si for adsorption sites on clay particles results in the release of P, which becomes easily available to plants. Plants can then absorb this nutrient through physio-chemical mechanisms, facilitated by the large surface area of mineral Si. (Owino-Gerroh & Gascho 2005). The large proportion of chemically adsorbed P was converted to insoluble phosphates with Al-P, Ca_8-P, Ca_{10}-P and Fe-P that reduced its bioavailability in the soil (Owino-Gerroh & Gascho 2005; Wang et al. 2010). However, Si at higher doses also increased the soil pH by reducing soil K availability and provided favorable environment for better growth of pakchoi (Wang et al. 2020) reported lower amount/values of soil organic matter and electrical conductivity in the presence of higher Si concentration and a significant correlation between soil properties and growth of plants. Literature has demonstrated that the concentration of silicon in soil plays a crucial role in improving soil nutrients and physicochemical properties necessary for the growth of plant roots and shoots, especially in the presence of heavy metal toxicity (Zhu et al. 2019). In the same context, the presence of a small amount of other elements like calcium, iron, magnesium, and manganese, in addition to silicon as mineral-Si, also contributed to the improvement of soil quality and facilitated plant growth (Ning et al. 2014). Moreover, the influence of silicon on the availability of soil mineral nutrients is not uniform, as various plant species possess varying abilities to accumulate silicon and other minerals that are associated with silicon aggregation (Greger et al. 2018). Hence, elucidating the comprehensive function of Si in various plant species remains challenging due to the abundance of studies conducted on Si accumulating plants rather than others (Deshmukh et al. 2017). A variety of silicate containing materials that can be used as Si fertilizers. The naturally occurring Si containing materials are wollastonite (21–25% Si; $CaSiO_3$), olivine (ca. 20% Si; $MgSiO_3$), diatomaceous earth (38–42% Si) that can be extracted from earth's surface and used as fertilizers (Haynes 2019). Furthermore, most of the Si fertilizers are by-products of various industrial materials Application of slags and wollastonite led to a notable increase in soil pH and soluble Si concentrations. This enhancement can be attributed to a strong interplay between soluble Si and soil pH levels. Although no strong correlation was observed between Si adsorption to soil particles at low pH values (5−6), an increase in pH facilitates Si adsorption to soil colloids, consequently boosting the availability of soluble Si. (Haynes 2014).

Since humus forms take into account biological, biochemical, and chemical factors, they are good indicators of soil functionality. Since the inception of soil science, the significance of humus forms and the necessity of humus form classifications have been acknowledged (Andreetta et al. 2011). Humus is an essential component of soil, resulting from the breakdown of plant and animal materials by microorganisms. It exists in various shades, from brown to black, and contains around 60 percent carbon, 6 percent nitrogen, as well as lesser amounts of phosphorus and sulfur. (Porte 2021) The surrounding vegetation determines the quantity and quality of organic matter that accumulates in the humipedon, and soil micro-, meso-, and macrofauna (Semeraro et al. 2023) as well as climate conditions (Zanella et al. 2018) influence how this organic matter decomposes, forming a unique layer sequence known as the humus form. (Jabiol et al. 2013). Humus forms can serve as an initial indicator of the soil's ability to act as a carbon sink because of their variability, which is a reflection of the differing rates at which organic matter degrades in various environments (Loranger et al. 2003). Soil organic matter and its transformation into small molecules must be ongoing. Today, global climate change and drought conditions have

a negative impact on the stability of biological processes in soils. As a result, land use and economic efficiency decrease. Therefore, it is very necessary to use products that are effective in improving the biological processes of the soil and maintaining the amount of nutrients in the soil.

Material and Methods

Experimental design and location

Research work was carried out in the field of Avez, Mirshod, Rustam F/H in the Bukhara region. The goal was to study how to influence the drugs of Aminosid-Aton, Aminosid-Silicon and Bionitrogen on humus and general and mobile nitrogen, phosphorus and potassium in conditions of stress and drought. The soil was cultivated in two rounds with these preparations. The first, cotton seeds processed with preparations for 24 hours, and then planted in the soil. Secondly, the suspension of preparations was sprayed on the soil in June. The options were allocated 0.0025 km 2 and 9 kg of seeds were planted. 100 g of the preparations were diluted by 5 liters.
Soil Sampling: The soil samples were collected at three depths: the 0-30, 30-70, 70-100 cm. Soil samples were processed in the laboratory by removing visible plant residues and stones larger than 2 mm immediately after sampling. Soil samplings were then air-dried.
Soil sample analyses: The air-dried soil samples were ground to pass through a 2 mm sieve for laboratory analysis. Soil samples were digested in a tri-acid mixture (HNO_3, $HClO_4$, and H_2SO_4 at a 3:1:1 ratio) for determining total phosphorus (Total P). The P concentration in the digest was determined colorimetrically using the vanadomolybdate method. Soil organic phosphorus (P) was determined by combustion at 5500C and extraction with 4 M H_2SO_4. The Michigan method was used to determine available P using the colorimetric method after the extraction with 1% $(NH_4)2CO_3$ (GOST 26205-9 2021). Soil inorganic P fraction: Inorganic P (P) fractions were measured according to a fractionation scheme of Ginzburg and Lebedeva (1971) and Ginzburg (1981) (Ginzburg, K.E., Lebedeva, L 1971). The amount of humus in the soil was determined by the method of I.V. Tyurin, taken from the 0-30, 30-70, 70-100 cm layers of the soil. Calculations of humus in the soil in tons were calculated based on the weight (mg) of the 0 - 30 cm layer of 1 cm cube of the specified area volume unit (Meylikovich et al. 2022).

Composition of preparations

Aminosid Aton-sodium ortho-nitrophenolate 2%, sodium para-nitrophenolate 2%, naphthylacetic acid 2%, Zinc (Zn) 0.5%, boron (B) 0.5%, Sulfur (S) 0.5%, molybdenum (Mo) 0.5%.;
Aminosid Silicon- silicon (Si) 17%, nitrogen (N) 9%, macro- and microelements; *Bionitrogen*-the basis of the biological product Bionitrogen" is the nitrogen-assimilating bacterium *Azotobacter chrooccoccum* and its natural compounds useful for plants - polysaccharides, vitamins, amino acids. The bacterium multiplies in the roots of plants and absorbs nitrogen from the air.

Processing of the obtained results. The obtained results were processed using GraphPad Prism 8.0.1(244) software. The arithmetic mean (M), standard deviation (±m) and statistical significance (P) were examined. Results less than $P<0.05$ were considered statistically significant.

Statistical Analysis

Analysis of variance (ANOVA) was performed to assess the differences in soil nutrients (humus, nitrogen, phosphorus, and potassium) across various treatments and soil depths using Microsoft Excel 2021. The collected data were first checked for normal distribution, and after satisfying the assumptions, data were analyzed using a completely randomized design (CRD). For multiple comparison tests among the treatments, the least significant difference (LSD) test at $p < 0.05$ was applied to determine significant differences between the means.

Results

Humus is classified into mor, mull, or moder formations according to the degree of its incorporation into the mineral soil, the types of organisms involved in its decomposition, and the vegetation from which it is derived. In terms of the amount of humus, the level of humus supply in the arable soil horizons of the study area is low. It can be seen (Figure. 1) that in the 0-30 cm layer in the control variant, 0.85% is observed, and in the experimental variants (processed with Aminosid-Aton and Bionitrogen in the soil) a slight increase is observed and approximately the same result, approximately 0.976 and 0.998% respectively.

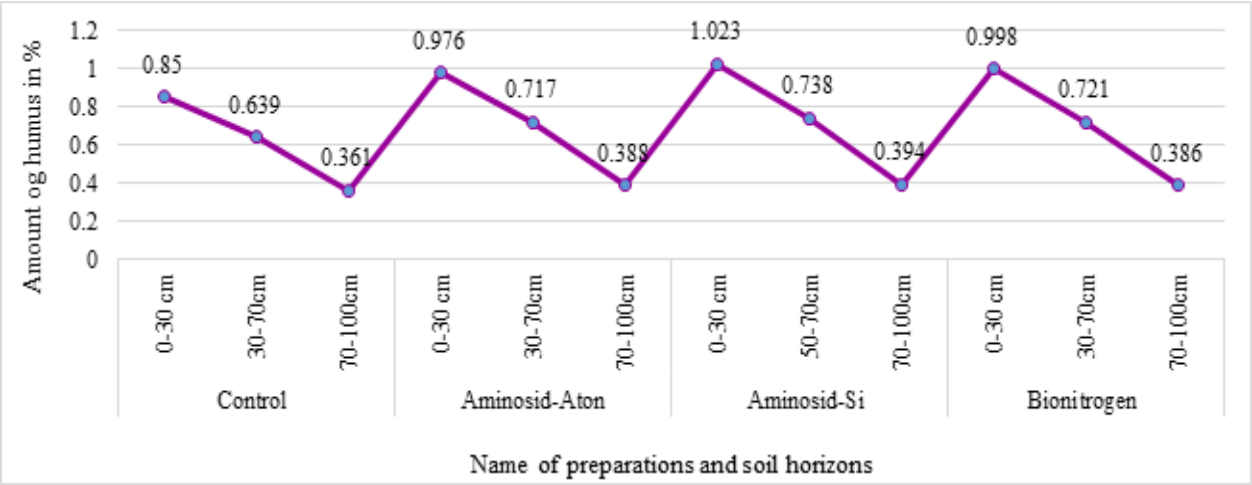


Figure. 1 (The influence of preparations on the humus content of soils in the study area)

The Aminosid-Si preparation showed a higher number of 1.023 compared to the control. This showed that the amount of humus in this preparation increased by 0.172% compared to the control. It has been established that the silicon contained in the preparation is of great importance for changing the biological activity of the soil under conditions of arid climate and low salinity. It can be said that the results are consistent with the literature (Kar 2021). Research work continues to study the total amount of nitrogen, phosphorus and potassium in the soil. The results are presented in Fig. 2.

As can be seen from the table, the level of total K, P and N_2 in the region is also in the low supply area. Soil treatment with the preparations was assessed by comparing the total content of K, P and N_2 with the control. In the control, the total amount of N in the 0-30 cm soil horizon was 0.071%. Despite this, it was found that the Aminosid Aton and Bionitrogen experiment variants increased compared to the control by 0.015% and 0.016%, respectively. Aminosid-Si had a significant effect on the amount of total N_2, increasing by 0.02% compared to the control. Towards the lower soil layer, the total amount of K, P and N_2 decreased.

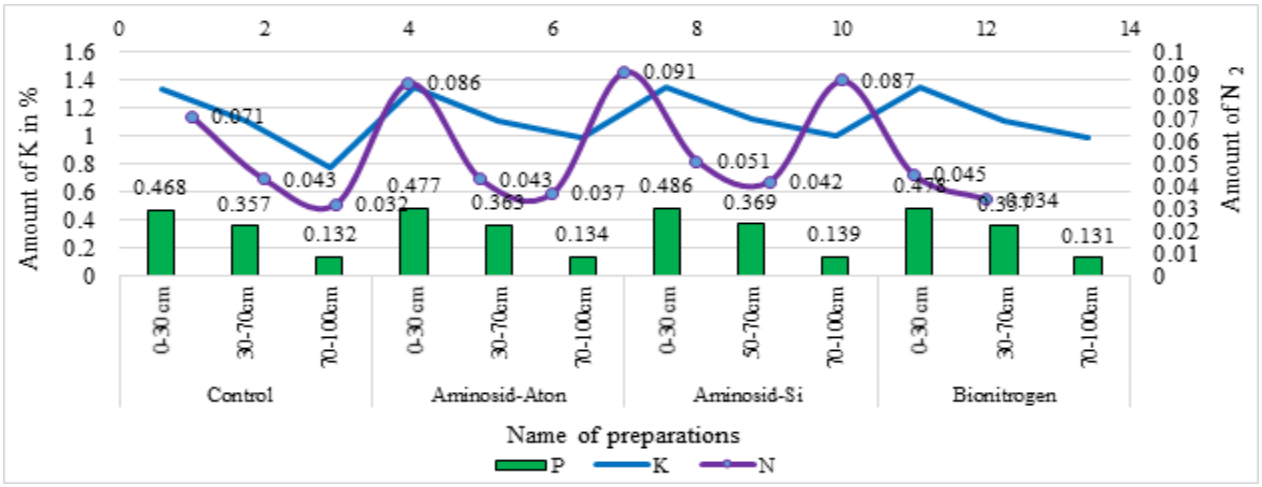
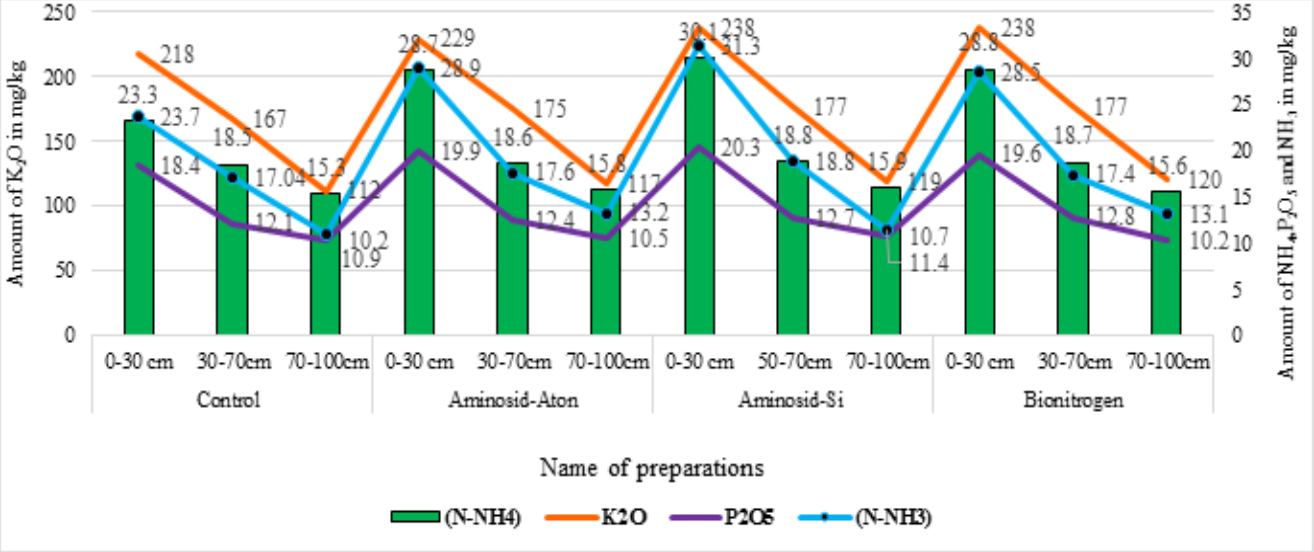


Figure. 2 (The influence of preparations on the content of gross nitrogen, phosphorus and potassium in soils of the study area.)

Small differences in the increase in Aminosid Aton, Bionitrogen and Aminosid-Si compared to the control were shown for 0.005, 0.002 and 0.01, respectively. This research work continues to study the effect of the preparation on the mobile forms of K, P and N_2. The results are presented in Fig. 3.

Figure. 3 (The influence of preparations on the content of mobile nitrogen, phosphorus and potassium in soils of the study area.)



It is known that sufficient amounts of nitrogen, phosphorus and potassium, assimilated by plants in the soil, ensure high productivity and, as a consequence, economic efficiency. Therefore, the soil must have a sufficient amount of (N-NH_4), (N-NH_3), P_2O_5, K_2O. The soils of the study area are also poor in mobile forms of N-NH_4, N-NH_3, P_2O_5, and K_2O. Today the climate is changing, so it is very important to use necessary and environmentally friendly soil preparations. It was noted that when using preparations, the amount of NH_4, N-NH_3, P_2O_5, and K_2O in mobile form increases. Thus, in the 0-30 cm soil horizon, the amount of N-NH_4 (mg/kg) increased by 5,4, 6,8, 5,5 mg/kg, respectively, in Aminosid-Aton, Aminosid-Si and Bionitrogen compared to the control. Additionally, it can be said that the amount of N-NH_3 in the soil in the control variant is 23.7 mg/kg and is considered low in

terms of the level of N-NH_3 supply in the soils of the study area. After treating the soil with Aminoside-Si, a transition to a moderately provided level occurred. In this case, it is advisable to evaluate the composition of the preparations by the presence of Si (17%) and N_2 (9%), as well as macro- and microelements. There is also increasing information in the literature about the significant role of silicon in soil under drought and salinity conditions (Matichenkov & Bocharnikova 2001; Pallavi & Prakash 2019). The amount of mobile P_2O5 and K_2O was higher in Aminosid-Si compared to other preparations. Compared to the control, higher values were obtained with an increase of 1.9 and 20 mg/kg, respectively.

Discussion

According to the results of studies conducted on irrigated meadow-alluvial soils, the amount of humus in the arable soil layer of the Kunji-Kala massif varies from 1.59% to 0.540%. In the lower layers, its indicators decrease horizontally. It ranges from (0.630% to 0.100%) in percentage terms. The upper limit of humus reserves was 62.56 t/g in the 0-30 cm horizon and in its lower layers the results were about 6.216 t/g. According to the FAO classification, in experiments conducted over 3 years, in the soils of the experimental area there was a shift from the lower part to the upper limit of the low humus content. Because increasing the amount of humus in the soil is a labor-intensive process of humification (Humification refers to the breakdown of organic materials in soils and composts leading to the formation of humus). But in addition to the initial organic products that fall into the soil, there are also intermediate components (with carbon, nitrogen, a small amount of sulfur and phosphorus) that continue to decompose (Abakumov et al. 2018; Adewara et al. 2024). It is the participation of groups of enzymes and certain types of microorganisms that catalyze the process of decomposition of these products. It is known from the literature that the preparations used above have a positive effect on the activity of biological processes in the soil.

In recent years, positive results have been increasing in all types of soil research with silicon fertilizers (Bocharnikova et al. 2010; Kovács et al. 2022; Dong et al. 2024).

Silicon can promote the decomposition of organic compounds by increasing microbial populations in the soil. For example, bacteria associated with the metabolic functioning of nitrogen and carbon in soil, such as Anaerolineae (Yan et al., 2018), Flavobacteriales (Bowman and Nichols, 2005), Nitrospirae (Xu et al., 2016), Bacillales (Logan and De Vos, 2011) were found in excess in soils enriched with silicon and heavy metals. During the implementation of this scientific work, it was found that silicon preparations actually stimulate nutrients in the soil, and it is clear that this is consistent with the results of the literature (Reithmaier et al. 2017; Schaller et al. 2019). Aminosid-Aton, Aminosid-Si, and Bionitrogen preparations, which are considered as research subjects, received positive results compared to the control. In particular, the Aminosid-Si preparation, which contains Si (17%), received relatively positive results. The stimulation of soil C: N: P amounts by Si processed to the soil environment was also analyzed by comparison with literature results (Jianfeng & Takahashi 1991).

Conclusion

In this work, experiments on the application of Si fertilizers to the soil were studied and the amount of humus, the amount of N2, K, P, as well as their mobile forms over the past three years were determined. The results show that research interest in studying the effects of silicon-based fertilizers on soil properties has increased rapidly in recent years. The scientific interest in conducting field experiments is to test how soil organic components and essential plant nutrients increase with the addition of fertilizers. Si, which shows the natural

motivation of researchers to achieve full utilization of this fertilizer and make it applicable to farmers. Considering that all experimental work on the application of silicon fertilizers to the soil has only a positive effect, it is necessary to provide a scientific explanation to farmers for the use of these fertilizers in arid climates, abiotic and biotic conditions. The application of these fertilizers to the soil in the conditions of Uzbekistan has shown truly significant results. Although this could not provide a high increase in the humus content and the number of mobile forms of N_2, P, K, nevertheless, a slight increase in their content was observed and their content remained longer in the soil. Consequently, application of these Si fertilizers to the soil over many years can lead to optimization of agrochemical and biological processes in the soil, which creates prospects for large-scale use of agricultural land and provides economic benefits.

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References

Adewara, O.A., Adebayo-Olajide, T.C., Ayedun, J.S., Kotun, B.C., Adeleke, A.J., Brown, A.D., Alabi, O.J. & Ogunbanwo, S.T. (2024). Soil Formation, Soil Health and Soil Biodiversity. In: Aransiola, S.A., Babaniyi, B.R., Aransiola, A.B., & Maddela, N.R. (eds) *Prospects for Soil Regeneration and Its Impact on Environmental Protection*. Springer Nature Switzerland. 95–121. https://doi.org/10.1007/978-3-031-53270-2_5

Andreetta, A., Ciampalini, R., Moretti, P., Vingiani, S., Poggio, G., Matteucci, G., Tescari, F., Carnicelli, S., 2011. Forest humus forms as potential indicators of soil carbon storage in Mediterranean environments. Biology and Fertility of Soils 47, 31–40.

Ali, N., Réthoré, E., Yvin, J.-C. & Hosseini, S.A. (2020). The Regulatory Role of Silicon in Mitigating Plant Nutritional Stresses. *Plants*, 9 (12), 1779. https://doi.org/10.3390/plants9121779

Campos, C.N.S. & Da Silva, B.C. (2023). Silicon Mitigates the Effects of Nitrogen Deficiency in Plants. In: De Mello Prado, R. (ed.) *Benefits of Silicon in the Nutrition of Plants*. Springer International Publishing. 87–100. https://doi.org/10.1007/978-3-031-26673-7_6

Deshmukh, R.K., Ma, J.F. & Bélanger, R.R. (2017). Editorial: Role of Silicon in Plants. *Frontiers in Plant Science*, 8, 1858. https://doi.org/10.3389/fpls.2017.01858

Epstein, E. (1999). SILICON. *Annual Review of Plant Physiology and Plant Molecular Biology*, 50 (1), 641–664. https://doi.org/10.1146/annurev.arplant.50.1.641

Greger, M., Landberg, T. & Vaculík, M. (2018). Silicon Influences Soil Availability and Accumulation of Mineral Nutrients in Various Plant Species. *Plants*, 7 (2), 41. https://doi.org/10.3390/plants7020041

Hao, Q., Yang, S., Song, Z., Li, Z., Ding, F., Yu, C., Hu, G. & Liu, H. (2020). Silicon Affects Plant Stoichiometry and Accumulation of C, N, and P in Grasslands. *Frontiers in Plant Science*, 11, 1304. https://doi.org/10.3389/fpls.2020.01304

Haynes, R.J. (2014). A contemporary overview of silicon availability in agricultural soils. *Journal of Plant Nutrition and Soil Science*, 177 (6), 831–844. https://doi.org/10.1002/jpln.201400202

Haynes, R.J. (2019). What effect does liming have on silicon availability in agricultural soils? *Geoderma*, 337, 375–383. https://doi.org/10.1016/j.geoderma.2018.09.026

Hou, L., Ji, S., Zhang, Y., Wu, X., Zhang, L. & Liu, P. (2023). The mechanism of silicon on alleviating cadmium toxicity in plants: A review. *Frontiers in Plant Science*, 14, 1141138. https://doi.org/10.3389/fpls.2023.1141138

Imtiaz, M., Rizwan, M.S., Mushtaq, M.A., Ashraf, M., Shahzad, S.M., Yousaf, B., Saeed, D.A., Rizwan, M., Nawaz, M.A., Mehmood, S. & Tu, S. (2016). Silicon occurrence, uptake, transport and mechanisms of heavy metals, minerals and salinity enhanced tolerance in plants with future prospects: A review. *Journal of Environmental Management*, 183, 521–529. https://doi.org/10.1016/j.jenvman.2016.09.009

Jabiol B., Feller C., Grève M.H., 2005, Quand l'humus est à l'origine de la pédologie. Etudes Gest. des Sols, 12: 123–134.

Khan, I., Awan, S.A., Rizwan, M., Ali, S., Hassan, M.J., Brestic, M., Zhang, X. & Huang, L. (2021). Effects of silicon on heavy metal uptake at the soil-plant interphase: A review. *Ecotoxicology and Environmental Safety*, 222, 112510. https://doi.org/10.1016/j.ecoenv.2021.112510

Klevtsova, L.E., Sazykin, I.S., Azhogina, T.N. & Sazykina, M.A. (2022). Influence of Agricultural Practices on Bacterial Community of Cultivated Soils. *Agriculture*, 12 (3), 371. https://doi.org/10.3390/agriculture12030371

Kim, Y.-H., Khan, A.L., Kim, D.-H., Lee, S.-Y., Kim, K.-M., Waqas, M., Jung, H.-Y., Shin, J.-H., Kim, J.-G. & Lee, I.-J. (2014). Silicon mitigates heavy metal stress by regulating P-type heavy metal ATPases, Oryza sativa low silicon genes, and endogenous phytohormones. *BMC Plant Biology*, 14 (1), 13. https://doi.org/10.1186/1471-2229-14-13

Korndörfer, G.H. & Lepsch, I. (2001). Chapter 7 Effect of silicon on plant growth and crop yield. In: *Studies in Plant Science*. Elsevier. 133–147. https://doi.org/10.1016/S0928-3420(01)80011-2

Li, Q., Wang, Y., Li, Y., Li, L., Tang, M., Hu, W., Chen, L. & Ai, S. (2022). Speciation of heavy metals in soils and their immobilization at micro-scale interfaces among diverse soil components. *Science of The Total Environment*, 825, 153862. https://doi.org/10.1016/j.scitotenv.2022.153862

Liang, Y., Si, J. & Römheld, V. (2005). Silicon uptake and transport is an active process in *Cucumis sativus*. *New Phytologist*, 167 (3), 797–804. https://doi.org/10.1111/j.1469-8137.2005.01463.x

Loranger, G., Ponge, J.F., Lavelle, P., 2003. Humus forms in two secondary semi-evergreen tropical 4 forests. European Journal of Soil Science, 54, 17-24.

Luo, X., Liu, Y., Li, S. & He, X. (2023). Interplant carbon and nitrogen transfers mediated by common arbuscular mycorrhizal networks: beneficial pathways for system functionality. *Frontiers in Plant Science*, 14, 1169310. https://doi.org/10.3389/fpls.2023.1169310

Ma, J.F., Yamaji, N. & Mitani-Ueno, N. (2011). Transport of silicon from roots to panicles in plants. *Proceedings of the Japan Academy, Series B*, 87 (7), 377–385. https://doi.org/10.2183/pjab.87.377

Matichenkov, V.V. & Bocharnikova, E.A. (2001). Chapter 13 The relationship between silicon and soil physical and chemical properties. In: *Studies in Plant Science*. Elsevier. 209–219. https://doi.org/10.1016/S0928-3420(01)80017-3

Nemerow, N.L., Agardy, F.J., Sullivan, P. & Salvato, J.A. (eds) (2009). *Environmental Engineering: Water, Wastewater, Soil and Groundwater Treatment and Remediation*. 1. ed Wiley. https://doi.org/10.1002/9780470432808

Ning, D., Song, A., Fan, F., Li, Z. & Liang, Y. (2014). Effects of Slag-Based Silicon Fertilizer on Rice Growth and Brown-Spot Resistance. Zhang, G. (ed.) (Zhang, G., ed.) *PLoS ONE*, 9 (7), e102681. https://doi.org/10.1371/journal.pone.0102681

Nortcliff, S., Hulpke, H., Bannick, C.G., Terytze, K., Knoop, G., Bredemeier, M., Schulte-Bisping, H., Auerswald, K., Litz, N., Mayer, R., Stoy, A., Alef, K., Kerndorff, H., Crössmann, G., Eikmann, T., Franzius, V., Grimsky, D., Möhlenbruch, N., Storm, P.-C. & Dworshak, U. (2006). Soil. In: Wiley-VCH Verlag GmbH & Co. KGaA (ed.) *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley-VCH Verlag GmbH & Co. KGaA. b07_613.pub2. https://doi.org/10.1002/14356007.b07_613.pub2

Owino-Gerroh, C. & Gascho, G.J. (2005). Effect of Silicon on Low pH Soil Phosphorus Sorption and on Uptake and Growth of Maize. *Communications in Soil Science and Plant Analysis*, 35 (15–16), 2369–2378. https://doi.org/10.1081/LCSS-200030686

Pavlovic, J., Kostic, L., Bosnic, P., Kirkby, E.A. & Nikolic, M. (2021). Interactions of Silicon with Essential and Beneficial Elements in Plants. *Frontiers in Plant Science*, 12, 697592. https://doi.org/10.3389/fpls.2021.697592

Porte, Dr.S.S. (ed.) (2021). *Latest Trends in Soil Science (Volume - 1)*. 1. ed Integrated Publications. https://doi.org/10.22271/int.book.33

Puppe, D. (2020). Review on protozoic silica and its role in silicon cycling. *Geoderma*, 365, 114224. https://doi.org/10.1016/j.geoderma.2020.114224

Rasoolizadeh, A., Labbé, C., Sonah, H., Deshmukh, R.K., Belzile, F., Menzies, J.G. & Bélanger, R.R. (2018). Silicon protects soybean plants against Phytophthora sojae by interfering with effector-receptor expression. *BMC Plant Biology*, 18 (1), 97. https://doi.org/10.1186/s12870-018-1312-7

Schaller, J., Puppe, D., Kaczorek, D., Ellerbrock, R. & Sommer, M. (2021). Silicon Cycling in Soils Revisited. *Plants*, 10 (2), 295. https://doi.org/10.3390/plants10020295

Semeraro, T., Scarano, A., Leggieri, A., Calisi, A., and De Caroli, M. (2023). Impact of climate change on agroecosystems and potential adaptation strategies. Land 12 (6), 1117. doi: 10.3390/land12061117

Sommer, M., Kaczorek, D., Kuzyakov, Y. & Breuer, J. (2006). Silicon pools and fluxes in soils and landscapes—a review. *Journal of Plant Nutrition and Soil Science*, 169 (3), 310–329. https://doi.org/10.1002/jpln.200521981

Tang, P., Chen, W., Xuan, D., Cheng, H., Poon, C.S. & Tsang, D.C.W. (2020). Immobilization of hazardous municipal solid waste incineration fly ash by novel alternative binders derived from cementitious waste. *Journal of Hazardous Materials*, 393, 122386. https://doi.org/10.1016/j.jhazmat.2020.122386

Urra, Alkorta, & Garbisu (2019). Potential Benefits and Risks for Soil Health Derived from the Use of Organic Amendments in Agriculture. *Agronomy*, 9 (9), 542. https://doi.org/10.3390/agronomy9090542

Wang, B., Chu, C., Wei, H., Zhang, L., Ahmad, Z., Wu, S. & Xie, B. (2020). Ameliorative effects of silicon fertilizer on soil bacterial community and pakchoi (Brassica chinensis L.) grown on soil contaminated with multiple heavy metals. *Environmental Pollution*, 267, 115411. https://doi.org/10.1016/j.envpol.2020.115411

Wang, J., Liu, W.-Z., Mu, H.-F. & Dang, T.-H. (2010). Inorganic Phosphorus Fractions and Phosphorus Availability in a Calcareous Soil Receiving 21-Year Superphosphate Application. *Pedosphere*, 20 (3), 304–310. https://doi.org/10.1016/S1002-0160(10)60018-5

Zanella A., Geisen S., Ponge J., Jagers G., Benbrook C.,2018c, Humusica 2, article 17: Techno humus systems and global change - Three crucial questions. Applied Soil Ecology, 122: 237–253. doi: 10.1016/j.apsoil.2017.10.010

Zhu, Y.-X., Gong, H.-J. & Yin, J.-L. (2019). Role of Silicon in Mediating Salt Tolerance in Plants: A Review. *Plants*, 8 (6), 147. https://doi.org/10.3390/plants8060147

Zhu, Z., Wei, G., Li, J., Qian, Q. & Yu, J. (2004). Silicon alleviates salt stress and increases antioxidant enzyme activity in leaves of salt-stressed cucumbers (Cucumis sativus L.). *Plant Science*, 167 (3), 527–533. https://doi.org/10.1016/j.plantsci.2004.04.020