Nuwarapaksha *et al. Carbon Footprints* **2025**, *4*, 4
DOI: 10.20517/cf.2024.31

Carbon Footprints

Original Article

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Estimation of the total carbon sequestration potential of coconut-gliricidia mixed cropping systems in Sri Lanka

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How to cite this article: Nuwarapaksha, T. D.; Dilhan, R. M. C. P.; Udumann, S. S.; Ranasinghe, C. S.; Egodawatta, W. C. P.; Dissanayaka, N. S.; Atapattu, A. J. Estimation of the total carbon sequestration potential of coconut-gliricidia mixed cropping systems in Sri Lanka. *Carbon Footprints* **2025**, *4*, 4. https://dx.doi.org/10.20517/cf.2024.31

Received: 31 Aug 2024 **First Decision:** 27 Nov 2024 **Revised:** 6 Jan 2025 **Accepted:** 16 Jan 2025 **Published:** 22 Jan 2025

Academic Editor: Junye Wang **Copy Editor:** Fangling Lan **Production Editor:** Fangling Lan

Abstract

Offsetting carbon footprints by sequestering carbon through plant biomasses has become a key concern under modern thinking on climate change mitigation. This study aimed to estimate the carbon sequestration capacities of coconut-based gliricidia mixed cropping systems in Sri Lanka and, importantly, to develop an allometric model for non-destructive estimation of carbon. Five major coconut age groups and four major gliricidia age groups were selected to estimate the total carbon stock. The age groups of coconut considered were 10, 20, 30, 40, and 50 years, with corresponding carbon stocks of 22.59, 34.99, 53.13, 63.40, and 66.03 Mg[C]ha^{-1}, respectively. In gliricidia stands, carbon stocks were 25.53, 46.16, 83.83, and 106.09 Mg[C]ha^{-1}, respectively, for age groups of 5, 10, 15, and 20 years. It is recommended that gliricidia be introduced as an intercrop in coconut plantations 20 years after the establishment of the latter. For this study, a 30-year-old coconut plantation with a 10-year-old gliricidia intercrop, along with its associated ground cover vegetation and soil carbon stock, were considered the benchmark agroforestry system. In the 30-year-old coconut monocropping system, the total carbon stock was 67.76 Mg[C]ha^{-1}, which consisted of uniform coconut, 1.24 Mg[C]ha^{-1} from ground cover vegetation and 13.39 Mg[C]ha^{-1} from the soil carbon stock at a depth of 30 cm. The overall carbon sequestration rate for this monocropping system was 2.25 Mg[C]ha^{-1}yr^{-1} and abated CO_2 in 8.23 Mg[CO_2]ha^{-1}yr^{-1}. In the 30-year-old coconut and 10-year-old gliricidia mixed cropping system, the total carbon stock was 114.83 Mg[C]ha^{-1}, which consisted of uniform coconut and Gliricidia, 1.05 Mg[C]ha^{-1} from ground cover plants, and 14.49 Mg[C]ha^{-1} from soil carbon stock at a depth of 30 cm. Compared to the coconut monocropping system, the coconut-gliricidia mixed cropping system had a higher carbon sequestration rate of 6.84 Mg[C]ha^{-1}yr^{-1} and abated CO_2 in 25.03 Mg[CO_2]ha^{-1}yr^{-1}, which are around three times higher than the monoculture system.

Keywords: Carbon sequestration, carbon stock, climate change mitigation, monocropping systems, non-destructive estimation

INTRODUCTION

Climate change is among the most urgent global challenges today, and carbon sequestration has become a key strategy for mitigating its effects[1,2]. Carbon sequestration is the process of keeping CO_2 in the atmosphere for a long time by using terrestrial ecosystems, such as forests, soils, or agricultural systems[3]. This process is considered to play a key role in regulating the Earth's carbon cycle and it has received a lot of attention due to its potential to reduce the rising levels of greenhouse gases (GHGs) in the atmosphere. Sri Lanka, an island nation in the Indian Ocean, is especially susceptible to the effects of climate change, such as rising sea levels, shifting rainfall patterns, and the growing frequency and severity of extreme weather events[4]. As a signatory to the Paris Agreement, Sri Lanka has pledged to cut down on GHG emissions and increase its carbon sinks[5]. In this context, exploring sustainable agricultural practices that can contribute to carbon sequestration has become a priority[6].

Thus, a specific strategy, such as the use of coconut-gliricidia mixed cropping systems, which offers numerous advantages - including good soil fertility, balance of nature, and good economic returns to smallholder farmers - has been practiced in Sri Lanka[7-9]. Gliricidia is a nitrogen-fixing leguminous tree that is often intercropped with coconut plantations to provide shade and improve soil health[10]. Carbon sequestration is the possibility of integrating coconut and gliricidia in a mixed cropping system in various ways[11-13]. Coconut palms, which have a perennial nature and a dense root system, can accumulate carbon in their biomass and enhance soil carbon through the decomposition of leaf litter and root exudates[14]. Additionally, gliricidia, a fast-growing tree species, can sequester carbon in its aboveground and belowground biomass, while also enhancing soil organic matter through the decomposition of its nitrogen-rich litter and pruned biomass[15].

Different approaches have been created to measure carbon capture in multi-purpose tree planting, such as allometric equations, remote sensing techniques, and process-based models[16]. Allometric equations link easily measurable tree characteristics, such as diameter at breast height (DBH) and height, to estimates of biomass and carbon content[17]. The application of such an allometric equation proves a veritably convenient and alternative technique to the destructive sampling of the carbon stock[18]. Deriving from the empirical link among dimensions of trees and their carbon content, this method enables producing data with high accuracy, as well as the ones that can be reproduced, while contributing to our understanding of carbon capture processes occurring within the interpreted ecosystem[19]. Process-based models, on the other hand, simulate the dynamics of carbon fluxes and pools within the system, considering various environmental and management factors[20]. Estimating the total carbon sequestration potential of coconut-gliricidia mixed cropping systems in Sri Lanka requires a multidisciplinary approach, combining field measurements, laboratory analyses, and modeling techniques.

Calculating the total carbon sequestration capacity of coconut-gliricidia mixed cropping systems is imperative for assessing their contribution to climate change mitigation, as well as informing policy decisions related to sustainable land management and their practices[21,22]. This study aims to quantify the amount of carbon that can be stocked by the coconut-gliricidia mixed cropping systems rather than coconut monocropping systems and develop an allometric model for non-destructive estimation of carbon stock. It involves assessing the carbon stocks in various components of the system, including the coconut stands, gliricidia stands, ground cover, and soils. By estimating the total carbon sequestration potential, this study contributes to the development of strategies for enhancing carbon sinks in agricultural landscapes. It also supports the implementation of climate-smart agriculture practices and the promotion of agroforestry systems as a means of mitigating greenhouse gas emissions while ensuring food security and sustainable livelihoods for farming communities in Sri Lanka[6,23].

METHODOLOGY

Location of the experiment

The experiment was conducted at the Coconut Research Institute of Sri Lanka, Lunuwila (7°19′39″ N, 79°52′5″ E), which is situated in the Low Country Intermediate Zone (IL1a) [Figure 1][24]. The data collection was done from January to December 2023. The dominant soil types of the IL1a Agro-Ecological Zone are the Red-Yellow Podzolic soils with mottled subsoils and Regosols on old red and yellow sands[25]. The area receives a mean annual rainfall of 1,660 mm and has an average temperature range of 23.8-30.4 °C[26].

Data collection

Carbon stock of coconut

Coconut stands belonging to age groups of 10, 20, 30, 40, and 50 years were selected. These particular age categories define the most important phases in coconut palm development, which in turn enables a sequential study of the plant morphological changes, biomass production, and yield parameters[27]. Since coconut palms are long-lived plants, by studying palms at early productive ages (10 years), middle-aged palms (20-30 years), and senescent palms (40-50 years), researchers are able to unravel complex patterns of vegetative development, photosynthesis, nutrient partitioning, and reproduction[27,28]. An orderly selection of age groups enables the quantitative evaluation of physiological processes, such as alterations in the structure of the leaves, root formation, and carbon sequestration.

A 0.2-hectare plot was designated for each age category, with an average density of approximately 32 coconut palms per plot. From each age category, 09 palms were randomly selected to assess aboveground and belowground carbon stocks. This sample size corresponds to approximately 30% of the total palms within the specified area for each age category. Overall, a total of 45 palms, spanning all age groups, were sampled and analyzed for carbon content. The selected trees were chosen through random sampling within each age category, ensuring a diverse and unbiased representation of the coconut palm population. The nuts, stems, and fronds were considered the aboveground section of the coconut palm, while the roots were considered the belowground section. The following allometric equations were used to determine the total carbon stock in each component.

Carbon stock of the aboveground section

Aboveground carbon stock was determined using several equations. This approach breaks down the palm into its main components - nuts, stem, and fronds and calculates the carbon content for each part separately before combining them for a total estimate.

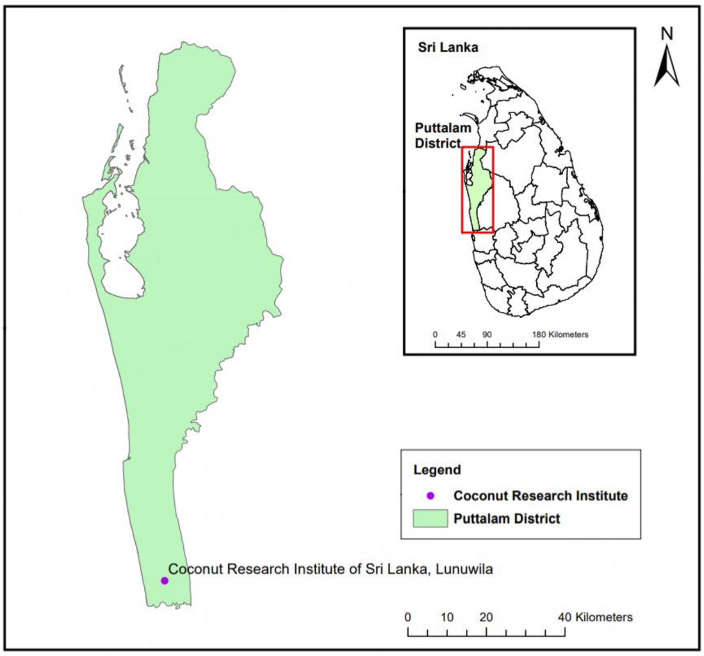

Figure 1. Experimental location. Created with QGIS (https://www.qgis.org/).

The dry weight of each nut was calculated using an equation developed for the tall variety of coconut[29].

$$\log DM = 0.1486 + 0.1472(L) - 0.000741(L^2)$$

where: DM - Total dry matter content of the nut (g); L - Vertical length of the nut along the vertical axis (cm).

To estimate the total dry weight of nuts on a palm, the average weight of nuts in a bunch was calculated. This average was multiplied by the number of nuts in the bunch. The weights of all bunches were summed to get the total dry weight of nuts per palm. This method allowed for a non-destructive estimation of the nut component of the aboveground carbon stock.

The carbon content of the stem part was calculated using equations from Friend & Corley[30]. For that, the stem density was estimated based on the age of the plantation. The stem dry weight of a palm was calculated by multiplying the stem's volume by its density (Friend & Corley[30], assuming the stem was cylindrical without considering its tapering towards the top.

$$D = 0.0079t + 0.18$$

where: D - Density (g cm^{-3}); t - Age after field planting (years).

The dry weight of a frond was calculated by measuring the cross-sectional area of the petiole at the point where the lowest leaflet is attached, taking both the width and depth of the petiole on the coconut leaves into account[30]. The total dry weight of the crown was then determined by multiplying the dry weight of a single frond by the total number of fronds in the canopy.

$$W = 0.13C - 0.25$$

where: W - Dry weight of the frond (g); C - Width × depth of the petiole.

The carbon content of the dry mass was assumed to be 0.5 g of carbon for 1 g of dry biomass[31,32].

Carbon stock of the belowground section

For the determination of the root carbon stock, root samples were collected by excavating a triangular pit in 1/8th of the root zone [Figure 2]. Soil particles were removed using a pressurized water gun and roots were collected to analyze the carbon content. The height of the coconut palms was measured utilizing a clinometer, a standard tool for height estimation in field studies. This device allows for accurate determination of tree height by measuring the angle between the observer's line of sight to the top of the tree and the ground.

Using the height of the coconut palms, the allometric relationship was created to accurately estimate the amount of carbon stocks in the roots of the entire palm[33].

$$R = 0.0074h + 0.0035$$

where: R - Root Carbon Stock of the palm; h - Height of the palm (m).

The value per palm was multiplied by the number of existing coconut palms in one hectare to calculate the total carbon stock per hectare.

Taking 1/8th of a coconut palm root system can serve as a representative sample due to the root system's inherently uniform and symmetrical growth pattern. Coconut palms develop a fibrous, adventitious root system that grows radially and evenly from the base of the stem in all three dimensions, with the main roots being uniform in size[34]. While the total number of roots can vary from 1,500 to 7,000 (or rarely up to 11,360) depending on the palm's age, bole girth, and soil characteristics, their distribution remains generally symmetrical[35]. The roots typically spread laterally up to 6 m from the base and can reach depths of 5 m in well-drained sandy soils, though most are concentrated in the top 1.5 m[36]. This uniform distribution pattern, combined with the continuous replacement of decayed roots by new growth from the basal stem, means that a 1/8th section would contain a proportional representation of the entire root system.

Carbon stock of gliricidia

Gliricidia stands belonging to age groups of 5, 10, 15, and 20 years were selected, and 5 palms were randomly selected from each age category to estimate the total above- and belowground carbon stock. Leaves, branches, and the main stem were considered for the aboveground sections, and roots were considered for the belowground section. All plant samples were taken destructively and analyzed by the wet oxidation method to calculate the carbon content[37].

Carbon stock of soil

Soil samples were randomly collected from the middle of the coconut square and the manure circle at a depth of 0-30 cm, using the soil core method with 10 replicates [Figure 3]. These samples represented a 30-year-old coconut monocropping system and a 30-year-old coconut mixed cropping system with

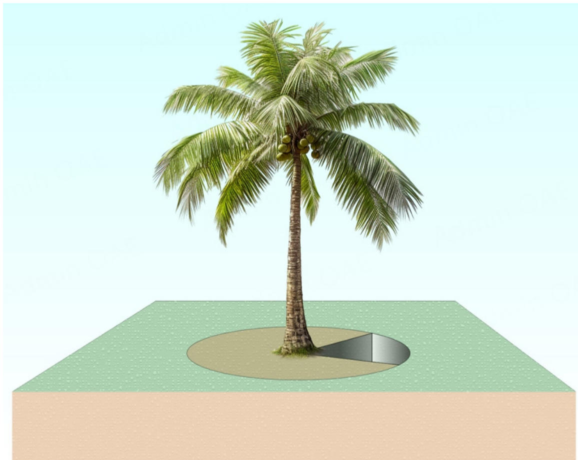

Figure 2. 1/8th of the root zone in coconut palm. Created with GIMP (https://www.gimp.org/) and Canva (https://www.canva.com/free/).

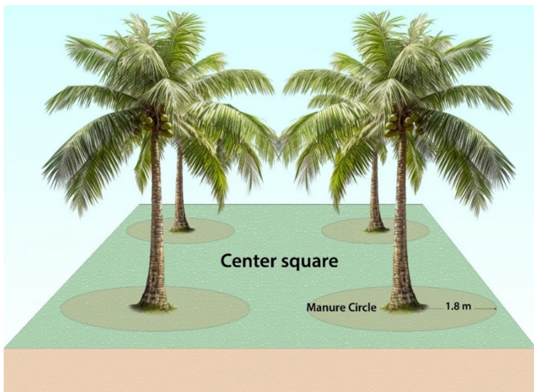

Figure 3. Visual concept of coconut center square and manure circle. Created with GIMP (https://www.gimp.org/) and Canva (https://www.canva.com/free/).

10-year-old gliricidia. A comprehensive analysis of soil properties was conducted as a preliminary study to gain a general understanding of soil variation. The analysis included pH, electrical conductivity, bulk density, nutrient content (N, P, K), and soil texture (sand, silt, and clay content. Air-dried and ground soil samples were sieved using 2 mm sieves to measure the carbon content in the soil by the wet oxidation method[37]. The dry weight of the soil collected with the soil sampler was measured to determine the soil mass per unit volume. Next, the total soil volume up to a depth of 30 cm was calculated and multiplied by the soil carbon percentage to assume the total carbon stock in the soil.

Carbon stock in ground cover

The botanical composition of the ground cover was divided into two major categories: (1) live ground cover; and (2) dead ground cover. The live ground cover was again divided into two main components: aboveground (aboveground parts of grasses, legumes, broad leaves, and sedges) and belowground (roots of grasses, legumes, broad leaves, and sedges). The litter layer of the ground cover was considered the dead ground cover. A quadrant with a 1 m × 1 m area was used to take the samples of ground cover, and 10 random samples were taken from the area except the manure circle area. It is important to note that in well-managed plantations, the manure circle is typically not covered with grass; thus, grass cover in the manure circle was not included in the calculations. The samples were collected from the 30-year-old age category of coconut monocropping systems and 30-year-old coconut with 10-year-old gliricidia mixed cropping systems. The carbon contents of the dead ground cover, aboveground live cover, and belowground cover were determined separately using the wet oxidation method proposed by Walkley & Black[37].

Statistical analysis

All the statistical analyses were conducted with R (4.1.3) statistical software to identify statistically significant variations among the mean carbon stock across different criteria. One-way Analysis of Variance (ANOVA) was applied at a 5% level of significance. Subsequently, Tukey's honestly significant difference (HSD) test was used to conduct pairwise comparisons and identify specific differences between the means. Regression analysis was employed to develop an allometric model to estimate the total carbon stock of coconut and gliricidia.

RESULTS AND DISCUSSION

Carbon stock of coconut

Table 1 clearly outlines the growth characteristics of palm trees across five age categories: 10, 20, 30, 40, and 50 years. The data are increasing over time and it is evident that the height and the size of the roots are growing. The palms show high vertical growth in the first 30 years, from 4.6 m at 10 years to 13 m at 30 years, while the further growth is much slower, reaching only 14.8 m at 50 years. At the same time, the root dry weight steadily increases throughout the palm's life cycle, rising from 91.48 kg at 10 years of age to 291.48 kg at 50 years. This growth reflects the significant underground growth that supports the palm's aboveground growth.

Variations in the carbon stock among coconut palms of five different age categories were investigated in this study. Results showed carbon stocks in coconut fronds declined significantly with the maturity ($P < 0.05$). The highest carbon stock of 8.92 Mg[C]ha^{-1} was observed in the 10-year age group, while the lowest value of 3.38 Mg[C]ha^{-1} was recorded in the 50-year age group [Figure 4A]. According to previous studies, this decline can happen due to the elongation of leaves up to 10 years followed by progressive reduction, a decrease in the length and width of the longest leaflets with age, and a decline in the total number of leaflets in mature green leaves after 20 years[38]. Significant differences in the total carbon stock of the stems were notably observed across the five age categories. The highest carbon stock of 42.99 Mg[C]ha^{-1} was observed in the 50-year age group, while the lowest value of 7.02 Mg[C]ha^{-1} was recorded in the 10-year age group. However, there was no notable significant difference ($P < 0.05$) between the 40 and 50-year-old palms nor between the 10 and 20-year-old ones [Figure 4B].

Carbon stock in coconut stems exhibited a consistent increase with age, with a notable accumulation observed between 20 and 40 years. Raveendra *et al.* reported similar carbon stock values for stem (28.72 Mg[C]ha^{-1}) for 30-year-old coconut palms[21]. Carbon stocks in nuts varied significantly across age categories, though no significant differences were observed between the 30, 40, and 50-year-old palms. The 10-year-old palms only showed significant differences [$P < 0.05$] in age groups 30, 40, and 50. The highest carbon stock of 1.89 Mg[C]ha^{-1} was observed in the 50-year age group, while the lowest value of 0.72 Mg[C]ha^{-1} was recorded in the 10-year age group [Figure 4C]. This result aligns with the findings of Raveendra *et al.*, who reported comparable carbon stock values (1.99 Mg[C]ha^{-1}) for nuts in 30-year-old coconut palms[21].

Root carbon stocks also varied among the five age categories, with 30, 40, and 50-year-old palms exhibiting no statistical difference. The highest carbon content of 17.85 Mg[C]ha^{-1} was observed in the 50-year age

Table 1. Mean heights and root dry weights of the palm for each age group

Age groups	Mean palm height (m)	Mean root dry biomass (kg)
10 years	4.6	91.48
20 years	8.6	174.46
30 years	13	200.02
40 years	13.33	227.65
50 years	14.8	291.48

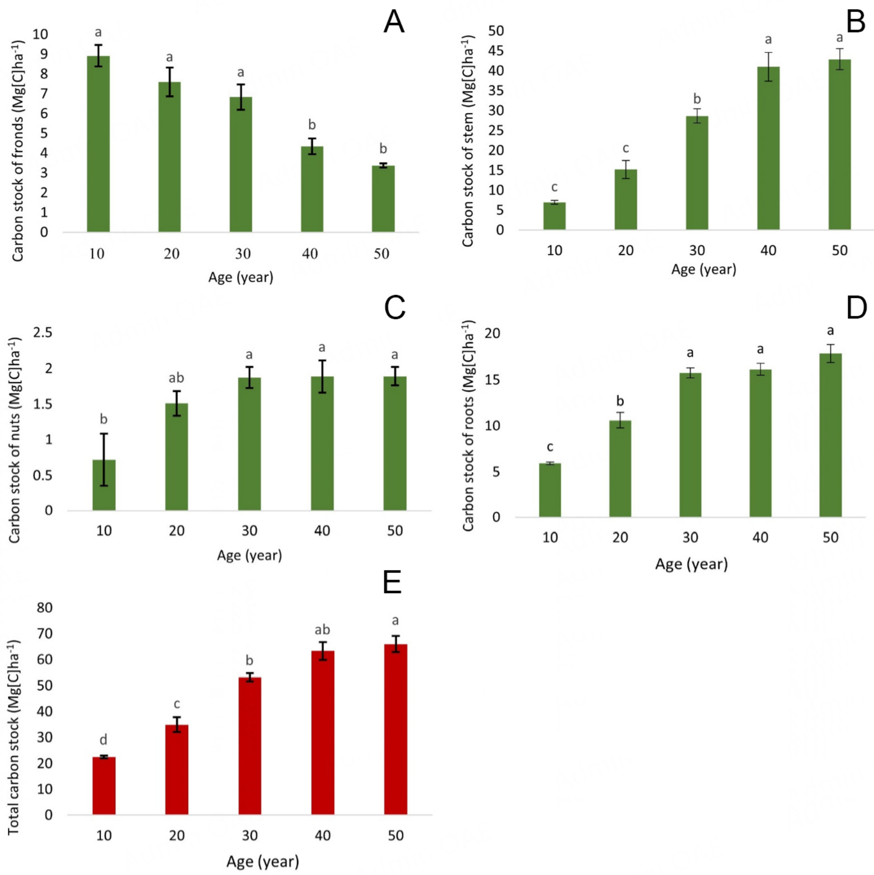

Figure 4. Variation of coconut carbon stock with different age groups. (A) Carbon stock of fronds, (B) Carbon stock of stems, (C) Carbon stock of nuts, (D) Carbon stock of roots, (E) Total carbon stock of the palm (Means that do not share a letter are significantly different at $P < 0.05$). The assumption: There are 158 coconut palms in one hectare.

group, while the lowest of 5.93 Mg[C]ha^{-1} was recorded for the 10-year age group [Figure 4D]. An increasing trend in root carbon stock was identified among the five age groups. Interestingly, significant differences ($P < 0.05$) in total carbon stocks among the five age categories were primarily observed in 50-year-old palms, with the carbon stock significantly differing ($P < 0.05$) from age groups 10 and 20. The highest total carbon stock of 66.03 Mg[C]ha^{-1} was observed in the 50-year age group, while the lowest value of 22.59 Mg[C]ha^{-1} was recorded in the 10-year age group [Figure 4E]. An increasing trend in total carbon stock was identified up to 40 years and then among the five age groups.

Carbon stock of gliricidia

This study examined the variation in carbon stock across different age categories of gliricidia plants. Significant differences ($P < 0.05$) in the total carbon stock of leaves were observed among the four age categories. Leaf carbon stocks exhibited a consistent increase with age, with no significant differences ($P < 0.05$) noted between the 10 and 15-year categories [Figure 5A]. The highest carbon stock of 1.89 Mg[C]ha^{-1} was shown in the 20-year age group, and the lowest value of 0.23 Mg[C]ha^{-1} was shown in the 5-year age group. Similarly, significant differences ($P < 0.05$) in carbon stocks of gliricidia branches were observed among age categories [Figure 5B]. The highest carbon stock of 16.64 Mg[C]ha^{-1} was shown in the 20-year age group, and the lowest value of 3.15 Mg[C]ha^{-1} was shown in the 5-year age group. However, the variability in carbon stocks diminished with older age groups, as similar carbon stocks were recorded between the 5 and 10-year age groups, as well as between the 15 and 20-year age groups. Atapattu *et al.* suggested that the ability to prune gliricidia stems to the same heights may contribute to the similarity in biomass and carbon stock among age classes. Nonetheless, an increasing trend in carbon stocks with age was observed in this study[7].

The carbon stock of gliricidia main stem also exhibited significant differences [$P < 0.05$] between the 5 to 10-year age groups and the 15 to 20-year age groups [Figure 5C]. The highest carbon stock of 29.86 Mg[C]ha^{-1} was shown in the 20-year age group, and the lowest value of 15.82 Mg[C]ha^{-1} was shown in the 5-year age group. Carbon stocks of gliricidia roots also exhibited significant differences among age categories, with biomass and carbon stocks increasing with age despite the impacts of pruning. The highest carbon stock of 57.69 Mg[C]ha^{-1} was shown in the 20-year age group, and the lowest value of 6.31 Mg[C]ha^{-1} was shown in the 5-year age group. There were significant differences ($P < 0.05$) among the four age groups [Figure 5D]. The regular pruning carried out at 6-month intervals across all age categories maintained similar leaf biomass, consequently resulting in comparable leaf carbon stocks across ages[39]. This suggests that once gliricidia trees are established for 10 years, they can consistently contribute to carbon stocks through stable leaf biomass production over time. The total carbon stock of gliricidia showed an increasing trend with increasing age. The highest carbon stock of 106.09 Mg[C]ha^{-1} was shown in the 20-year age group, and the lowest value of 25.53 Mg[C]ha^{-1} was shown in the 5-year age group [Figure 5E]. There was a significant difference between the 5-year and 15-to-20-year age groups at $P < 0.05$. In comparison with previous studies by Mulyana *et al*. and Raveendra *et al.*, lower carbon stock values were recorded in this study[21,40]. This difference could be attributed to methodological variations, as the current study employed destructive sampling for carbon stock estimation, compared to previous studies that relied on allometric equations. Consequently, the current study provides a more precise and realistic estimation of carbon stocks in gliricidia trees.

Soil carbon stock

According to the preliminary study, the mean values of soil characteristics showed minor variations across all selected research plots. The soil is slightly acidic, with a pH ranging from 6.0 to 6.5[41]. Electrical conductivity is low (0.02-0.03 S/m), indicating minimal salinity[42]. The bulk density ranged between 1.70 and 1.75 g/cm^3, suggesting a moderately compact soil structure[43]. In terms of nutrients, total nitrogen levels range from 0.05% to 1.5%, phosphorus is moderate at 6-7 mg/kg, and potassium is relatively low at 0.02% to 0.035%. Soil texture analysis classifies the soil as sandy loam, primarily composed of sand (70%-75%), with smaller proportions of clay (20%-25%) and silt (8%-9%)[44]. The total carbon stock in a one-hectare coconut monocropping system was 13.39 Mg[C]ha^{-1} [Table 2]. In contrast, a mixed cropping system combining coconuts with Gliricidia showed a higher carbon stock of 14.49 Mg[C]ha^{-1} [Table 2]. According to the results, the total carbon stock in the coconut-gliricidia mixed cropping system was higher than in the coconut monocropping system. However, there was no significant difference in soil carbon stocks between the monocropping and mixed cropping systems. Nevertheless, a significant difference was observed in soil

Table 2. Soil carbon stock in different cropping systems

Cropping system	Soil carbon stock (Mg[C]ha^{-1})	
	In the manure circle	In the center square
Coconut monocropping system	3.05	10.34
Coconut-gliricidia mixed cropping system	3.22	11.27

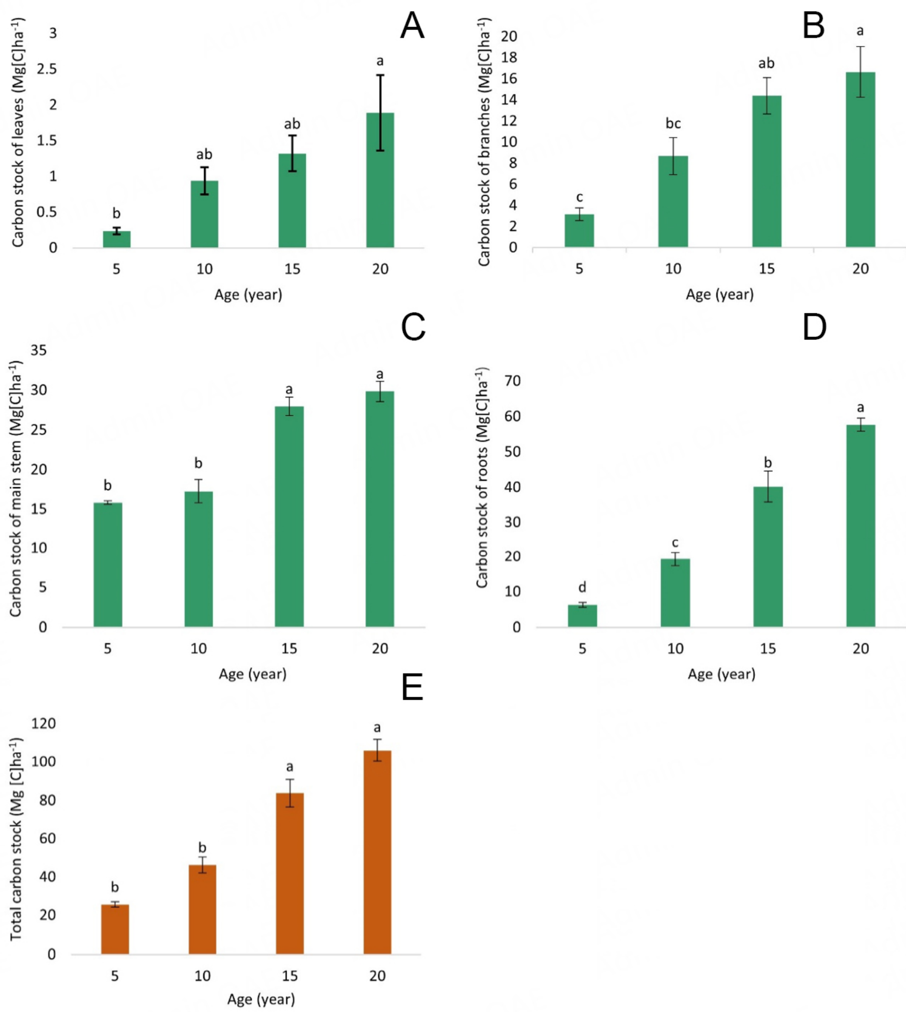

Figure 5. Variation of gliricidia carbon stock with different age groups. (A) Leaves carbon stock, (B) Branches carbon stock, (C) Stem carbon stock, (D) roots carbon stocks, (E) Total plant carbon stock (Means that do not share a letter are significantly different at $P < 0.05$). The assumption: There are 2,400 gliricidia plants in one hectare under coconut.

carbon stocks between the manure circles in both collection sites. Saha *et al.*. found that with increasing depth, carbon stocks declined, but no significant differences were observed between the topsoil layer and subsoil layer of coconut fields[45]. A study by Ranasinghe and Thimothias[46] found that soil carbon stocks in monoculture coconut systems varied between 14.15 to 44.17 Mg[C]ha^{-1}. The differences observed between the studies might be attributed to variations in microclimate, soil, and related conditions across the study sites, as they were conducted in different agroecological areas and soil series. Soil properties such as texture, pH, bulk density, and nutrient levels create a complex framework that influences carbon dynamics[47]. Sandy soils may have a problem with carbon storage because the carbon decomposes faster than in other soils, while clay soils have high carbon storage capacity[48]. Optimal soil pH and nutrient availability promote microbial activity and plant productivity, which drive carbon inputs.

Carbon stock in ground cover

In both the coconut monocropping and coconut-gliricidia mixed cropping systems, four main categories within the botanical composition of the ground cover: grasses, legumes, broad leaves, and sedges were identified. In the coconut monocropping system, the ground cover was predominantly composed of grasses, making up 78% of the total, followed by 10% legumes, 8% broad leaves, and 4% sedges [Figure 6A]. Under the mixed cropping system, the ground cover showed 75% grasses, 13% legumes, 8% broad leaves, and 4% sedges [Figure 6B]. Grasses were the dominant category at both sites compared to the other three categories. Additionally, sedges comprised the lowest composition at both respective sites. Across all collected samples, *Pueraria phaseoloides* was the most prominent legume species.

According to the results, in coconut monocropping systems, the live aboveground ground cover contained 0.99 Mg[C]ha^{-1}, and the live belowground ground cover contained 0.18 Mg[C]ha^{-1}. Additionally, the litter carbon stock was 0.16 Mg[C]ha^{-1}. Therefore, the total ground cover carbon stock was estimated at 1.24 Mg[C]ha^{-1} [Figure 7A]. In coconut-gliricidia mixed cropping systems, the live aboveground ground cover showed 0.74 Mg[C]ha^{-1}, and the live belowground ground cover showed 0.15 Mg[C]ha^{-1}. However, the litter carbon stock showed the same value as in the coconut monocropping system, which was 0.16 Mg[C]ha^{-1}. Finally, the total ground cover carbon stock in the coconut-gliricidia mixed cropping systems was 1.05 Mg[C]ha^{-1} [Figure 7B]. The total carbon content in the ground cover of the coconut-gliricidia mixed cropping systems was lesser than in the coconut monoculture. However, there was no significant difference in carbon content among each category of ground cover when comparing the monocropping and mixed cropping systems. In the coconut-gliricidia mixed cropping systems, it was identified that the ground cover was less vigorous under the gliricidia canopy due to low light penetration to the ground level. This could be the reason for the lesser value of carbon stock in the coconut-gliricidia mixed cropping systems. A study by Ranasinghe and Thimothias[46], in two different land suitability classes and three different agroecological zones and soil series, recorded higher grass cover and litter C stocks. The C stocks recorded in the aforementioned study ranged between 0.73 to 1.91 Mg[C]ha^{-1}. The difference between these two studies was due to differences between soil texture, land suitability classes, and agroecological zones that affect the grass cover carbon stock of the coconut agroecosystem. Another study by Raveendra *et al.* stated that the C stock of aboveground parts was 1.69 Mg[C]ha^{-1} for the coconut monoculture system[21].

Total agroecosystem carbon stock: 30-year-old coconut monocropping system *vs.* 30-year-old coconut with 10-year-old gliricidia mixed cropping system

Gliricidia as an intercrop is recommended to be introduced after 20 years of coconut plantations due to canopy shading. Therefore, when the coconut is 30 years old, the gliricidia crop reaches an age of 10 years. Four main components were identified in the coconut-gliricidia mixed cropping system on the basis of C stock distribution. According to the results, in the 30-year-old coconut monocropping system, the total carbon stock is 53.13 Mg[C]ha^{-1} from the coconut palms, and 13.39 Mg[C]ha^{-1} from the soil, and 1.24 Mg[C]ha^{-1} from the ground cover [Figure 8A]. According to the results, in the 30-year-old coconut-gliricidia mixed cropping system, the 30-year-old coconut palms sequestrate 53.13 Mg[C]ha^{-1}, the 10-year-old gliricidia sequestrates 46.16 Mg[C]ha^{-1}, the soil sequestrates 14.49 Mg[C]ha^{-1}, and the ground cover sequestrates 1.05 Mg[C]ha^{-1} [Figure 8B].

Whereas the carbon stock of the 30-year-old coconut monocropping system was 67.76 Mg[C]ha^{-1} with a carbon sequestration rate of 2.25 Mg[C]ha^{-1}yr^{-1} [Figure 9A], the carbon stock of the 30-year-old coconut-

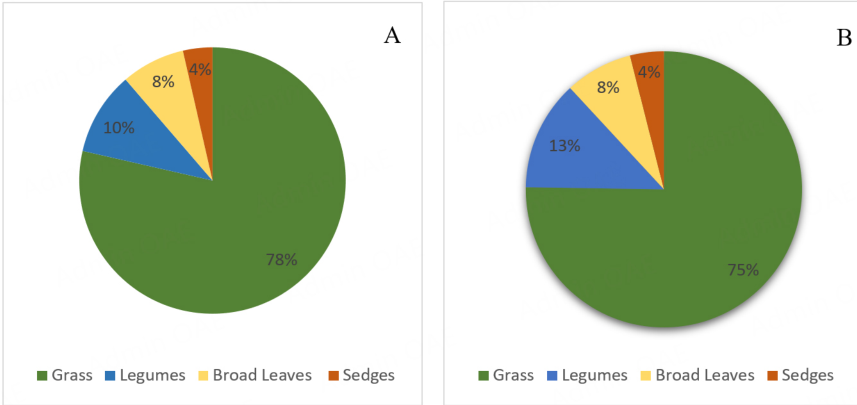

Figure 6. Botanical composition of the experimental field. (A) Coconut monocropping system; (B) Coconut gliricidia mixed cropping system.

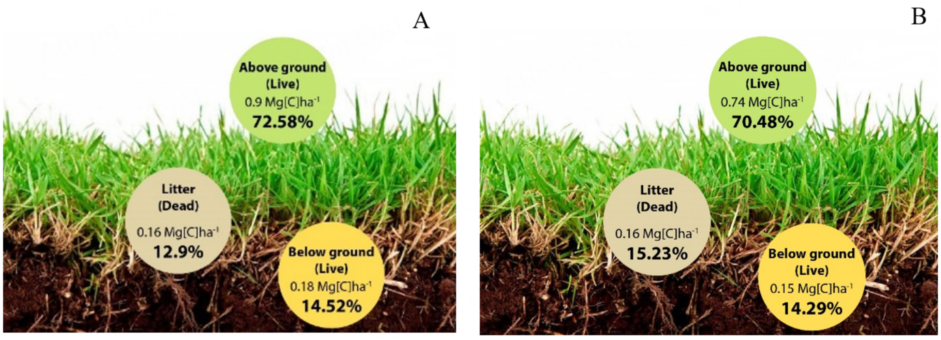

Figure 7. Total ground cover carbon stock with major components. (A) coconut monocropping system; (B) coconut gliricidia mixed cropping system. Created with GIMP (https://www.gimp.org/) and Canva (https://www.canva.com/free/).

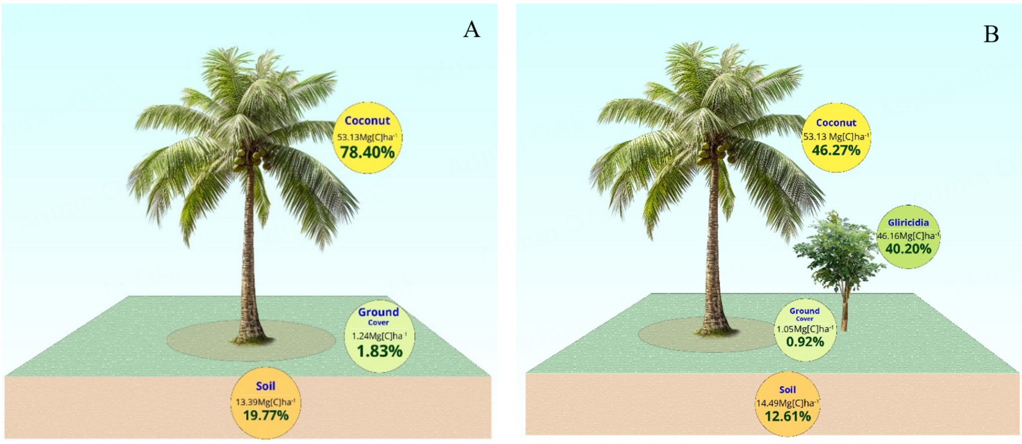

Figure 8. Visual concept of component-based carbon stock. (A) 30-year-old coconut monocrop system; (B) 30-year-old coconut and 10-year-old gliricidia mixed cropping systems. Created with GIMP (https://www.gimp.org/) and Canva (https://www.canva.com/free/).

gliricidia mixed cropping system was 114.83 Mg[C]ha^{-1} with a carbon sequestration rate of 6.84 Mg[C]ha^{-1}yr-^{1} [Figure 9B]. A study by Raveendra *et al.* reported C stocks of 138.79 and

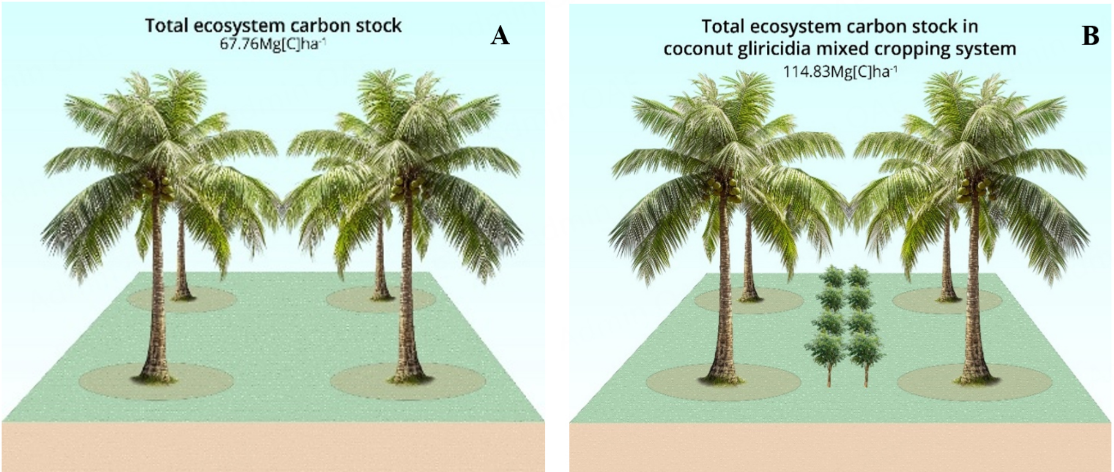

Figure 9. Visual concept of total carbon stock of (A) 30-year-old coconut monocrop systems and (B) 30-year-old coconut and 10-year-old gliricidia mixed cropping systems. Created with GIMP (https://www.gimp.org/) and Canva (https://www.canva.com/free/).

60.01 $Mg[C]ha^{-1}$, respectively, in a 30-year-old coconut and 6-year-old gliricidia in a coconut-gliricidia mixed cropping system and coconut monoculture system[21]. In the current study, the coconut C stock was relatively higher because both aboveground and belowground C stocks of palms were taken into account, but only the aboveground C stock was taken in Raveendra *et al.*'s study[21]. Additionally, the total carbon stock in coconut-gliricidia mixed cropping systems in their study was slightly higher than in the current study. This discrepancy can be attributed to differences in soil types, agro-climatic zones, and other environmental factors between these two studies.

According to Table 3, the 30-year-old coconut monocrop agroecosystem abated 8.23 $Mg[CO_2]ha^{-1}yr^{-1}$, while the 30-year-old coconut with 10-year-old gliricidia mixed cropping system abated 25.03 $Mg[CO_2]ha^{-1}yr^{-1}$. The coconut-gliricidia mixed cropping system resulted in approximately three times greater CO_2 sequestration rate compared to the coconut monocropping system. A study by Rathnayake & Mizunoya[49] showed a carbon sequestration rate of 4.89 $Mg[C]ha^{-1}yr$-^{1} and an abated CO_2 value of 17.78 $Mg[CO_2]ha^{-1}yr^{-1}$ in a coconut agroecosystem. The difference in these values from our study is due to the difference in the age group of coconut and the differences in carbon stock in other ecosystem factors.

Developed allometric models and validation

An allometric equation was developed to accurately estimate the total carbon stock in coconut palms. This equation, expressed as $TC = (0.0275 \times h) + 0.0039$, where "TC" represents total carbon stock (Mg[C]palm) and "h" denotes plant height in meters, demonstrated a robust fit with an impressive R^2 value of 0.92. This high R^2 value affirms the model's efficacy and accuracy, indicating that plant height is a significant determinant in estimating carbon storage within coconut palm agroecosystems. Growers can apply this allometric model to accurately estimate the carbon sequestration potential of their coconut palm plantations. By measuring the height of their coconut palms, they can use the equation to determine the total carbon stock within their agroecosystems. This practical tool not only aids researchers in studying carbon dynamics but also enables practitioners to implement more effective carbon management and sustainability practices in their operations.

The derived equation thus serves as a valuable resource for both scientific research and practical application, providing a reliable means to evaluate and enhance the carbon sequestration capabilities of coconut palm agroecosystems.

Table 3. Summary of total carbon stock and total abated CO_2 in 30-years-old coconut monocropping system and 30-years-old coconut with 10-years-old gliricidia in a coconut-gliricidia mixed cropping system

Cropping system	Crop carbon stock ($Mg[C]ha^{-1}$)	Soil carbon stock ($Mg[C]ha^{-1}$)	Ground cover carbon stock ($Mg[C]ha^{-1}$)	Total carbon stock ($Mg[C]ha^{-1}$)	Total carbon sequestration rate ($Mg[C]ha^{-1}yr^{-1}$)	Total abated CO_2 ($Mg[CO_2]ha^{-1}yr^{-1}$)
Coconut monocropping	53.13	13.39	1.24	67.76	2.25	8.23
Coconut-gliricidia mixed cropping	53.13 + 46.16	14.49	1.05	114.83	6.84	25.03

A robust allometric equation was developed to accurately estimate the total carbon stock in gliricidia plants. The equation, represented as TG = (0.0011 × g) - 0.0095, where "TG" represents the total carbon stock (Mg[C]plant) in gliricidia and "g" signifies the girth taken at 30 cm from ground level plant height in cm, showcased a robust fit with an impressive R square (R^2) value of 0. 90, affirming its efficacy as a predictive model. This equation provides a reliable framework for predicting carbon sequestration potential based on diameter at 30 cm gliricidia height, offering valuable insights for carbon accounting and management strategies in agroforestry systems. In allometric models, the R^2 is a statistical statistic that denotes the proportional part of the complete variance of the dependent variable explained by independent variables. In models with higher R^2 values, the data fit better, indicating that the model is more accurate[50,51].

CONCLUSION

The coconut-gliricidia intercropped system, while providing a promising agroforestry practice in Sri Lanka for carbon sequestration and mitigation of climate change effects, came out as a winner. The research results noted that a 30-year-old coconut plantation intercropped with a 10-year-old gliricidia stand sequestered an incredible amount of 69.46% higher carbon stock compared to a 30-year-old monocropping system based on coconut trees. The above-mentioned major disparity brings insight into the symbiotic benefits of combining coconut and gliricidia species by using their own soil carbon storage (biomass for soil). The research design of this study, which considered both groundcover and aboveground biomass, in conjunction with the soil, is a more holistic approach to understanding the carbon dynamics in this complex and intricate agroforestry system. With the use of destructive sampling and the conventional method of laboratory procedures, the study was based on a realistic and exact estimation of carbon stocks, not slipping the limitations of the previous studies that were only built on allometric equations. It turns out that the developed allometric models for coconut and gliricidia have become useful non-destructive methods for estimating the carbon stocks in these two commodities.

These models make it possible for scientists and staff to detect carbon more accurately without the use of destructive sampling in agricultural forestry. However, the paper goes further and shows how coconut-gliricidia associative farming contributes to the solution of interrelated issues of climate change, food shortage, and sustainable livelihoods at local and global levels. Through the method of carbon dioxide sequestration, improvement in soil capacity, and economic benefits, the systems take a complete system and can achieve the United Nations Sustainable Development Goals (SDGs), with particular attention to those related to life on land, responsible consumption and production, and climate action. This study serves as one of the main contributions in the research area of agroforestry and climate change mitigation in Sri Lanka. The findings provide an informed base to design sustainable and climate-resilient agricultural strategies. To enhance the broader applicability of these equations, future research should collect data across multiple agroecological zones, incorporate climate variables, and develop correction factors for different temperature and rainfall conditions.

DECLARATIONS

Acknowledgments

The authors would like to express sincere appreciation to the dedicated team at the Agronomy Division of the Coconut Research Institute of Sri Lanka for their invaluable assistance.

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All authors have read and agreed to the published version of the manuscript.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Financial support and sponsorship

None.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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