

Research Article

Comparative Analysis of Understorey Floristic Diversity and Carbon Stocks in Poorly and Intensively Managed *Tectona grandis* Plantations

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The role of forest plantations in carbon sequestration and biodiversity conservation is a topical issue among researchers and policymakers globally. This study compares understorey floristic diversity and carbon stock of a 15-year-old monoculture *Tectona grandis* plantation under intensive and poor management in a dry semideciduous ecological zone of Ghana. The study employed a nested plot design with twelve (12) 50 m × 50 m plots laid at 50 m intervals along a diagonal line transect on both study sites for the sampling of *Tectona grandis* trees. Understorey trees, shrubs, and climbers were sampled within 10 m × 10 m subplot, whilst grasses and herbs were sampled within 1 m × 1 m quadrats. The study revealed a significantly higher understorey species diversity in the intensively managed plantation (Shannon index; species richness) compared with that of the poorly managed plantation. Similarly, total biomass (189.80 ± 1.846 Mg/ha) and carbon stock (94.90 ± 0.92 Mg C/ha) in the intensively managed plantation were observed to be significantly higher than the poorly managed plantation (biomass: 138.54 ± 3.70 Mg/ha; carbon stock: 64.27 ± 1.85 Mg C/ha), while the species composition between the two sites was different (Sorenson's similarity index: 0.47). The study, therefore, concludes that silvicultural forest management interventions improve the understorey floristic diversity and carbon stock in monoculture plantations. Consequently, the study recommends the adoption of silvicultural interventions in plantation management in Ghana to improve their contributions to carbon sequestration and floristic diversity conservation.

1. Introduction

Climate change and biodiversity loss are among the most prominent environmental challenges in the 21st century [1]. These challenges have therefore received critical global attention with many governments, researchers, and policymakers debating and developing innovative measures to ensure a balance between conservation, climate mitigation, and development goals [2, 3]. Also, in recent years, most human efforts have been aligned towards climate change mitigation and biodiversity conservation including sustainable forest management which has been widely recognized to possess a huge potential to find lasting solutions to these environmental challenges [4].

Many researchers have also argued that a collective global effort aimed at arresting deforestation and forest degradation together with massive reforestation and afforestation can play an essential role in addressing these challenges [5, 6], particularly through the sequestration of carbon from the atmosphere and conservation of biodiversity. However, despite this recognized potential and considerable global efforts towards forest conservation, vast areas of natural forests continue to be converted into other land uses annually [1]. For instance, the FAO [7] estimated that, between 2000 and 2010, the global rate of natural forest loss was around 13 million hectares per year. With the continuous increase in global demand for timber and depletion of limited natural forests, many countries have

endorsed commercial plantations establishment as an alternative to ease pressure on natural forest resources [1].

Consequently, vast areas of degraded forest lands globally are being converted into plantations of different tree species (both indigenous and exotic) in single or mixed-species stands. According to Payn et al. [8], the global cover of plantation forests increased from 167.5 million ha in 1990 to 277.9 million ha in 2015 with a majority of these plantations being monocultures of *Eucalyptus*, *Pinus*, *Acacia*, *Tectona*, *Picea*, and *Pseudotsuga*. Among these plantation species, *Tectona grandis* has been reported to be the most valuable and widely produced species globally with commercial plantations in about 70 tropical and subtropical countries in Asia, Africa, America, and Oceania [9, 10].

Plantations are thus expected to reduce the pressure on the existing natural forests, promote biodiversity conservation and carbon sequestration, restore degraded forests, reduce soil erosion, connect fragmented landscapes, and provide alternative livelihood for forest-fringe communities [1, 11, 12]. According to Nilsson and Schopfhauser [13], plantation establishment could result in 345 million hectares of new forests that would sequester about 1.5 Gt of carbon per year, equivalent to about 30 percent of global anthropogenic carbon emissions. Niu and Duiker [14] also reported that the afforestation of marginal agricultural lands in the Midwestern United States could offset 6–8 percent of regional CO₂ emissions. Many studies have also reported the potential of plantation forests for biodiversity restoration in degraded lands [15, 16]. However, according to Kollert and Kleine [9], without appropriate silvicultural interventions, these services would be severely compromised.

The situation in Ghana, a sub-Saharan tropical African country, is not different from what persists in other countries globally despite the nation's well-established forest policies and management plans. Population pressure, agricultural expansion, bush fires, unsustainable logging, and mining have led to the wanton deforestation and degradation of approximately 80% of the primary forest cover with associated problems such as loss of biodiversity, climate change, and loss of livelihoods [11, 17]. As a result, the government of Ghana initiated the National Forest Plantation Development Program aimed at integrating socio-economic development and environmental sustainability principles in the restoration of degraded forest landscapes into plantation [18]. Through this initiative, a total of 169,489.76 ha of pure and mixed plantations were established in degraded forests in Ghana from 2002 to 2012 [12]. However, according to Foli et al. [20], over 50–70% of these plantations are *Tectona grandis* monocultures largely due to its fast growth, market demand, economic potential, and pest and fire resistance.

Despite the significant contributions of *Tectona grandis* plantations to the economy of Ghana, the species has come under serious criticism as many have raised concerns among others over its impacts on understorey species diversity, carbon stocks, and soil nutrient dynamics [1, 21, 22]. It has also been condemned for its negative impact on nontimber forest products of livelihood importance and labeled as a threat to livelihood

sustainability in forest-fringe communities [23]. However, many authors have argued that these negative impacts could be reversed through the adoption of appropriate silvicultural practices in the management of these plantations [3, 24]. According to the authors, silvicultural management practices such as pruning, thinning, and weeding may play a key role in enhancing the productivity, quality of wood, understorey diversity, and carbon sequestration potential of plantation forests.

Many empirical studies in recent years have therefore given substantial attention to the development of modern approaches and tools to ensure sustainable management of forest plantations. *Tectona grandis* being the most extensively grown species globally has received a fair share of current forestry research attention. However, majority of these studies have largely focused on its genetic variations [25, 26], growth performance [27, 28], vegetative propagation [28] 1998), and market potential [29, 30] with only a few studies exploring management techniques to enhance its productivity, understorey floristic diversity, and carbon stock [9, 31].

In Ghana, studies on plantations have largely focused on floristic diversity and composition [32], productivity, pest tolerance [28], and survival and growth performance [33] in mono and mixed plantations. To date, limited studies have focused on the effects of different silvicultural management techniques on understorey floristic diversity, stand productivity, and carbon stocks [9, 31], particularly, in the widely established *Tectona grandis* monoculture plantations. This study, therefore, seeks to assess the productivity, carbon stock, and understorey floristic diversity in *Tectona grandis* plantation under different silvicultural management regimes in the dry semideciduous ecological zone of Ghana. The study specifically examines the influence of silvicultural management on (a) understorey floristic diversity; (b) dendrometric parameters (height and diameter); and (c) carbon stock of *Tectona grandis* plantation. The study is expected to provide the necessary data to bridge the gap in knowledge on the effects of silvicultural management on floristic diversity and carbon stock of *Tectona grandis* plantations. It is also expected to provide the necessary information for the development of strategies to improve current plantation schemes for the sustainable management of plantations.

2. Materials and Methods

2.1. Description of the Study Area. The study was conducted in the Asubima Forest Reserve in the dry semideciduous ecological zone of Ghana (Figure 1). The Reserve lies within a grid reference of 7.4135°N, 1.8874°W, near Akumadan, Ghana [34]. It covers a total area of 7,870 hectares. The reserve has a tropical monsoon climate with alternating wet and dry seasons. The long-wet season starts around mid-March and ends in mid-July and is followed by a short dry season until the end of August. Its mean annual temperature is about 26°C. The reserve is a habitat of important timber species such as *Triplochiton scleroxylon*, *Millicia excels*, *Entandrophragma cylindricum*, and *Pericopsis elata* [35].

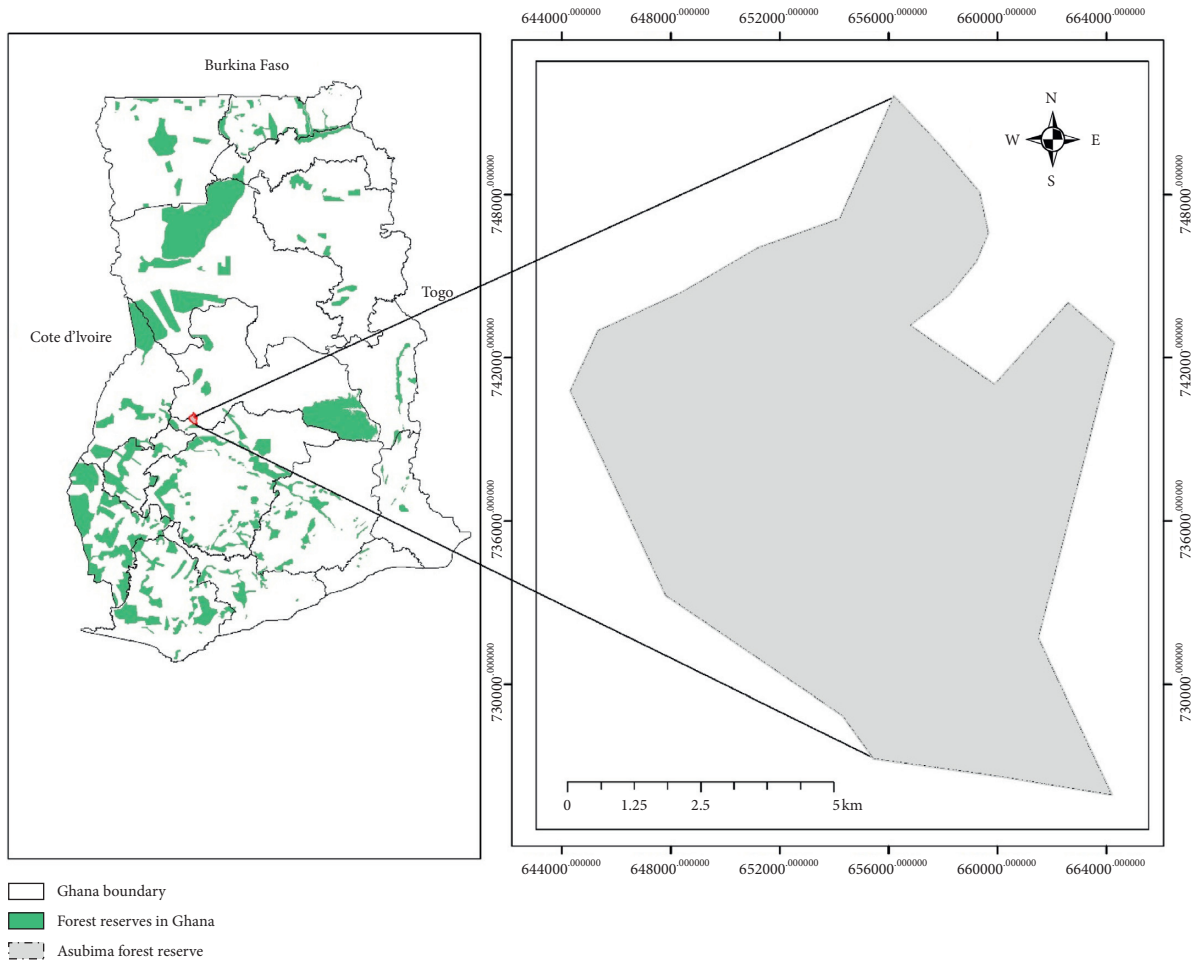


FIGURE 1: Map of Ghana showing the study area.

2.2. Sampling Design and Data Collection. A combination of stratified and systematic sampling techniques was employed in this study. *Tectona grandis* plantations were stratified into two different management regimes (i.e., intensively and poorly managed). The intensively and poorly managed *Tectona grandis* plantations were both 15 years old (Table 1).

A nested plot design with twelve 50 m × 50 m plots laid at 50 m intervals along a diagonal line transect at both study sites (the intensively and poorly managed *Tectona grandis* plantation) were used for this study (Figure 2). The plots were appropriately laid to eliminate the confounding effects of slope on the understorey floristic diversity and composition responses with the aid of a compass and a measuring tape. The 50 m × 50 m plots were used for sampling *Tectona grandis* trees. Also, twelve 10 m × 10 m subplots were established in the middle of the main plot (i.e., 50 m × 50 m) to sample the understorey trees (20 cm height <10 cm dbh), shrubs, and climbers due to their sparsely distributed nature. Twelve 1 m × 1 m quadrats, one in the middle of each 10 m × 10 m subplot, were laid for the sampling of grasses and herbs. Only plants with a diameter at breast height (dbh) <10 cm (seedlings and saplings) were sampled as regeneration during the understorey vegetation sampling [36]. Within the 10 m × 10 m subplots, all understorey trees (≥2 cm ≤10 cm dbh), shrubs

(dbh <10 cm), and climbers were sampled. Herbs and grasses were also sampled within the 1 m × 1 m quadrats. Understorey plants were identified to the species level in the field with the aid of a botanist from the Forest Research Institute of Ghana (FORIG) and photo guide for forest trees in Ghana [27]. Voucher specimens of plants that could not be identified on the field were collected, labeled, pressed, and dried for subsequent identification through comparison with preserved specimens at the Resource Management Support Centre of the Forestry Commission (RMSC) herbarium in Kumasi, Ghana. Dead species were not considered in this study due to difficulties in identification. The diameter at breast height (DBH) of the *Tectona grandis* trees was measured using a tree caliper and diameter tape, while the height was determined with Vertex IV and Transponder III.

2.3. Estimation of Understorey Diversity, Species Composition, Similarity. The diversity and evenness of understorey flora for each plot were determined using the number of species per unit area and two widely used indices, including Shannon Wiener's diversity index (H') [38] and Pielou's evenness index (J) [39]. The indices were computed using the following formula:

TABLE 1: Management regimes and their corresponding definitions.

Management regimes	Description
Intensively managed	Plantation raised with pruning (8 times in 15 years, i.e., from 2002 to 2009), thinning (600 trees/ha in 2010 and 450 trees/ha in 2012), and weed control (3 times per year up to 4 years with a mean stocking density of 301)
Poorly managed	Plantation raised with no pruning, no thinning, and weeding was done once a year up to 2 years with a mean stocking density of 359

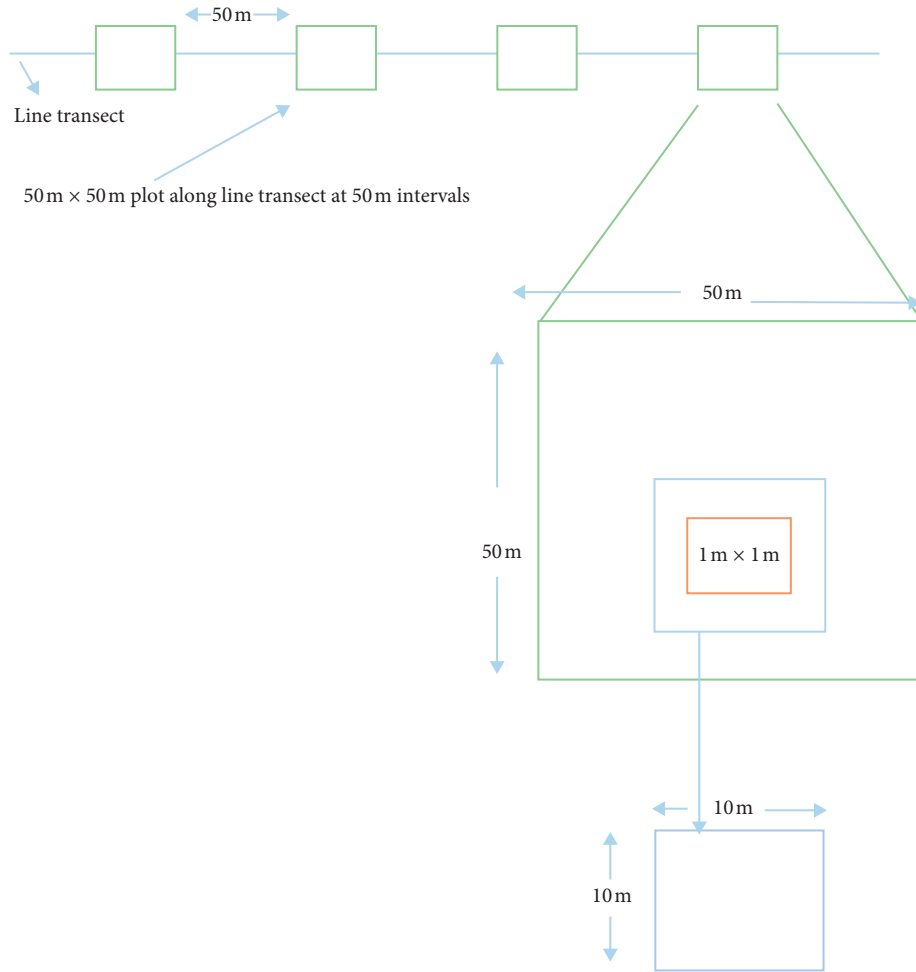


FIGURE 2: Experimental plot layout of nested plot design; 1 m × 1 m for herbs and grasses; 10 m × 10 m plot for sampling climbers, shrubs, and tree life forms (20 cm height <10 cm dbh); and 50 m × 50 m plot for sampling *Tectona grandis* trees.

$$H' = - \sum_{i=1}^s p_i \ln p_i \quad (1)$$

The Pielou's evenness index is defined as

$$J = \frac{H'}{\ln S} \quad (2)$$

where (H') is the Shannon diversity index and $\ln S$ is the natural logarithm of the total number of species.

The similarity in species composition between the intensively managed and the poorly managed *Tectona grandis* plantations was evaluated using Sorenson's coefficient similarity index (SCSI) defined as follows:

$$SCSI = \left(\frac{2c}{(a + b + 2c)} \right), \quad (3)$$

where c = number of species occurring in two sites (common occurrence species), a = number of species occurring in site A only, and b = number of species occurring in site B only.

SCSI close to 1 indicates areas with most of their species in common, and for dissimilar areas, the value is close to 0. Sites with an index <0.5 are considered different in terms of species composition, whilst sites with an index >0.5 are considered similar in species composition [40].

2.4. *Tectona grandis* Aboveground and Belowground Biomass and Carbon Stock Estimation. In each 50 m × 50 plot, the diameter at breast height (DBH in centimeters) and total tree height (H in meters) of each *Tectona grandis* trees were measured. The dendrometric records of the individual *Tectona grandis* trees and the wood specific gravity ρ (g/cm³) of *Tectona grandis* obtained from the global wood density database [41] were entered into an allometric equation to determine the aboveground biomass [42]:

$$AGB_{est} = 0.0673 \times (\rho D^2 H)^{0.976}, \quad (4)$$

where AGB = aboveground *Tectona grandis* biomass (kg); ρ = wood specific gravity (g/cm³); D = *Tectona grandis* tree diameter in cm (dbh at 1.3 m above the ground), and H = total tree height (m).

Belowground biomass (BGB) of *Tectona grandis* was estimated using the allometric equation developed by Kuyah et al. [43] as follows:

$$BGB_{est} = 0.048 \times (dbh)^{2.303}. \quad (5)$$

The total biomass for each 50 m × 50 m plot was estimated from the total AGB and BGB (kg) and the value divided by the area of the sampling plot (2500 m²) to obtain the biomass stock density in kg/m² and converted to Mg/ha. The carbon content of each tree in the plots was calculated by multiplying the modeled dry weight biomass by 0.5 [44]. The carbon dioxide equivalent (CO₂e) was estimated by multiplying the carbon stock by 3.67 [45].

2.5. Statistical Analysis. The mean values of Shannon diversity and Pielou's evenness indices, dendrometric parameters (diameter and height), total biomass, and carbon stocks were subjected to normality and homogeneity of variance test. This was followed by an independent sample t test to determine the difference between the intensively and the poorly managed plantations. Those that violated the normality and equality of variance assumptions were compared using the MannWhitney nonparametric test. All statistical analyses were performed using IBM SPSS version 21.

3. Results

3.1. Understorey Species Composition. A total of 84 understorey species distributed over 35 families were identified in the intensively and poorly managed *Tectona grandis* plantations. Out of this number, the intensively managed plantation recorded 67 species distributed over 32 families, while the poorly managed plantation recorded only 43 species distributed over 20 families (Table 2). The five most common families in the intensively managed plantations were *Moraceae* (6 species), *Combretaceae* (5 species), *Euphorbiaceae* (5 species), *Rubiaceae* (5 species), and *Sapindaceae* (5 species) (Table 3). Common families under the poorly managed plantation were *Gramineae* (10 species), *Moraceae* (5 species), and *Papilionaceae* (5 species). Sorensen's coefficient similarity index (Sorensen's index,

hereafter) of understorey floristic species between the intensively managed and poorly managed plantations was 0.47 (Table 3). However, in terms of life forms, Sorensen's index for understorey trees, grasses, shrubs, climbers, and herbs between the intensively and poorly managed plantations was 0.46, 0.57, 0.57, 0.46, and 0.36, respectively. Twenty-three understorey tree species were unique to the intensively managed plantation, whereas only 5 tree species were exclusive to the poorly managed plantation.

3.2. Comparison of the Overall Understorey Floristic Diversity between the Intensively and Poorly Managed *Tectona grandis* Plantation. An independent sample t test was used to compare the overall understorey mean species diversity, richness, and evenness between the intensively and poorly managed *Tectona grandis* plantation. Generally, species richness in the intensively managed plantation (mean ± SE: 16.417 ± 1.479) was significantly higher ($t(22) = 4.210$, $p \leq 0.01$) compared with that in the poorly managed plantation (9.333 ± 0.801). Similarly, the understorey vegetation of the intensively managed plantation was more diverse (2.450 ± 0.086) ($t(22) = 5.807$, $p \leq 0.01$) than that of the poorly managed plantation (1.753 ± 0.084). Floristics species were more evenly distributed in the intensively managed plantation (0.898 ± 0.020) ($t(22) = 3.455$, $p \leq 0.01$) than those in the poorly managed (0.795 ± 0.022) (Table 4).

3.2.1. Comparison of Understorey Species Diversity in Terms of Life Forms between the Intensively and Poorly Managed *Tectona grandis* Plantation. The MannWhitney nonparametric test showed that the intensively managed *Tectona grandis* plantation recorded significantly higher ($p < 0.01$) understorey trees and climbers diversity compared with that of the poorly managed plantation. The diversity of grasses was significantly higher ($p < 0.01$) in the poorly managed plantation (Table 5).

Understorey diversity of trees, shrubs, and climbers was estimated at the subplot (10 m × 10 m) levels whilst that of grasses and herbs was estimated at quadrat (1 m × 1 m) levels.

3.2.2. Spearman's Rank Correlation Matrix of the Different Life Forms of the Understorey Species. Spearman's rank correlation indicated the following life form pairs, herbs/climbers ($r = 0.325$), shrubs/climbers ($r = 0.128$), trees/climbers ($r = 0.305$), trees/herbs ($r = 0.245$), trees/shrubs ($r = 0.398$), herbs/grasses ($r = 0.02$), and herbs/shrubs ($r = 0.029$), recorded a positive correlation though not statistically significant ($p > 0.01$) whilst the following life form pairs, shrubs/grasses ($r = -0.283$) and climbers/grasses, recorded nonsignificant ($p > 0.05$) negative correlations (Table 6). However, the understorey floristic diversity of trees and grasses showed a highly significant negative correlation ($r = -0.707$, $p < 0.01$) suggesting that as understorey grasses diversity increases, understorey trees diversity tends to decrease significantly (Table 7).

TABLE 2: Understorey species found in the intensively and poorly managed *Tectona grandis* plantations.

No.	Family	Species	Star rating	Habit	IM	PM
1	Anarcadiaceae	<i>Spondias mombin</i>	Green	Tree	1	0
2	Apocynaceae	<i>Holarrhena floribunda</i>	Green	Tree	1	1
3		<i>Motandra guineensis</i>	Green	Climber	1	0
4	Araceae	<i>Anchomanes difformis</i>	Green	Herb	1	1
5	Asclepiadaceae	<i>Gongronema latifolium</i>	Green	Climber	0	1
6	Asteraceae	<i>Chromolaena odorata</i>	Green	Shrub	1	1
7	Bignoniaceae	<i>Newbouldia laevis</i>	Green	Tree	0	1
8		<i>Markhamia tomentosa</i>	Green	Tree	1	0
9		<i>Spathodea campanulata</i>	Green	Tree	1	0
10	Bombacaceae	<i>Ceiba pentandra</i>	Pink	Tree	1	0
11	Caesalpiniaceae	<i>Griffonia simplicifolia</i>	Green	Climber	1	1
12		<i>Mezoneuron benthamianum</i>	Green	Climber	0	1
13	Capparaceae	<i>Euadenia eminens</i>	Blue *	Tree	1	0
14	Chrysobalanaceae	<i>Maranthes kerstingii</i>	Blue *	Shrub	0	1
15	Combretaceae	<i>Combretum zenkeri</i>	Blue *	Climber	1	0
16		<i>Combretum cuspidatum</i>	Blue *	Climber	1	1
17		<i>Combretum racemosum</i>	Green	Climber	1	0
18		<i>Combretum smeathmannii</i>	N/A	Climber	1	0
19		<i>Terminalia glauscens</i>	N/A	Tree	1	0
20	Compositae	<i>Aspilia africana</i>	N/A	Herb	0	1
21		<i>Spilanthes filicaulis</i>	N/A	Herb	1	0
22		<i>Synedrella nodiflora</i>	N/A	Herb	1	0
23	Connaraceae	<i>Cnestis ferruginea</i>	Green	Climber	1	1
24		<i>Cnestis longiflora</i>	Green	Climber	1	1
25	Convolvulaceae	<i>Ipomoea hederifolia</i>	N/A	Climber	1	0
26	Cucurbitaceae	<i>Momordica charantia</i>	N/A	Climber	1	0
27	Cyperaceae	<i>Mariscus alternifolius</i>	N/A	Herb	0	1
28	Dichapetalaceae	<i>Dichapetalum madagascariense</i>	Green	Tree	1	0
29	Ebenaceae	<i>Diospyros monbuttensis</i>	Green	Tree	1	0
30	Euphorbiaceae	<i>Acalypha ciliata</i>	N/A	Herb	1	0
31		<i>Alcornea cordifolia</i>	Green	Shrub	1	0
32		<i>Croton lobatus</i>	N/A	Herb	1	0
33		<i>Euphorbia herterophylla</i>	N/A	Herb	1	1
34		<i>Mallotus oppositifolius</i>	Green	Shrub	1	1
35	Gramineae	<i>Andropogon tectorum</i>	N/A	Grass	0	1
36		<i>Imperata cylindrica</i>	N/A	Grass	0	1
37		<i>Panicum maximum</i>	N/A	Grass	0	1
38		<i>Pennisetum polystachyum</i>	N/A	Grass	0	1
39		<i>Pennisetum purpureum</i>	N/A	Grass	0	1
40		<i>Rottboellia cochinchinensis</i>	N/A	Grass	1	1
41		<i>Rottboellia exaltata</i>	N/A	Grass	1	1
42		<i>Setaria barbata</i>	N/A	Grass	1	1
43		<i>Sorghum arundinaceum</i>	N/A	Grass	1	1
44		<i>Sporobolus pyramidalis</i>	N/A	Grass	0	1
45	Loganiaceae	<i>Spigelia anthelmia</i>	N/A	Herb	1	0
46	Meliaceae	<i>Trichilia preuriana</i>	Green	Tree	1	0
47		<i>Trichilia tessmannii</i>	Green	Tree	1	0
48	Menispermaceae	<i>Albertisia scandens</i>	Gold	Climber	1	0
49		<i>Triclisia dictyophylla</i>	Green	Climber	1	0
50	Mimosaceae	<i>Albizia adianthifolia</i>	Green	Tree	1	1
51		<i>Albizia zygia</i>	Green	Tree	0	1
52	Moraceae	<i>Antiaris toxicaria</i>	Red	Tree	1	1
53		<i>Broussonetia papyrifera</i>	Invasive	Tree	1	1
54		<i>Ficus exasperata</i>	Green	Tree	1	0
55		<i>Ficus sur</i>	Green	Tree	0	1
56		<i>Ficus vogeliana</i>	Green	Tree	1	0
57		<i>Milicia excelsa</i>	Scarlet	Tree	1	1
58		<i>Morus mesozygia</i>	Green	Tree	1	1
59	Palmae/Arecaceae	<i>Elaeis guineensis</i>	Pink	Tree	1	1
60	Pandaceae	<i>Microdesmis puberula</i>	Green	Tree	1	0

TABLE 2: Continued.

No.	Family	Species	Star rating	Habit	IM	PM
61	Papilionaceae	<i>Baphia nitida</i>	Green	Tree	1	1
62		<i>Baphia pubescens</i>	Green	Tree	0	1
63		<i>Centrosema pubesens</i>	Green	Climber	1	1
64		<i>Dalbergia saxatilis</i>	Green	Climber	0	1
65		<i>Gliricidia sepium</i>	N/A	Tree	1	0
66		<i>Milletia rhodantha</i>	Green	Tree	0	1
67		<i>Milletia zechiana</i>	Green	Tree	1	0
68	Polygalaceae	<i>Carpolobia lutea</i>	Green	Tree	1	0
69	Rubiaceae	<i>Morinda lucida</i>	Green	Tree	1	1
70		<i>Morinda morindoides</i>	Green	Climber	1	1
71		<i>Musseanda erythrophylla</i>	Green	Climber	1	0
72		<i>Psychotria ivorensis</i>	Gold	Shrub	1	0
73		<i>Rothmannia longiflora</i>	Green	Tree	1	0
74	Sapindaceae	<i>Blighia sapida</i>	Green	Tree	1	1
75		<i>Blighia unijugata</i>	Green	Tree	1	0
76		<i>Deinbollia grandifolia</i>	Green	Tree	1	0
77		<i>Leucanodiscus cupanoides</i>	Green	Tree	1	0
78		<i>Paullinia pinnata</i>	Green	Climber	1	0
79	Sapotaceae	<i>Malanchata alnifolia</i>	Green	Tree	1	0
80	Sterculiaceae	<i>Cola caricifolia</i>	Green	Tree	1	1
81		<i>Cola gigantea</i>	Green	Tree	1	0
82		<i>Sterculia tragacantha</i>	Green	Tree	1	1
83	Verbenaceae	<i>Clerodendron capitatum</i>	Green	Climber	1	0
84	Violaceae	<i>Rinorea yaundensis</i>	Green	Tree	1	0
	35	84				

1 = present, 0 = absent, N/A = unknown, IM = intensively managed, and PM = poorly managed. Species in bold with asterisk symbol are rated as blue star species while those in bold are rated gold star.

TABLE 3: Overall understorey species similarity in life forms in the intensively and poorly managed *Tectona grandis* plantation.

Life forms	Unique species		Shared species	Sorenson's coefficient similarity index
	Intensively managed	Poorly managed		
Trees	23	5	12	0.46
Grasses	0	6	4	0.57
Shrubs	2	1	2	0.57
Climbers	11	3	6	0.46
Herbs	5	2	2	0.36
Overall species	41	17	26	0.47

SCSI <0.5 is considered different (dissimilar) in species composition.

TABLE 4: Comparison of mean understorey species diversity, richness, and evenness in the intensively and poorly managed *Tectona grandis* plantation.

Management regimes		Species richness	Shannon Wiener's diversity index	Pielou's evenness
Intensively managed	Mean ± SE	16.417 ± 1.479	2.450 ± 0.086	0.898 ± 0.020
	Min-max	7.000-23.000	1.873-2.832	0.728-0.964
Poorly/unmanaged	Mean ± SE	9.333 ± 0.801	1.753 ± 0.084	0.795 ± 0.022
	Min-max	6.000-17.00	1.160-2.274	0.647-0.934
<i>T</i>		4.210	5.807	3.455
<i>df</i>		22	22	22
<i>p</i> value		≤0.001	≤0.001	≤0.001

Calculations were done according to the entire study plots. ±standard error.

3.3. *Dendrometric Parameters of 15-Year-Old Tectona grandis Plantation under Intensive and Poor Management.* The mean total height (22.38 ± 0.09 m) of *Tectona grandis* in the intensively managed plantation was significantly higher ($t(658) = 15.889$, $p \leq 0.01$) compared with that in the poorly

managed plantation (20.15 ± 0.10 m) (Table 8). Similarly, the mean diameter of *Tectona grandis* in the intensively managed plantation (27.99 ± 0.22) was significantly higher ($t(658) = 20.476$, $p \leq 0.001$) than that in the poorly managed plantation (22.98 ± 0.13) (Table 6).

TABLE 5: Understorey floristic diversity of life forms in the intensively and poorly managed *Tectona grandis* plantation.

Management regimes	Trees	Grasses	Shrubs	Climbers	Herbs
Intensively managed	1.785	$1.0e^{-4}$	$1.0e^{-4}$	1.141	$1.0e^{-4}$
Poorly/unmanaged	1.019	0.800	$1.0e^{-4}$	0.349	$1.0e^{-4}$
MannWhitney (<i>U</i>)	15.5	20.5	59	25	50
<i>Z</i> score	-3.263	-3.032	-0.987	-2.737	-1.671
<i>p</i> value	≤ 0.001	0.002	0.324	0.006	0.095

TABLE 6: Mean total height and diameter at breast height of *Tectona grandis* under intensive and poor management.

Management regimes	Total height (m)	Diameter at breast height (cm)
Intensively managed	22.38 ± 0.09	27.99 ± 0.22
Poorly managed	20.15 ± 0.10	22.98 ± 0.13
<i>T</i>	15.889	20.476
<i>df</i>	22	22
<i>p</i> value	≤ 0.001	≤ 0.001

±standard error of the mean.

TABLE 7: Spearman's rank correlation matrix of Shannon Wiener's diversity index ($N = 24$).

	Trees	Grasses	Shrubs	Climbers	Herbs
Trees	1				
Grasses	-0.707**	1			
Shrubs	0.398	-0.283	1		
Climbers	0.305	-0.234	0.128	1	
Herbs	0.245	0.02	0.029	0.325	1

**Correlation is significant at the 0.01 level (2-tailed).

TABLE 8: Tree density, total biomass, and carbon stock in intensively and poorly managed *Tectona grandis* plantations.

Management regimes	Density (trees/ha)	Total biomass (Mg/ha)	Total biomass (Mg/tree)	Total carbon (Mg/ha)	Total CO ₂ equivalent (Mg/ha)
Intensively managed	301.00 ± 3.76	189.80 ± 1.85	0.63 ± 0.01	94.90 ± 0.92	348.28 ± 3.39
Poorly/unmanaged	359.00 ± 21.44	138.54 ± 3.70	0.39 ± 0.02	69.27 ± 1.85	254.22 ± 6.78
<i>t</i>	-2.664	12.406	13.638	12.407	12.407
<i>df</i>	6	6	6	6	6
<i>p</i> value	0.037	≤ 0.001	≤ 0.001	≤ 0.001	≤ 0.001

±standard error.

3.4. Total Biomass and Carbon Stock of 15-Year Old *Tectona grandis* Plantation under Intensive and Poor Management. Total biomass (189.80 ± 1.846 Mg/ha), total biomass per tree (0.63 ± 0.01 Mg/tree), and carbon stock (94.90 ± 0.92 Mg C/ha equivalent to 348.28 ± 3.4 Mg CO₂e/ha) of *Tectona grandis* plantation in the intensively managed plantation were significantly higher ($p \leq 0.001$) than those in the poorly managed plantation (Table 8). However, the density of trees in the poorly managed plantation (359.00 ± 21.44 trees/ha) was significantly higher ($t(6) = -2.664$, p value = 0.037) than that in the intensively managed plantation (301 ± 3.76 trees/ha) (Table 8).

4. Discussion

4.1. Understorey Floristic Diversity, Richness, and Evenness under Different Management Regimes. The role of forest plantations in carbon sequestration and biodiversity

conservation is a topical issue in recent years [46]. This study assessed and compared understorey floristic diversity and carbon stock of a 15-year-old monoculture *Tectona grandis* plantation under intensive and poor management in a dry semideciduous ecological zone of Ghana. The study revealed significantly higher understorey species diversity, richness, and evenness in the intensively managed compared with those in the poorly managed *Tectona grandis* plantation (Table 7). The high understorey floristic diversity in the intensive compared with the poorly managed plantations could be attributed to the prevalence of silvicultural practices (weeding, pruning, and thinning) in the intensively managed *Tectona grandis* plantation. These silvicultural practices open the forest canopy to light penetration encouraging the massive recruitment of pioneer and nonpioneer light-demanding species which largely survive under such environmental conditions. According to Gang et al. [47], pioneer and nonpioneer light demanders benefit from the increase in

light availability as a result of forest canopy opening from silvicultural operations resulting in higher regeneration compared to an unmanaged plantation. Also, pruning and thinning in the intensively managed plantations reduce soil water and nutrient competition under the canopy which creates optimal conditions for the recruitment of understorey species [47, 48]. Furthermore, the increase in light penetration, temperature, and moisture conditions created in the forest floor as a result of canopy opening under these silvicultural practices create optimal conditions for the breaking of the dormancy of the hard-coated seeds of pioneer and nonpioneer light-demanding species in the soil seed bank increasing the species diversity and richness [1, 12, 43]. Though periodic weeding in the intensively managed plantation may temporarily compromise understorey vegetation characteristics negatively, its interaction with other silvicultural practices such as pruning and thinning in the intensively managed plantation creates optimal conditions for the long-term positive effect on understorey vegetation [44]. However, in the poorly managed plantation, the dense canopy and competing vegetation prevent light penetration into the forest floor which suppressed the regeneration of understorey floral species. Only the soft leathery seeds of shade-tolerant species in the soil seed bank can generate and survive under these plantations compared with the greater numbers of pioneer and nonpioneer light-demanding species regenerating under the intensively managed plantation [17, 47]. In addition, the broadleaf morphology of *Tectona grandis* provides enough canopy cover in the poorly managed plantation until latter stages of the dry season where environmental conditions may be unsuitable for the regeneration of understorey species [4, 50]. These results are also consistent with the findings of many empirical studies that have reported the positive response of understorey species to forest canopy disturbance through pruning and thinning and long-term succession and recovery of degraded forest ecosystems [4, 10, 47, 48]. Our findings also cohered with many empirical studies that have reported high diversity and richness of understorey species under intensively managed *Tectona grandis* plantations [51–53]. Kyereh et al. [54] also reported that a greater percentage of West African plant species are pioneer species that respond positively to silvicultural interventions, which alter forest canopy characteristics. However, in terms of life forms, the intensively managed plantation supported a greater diversity of trees and climbers and low diversity of grasses whilst the poorly managed supported a greater diversity of grasses and low diversity of trees. The higher diversity of grasses in the poorly managed compared with the intensively managed plantation could be attributed to the prolific breeding and competitive characteristics of grasses compared with other life forms. Comparative studies of the understorey trees and grasses diversity in plantation forests have revealed a significant decrease in tree species diversity and increase the diversity of grasses in poorly managed plantations [55, 56]. According to Anguyi [55], poor management of plantations encourages the regeneration of grasses, which, through their competitive advantage, suppresses the regeneration of trees and other life

forms in the understorey of plantations. This presupposes that, in poorly managed plantations, particularly *Tectona grandis* plantation, grasses become the dominant understorey vegetation and eventually out-compete all other life forms resulting in the reduction in the diversity of naturally regenerated native trees (Table 6).

4.2. Understorey Species Composition Similarity. The study revealed a marginally low level of similarity among the species on the two study sites. The similarity of understorey species composition between the intensively managed and poorly managed was 0.470 (47%), indicating that about 47% of the understorey species between the intensive and the poorly managed *Tectona grandis* plantations are similar (Table 5). This suggests that about 53% of species between the two areas are completely different. According to Akoto et al. [32], Sorenson's coefficient similarity index less than 0.5 indicates different species composition. The differences in species composition on the two study sites could be attributed to the interactive effects of several environmental factors that are modified by the silvicultural operations in the intensive compared with the poorly managed plantation. The opening of the forest canopy as a result of the pruning and thinning operations in the intensively managed plantation increases light penetration into the forest floor. According to Poorter [57], high light penetration into the forest floor increases the competitive advantage and influence the recruitment and survival of light-demanding species at the expense of shade-tolerant species. The reduced soil moisture and nutrient competition in the intensively managed plantation create suitable microenvironmental conditions, readily available resources, and space for the recruitment of understorey light-demanding plant species, which forms a large percentage of the soil seed bank [58]. This may have contributed to the dissimilarities in species composition between the two sites. However, the similar species recorded on both study sites may be due to the similarity in soil seed bank characteristics for both study sites. This result is consistent with the findings of Boakye [59], who reported a higher composition of native plant species under Taungya plantations compared with natural and unmanaged plantation in Ghana. According to the author, silvicultural interventions such as weeding, thinning, and pruning in Taungya plantations significantly increase the natural regeneration diversity of species in plantations. The results are also consistent with Zhu et al.'s results [4] who reported species composition under open canopy plantation to be 2 to 3 times higher than plantations with a closed canopy.

Two different sites had shared species compositions of 0.46, 0.36, and 0.46 for trees, herbs, and climbers, respectively. This suggests that the two areas had approximately 54%, 64%, and 54% dissimilarity in understorey composition of trees, herbs, and climbers, respectively (Table 5). The differences in understorey species composition in both sites could probably be due to the different silvicultural management regimes. Similar studies have revealed that silvicultural management interventions have a great influence on understorey species composition [55, 56]. Yang et al. [48] also reported dissimilarities in herbaceous understorey

species composition in intensive and poorly managed monoculture pine and spruce plantations in China. However, the intensive and the poorly managed plantations had a shared species composition of approximately 0.57 (i.e., 57% similar species) each for understorey grasses and shrubs (Table 4), suggesting similar composition of grasses and shrubs in the two sites. The similar species composition of understorey grasses between the intensive and the poorly managed *Tectona grandis* plantations (Sorenson's index = 0.57) in contrast with the significantly higher diversity of grasses in the poorly managed (median = 0.80) compared with that in the intensively managed (median = 0.00) plantations.

4.3. Dendrometric Parameters of 15-Year-Old *Tectona grandis* Plantation under Intensive and Poor Management. Both the mean total height (22.38 ± 0.09 m) and diameter at breast height (dbh) (27.99 ± 0.22) of *Tectona grandis* in the intensively managed plantation were significantly higher ($p \leq 0.001$) than those in the poorly managed plantation (height: 20.15 ± 0.10 m; diameter: 22.98 ± 0.13) (Table 8). According to Kollert and Kleine [9], despite the ability of *Tectona grandis* to survive under variable environmental conditions, their growth and productivity are limited under unfavorable site conditions. According to the authors, appropriate site conditions and silvicultural management practices in plantation forests increase the productivity of standing trees. Binkley and Fisher [60] also reported that forest productivity is not only limited by the lack of specific required resources but also by the limited supply of multiple required resources. In dense stands with closed canopy cover, the lateral and apical growth of trees is restricted, resulting in a reduction in the height and diameter of the standing tree. Silvicultural manipulation of forest canopy through thinning of an undesirable tree, therefore, warrants optimum light, water, and nutrient use efficiency as well as the photosynthetic capacity for maximum productivity of the standing trees [4, 48, 61]. Also, the increase in solar radiation reaching the forest floor as a result of thinning and pruning operations in intensively managed plantations influences the soil temperature, microbial activity, and mineralization of organic matter which make nutrient readily available to standing trees [12]. This might have contributed to the higher mean height and diameter of trees in the intensive compared with the poorly managed plantation. This result is consistent with many studies that have reported higher growth performance of trees in intensive compared with that in unmanaged plantation [9, 10, 17, 51], e.g., in a study conducted to assess the impact of silvicultural management on the growth performance of *Tectona grandis* in Costa Rica, Kanninen et al. [51] reported 30% and 12% increases in dbh and height, respectively, in thinned compared with unthinned plots after 8 years of growth. Similarly, in a farm level trial, to influence the adoption of silvicultural management techniques by smallholder plantation managers, Roshetko et al. [10] also reported 60% and 124% increment in dbh and tree height, respectively, in thinning and pruning

treatment plots compared with that in control plot after 2 years. According to the authors, this contributed to a three times' increase in farmers' income. This, therefore, implies that silvicultural practices do not only increase the growth performance but also the value of the standing timber and long-term productivity of plantations.

4.4. Total Biomass and Carbon Stock of 15-Year-Old *Tectona grandis* Plantation under Intensive and Poor Management. Forests have been recognized as the most significant sinks for atmospheric carbon dioxide [62]. Recent afforestation and reforestation projects, therefore, aim among other things at increasing carbon stocks of the forest to reduce global climate change [63]. The study, therefore, estimated the total biomass and carbon stock of *Tectona grandis* plantations under different management regimes. The study revealed a significantly higher ($p \leq 0.001$) total biomass (189.80 ± 1.846 Mg/ha) and carbon stock (94.90 ± 0.92 Mg C/ha equivalent to 348.28 ± 3.4 Mg CO₂e/ha) in the intensively managed *Tectona grandis* plantation compared with the total biomass (138.54 ± 3.70 Mg/ha) and carbon stock (64.27 ± 1.85 Mg C/ha equivalent to 254.22 ± 6.78 Mg CO₂e/ha) in the poorly managed plantation. The significantly higher accumulation of total biomass and carbon stock of *Tectona grandis* in the intensively managed plantation was expected due to a significant increase in mean diameter and height of *Tectona grandis* in the intensive compared with that in the poorly managed (Table 8). These results may be due to several factors. According to Kollert and Kleine [8], the biomass productivity and carbon sequestration potential of plantation forests are influenced by a complex interaction of vegetation characteristics, microclimatic conditions, and silvicultural management practices. Therefore, forests with high stand density and closed canopy cover increase the competition for the limited environmental resources which impacts negatively on its biomass accumulation and carbon sequestration potential. Also, narrow spacing in the high-density stands of poorly managed plantations reduces the lateral expansion ability of trees which results in reduced diameter growth and hence the total biomass of the stand. However, the wider spacing in the intensively managed stand as a result of pruning and thinning influenced the absorption and conversion of solar energy into biomass for the lateral expansion of standing trees [9]. Furthermore, the periodic weeding exercises in the intensively managed plantation reduce light, water, and nutrient competition from understorey species and ensure maximum utilization of these resources for biomass production. This may have contributed to the higher biomass accumulation and carbon sequestration in the intensive compared with the poorly managed plantation. This implies that, apart from the economic potential, intensive management of *Tectona grandis* plantations may also increase their long-term capacity to sequestering carbon from the atmosphere. This result is consistent with the findings of many studies that have reported higher biomass accumulation and carbon stocks in intensively managed plantations [9, 64, 65] It is also in agreement with Ullah et al. [66] and Rahman et al. [2] who found mean diameter and height to have a strong positive relationship with total biomass and total carbon stock.

5. Conclusion

It could be concluded from the findings of this study that silvicultural management interventions have significant positive effects on understorey floristic diversity, dendrometric parameters (height and diameter), and carbon stock of *Tectona grandis* monoculture plantations in the dry semideciduous ecological zone of Ghana. From the study, nearly all measures of diversity indicated that the intensively managed *Tectona grandis* plantation performed significantly better than the poorly managed plantation. This attests to the widely held notion that silvicultural practices are important for enhancing understorey diversity of naturally regenerated native species in monoculture plantations. Furthermore, the total biomass and carbon stock of *Tectona grandis* plantation under the intensive silvicultural management were significantly higher than those of the poorly managed *Tectona grandis* plantation. Consequently, rehabilitation projects in degraded forests in the dry semideciduous ecological zone of Ghana need to adopt appropriate silvicultural management practices to enhance stand productivity, recruitment of native plant species, and carbon sequestration. In addition, the vast area of unmanaged monoculture *Tectona grandis* plantation needs silvicultural intervention to increase the biodiversity conservation and carbon sequestration. Nevertheless, further studies need to consider how understorey regeneration diversity and carbon sequestration vary across different ecological zones, seasons, and soil types under *Tectona grandis* plantations in Ghana.

Data Availability

Data used to support the study will be made available from the corresponding author upon request.

Conflicts of Interest

The authors report no conflicts of interest.

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