Above-ground carbon stocks and timber value of old timber plantations, secondary and primary forests in southern Ghana

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ABSTRACT

High deforestation rates, especially in the tropics, currently result in the annual emission of large amounts of carbon, contributing to global climate change. There is therefore an urgent need to take actions to mitigate climate change both by slowing down deforestation and by initiating new sinks. Tropical forest plantations are generally thought to sequester carbon rapidly during the initial years but there is limited knowledge on their long-term potential. In this study, we assessed the carbon sequestration in old (42–47 years) timber plantations of *Aucoumea klaineana*, *Cedrela odorata*, *Tarrietia utilis*, and *Terminalia ivorensis*, and secondary forests of similar ages, by comparing their basal areas and above-ground carbon stocks (AGC) to that of nearby primary forests. Additionally, we estimated and compared timber volume and stumpage value in the three forest types.

Systematic random sampling of ninety-three 20 m × 20 m plots in eleven forest sites (2 secondary forests, 2 primary forests, and 7 timber plantations) was undertaken to determine the effect of forest type on AGC, basal area, timber volume, and stumpage value.

After 42 years of growth, mean AGC of the timber plantations (159.7 $\pm$ 14.3 Mg ha^{-1}) was similar to that of primary forests (173.0 $\pm$ 25.1 Mg ha^{-1}) and both were significantly higher than the mean AGC of the secondary forests (103.6 $\pm$ 12.3 Mg ha^{-1}). Mean basal area and timber volume of the timber plantations and secondary forests were similar to that of the primary forests, though in each case the timber plantations had significantly higher values compared to the secondary forests. Mean timber value of the plantations ($8577 ha^{-1}) was significantly higher than both secondary ($1870 ha^{-1}) and primary forests ($3112 ha^{-1}). Contrary to our expectations, naturally regenerated trees (woody recruits) within the timber plantations had similar AGC levels, basal area, timber volume, and value compared to the secondary forests.

Long-rotation tropical forest plantations under low-intensity management could achieve higher AGC levels and thus have higher climate change mitigation potential and timber values compared to naturally regenerated secondary forests, and are able to reach values similar to primary forests. Monoculture timber plantations could facilitate the successful colonization of their understoreys by native woody recruits that contribute considerably to stand AGC and timber values. Long-rotation forest plantations in the tropics therefore have a critical role to play in forest rehabilitation and climate change mitigation while having the potential to provide modest financial returns to landowners through selective harvesting of timber and/or payments for carbon sequestration.

1. Introduction

Parties to the 2015 Paris Climate Change Agreement committed themselves to carrying out actions limiting the Earth's temperature increase to 1.5–2 °C above pre-industrial levels (UNFCCC, 2015).

However, total greenhouse gas emissions, including from land-use change continue to rise, reaching a record high of 53.5 PgCO$_2$e in 2017, an increase of 0.7 PgCO$_2$e compared with 2016 and almost double to 1970 levels (UNEP, 2018a). Forests are an available, and potentially cost-efficient solution with the potential to provide up to a third of the

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mitigation required to keep global warming well below 2 °C by halting forest loss and degradation, and implementing sustainable forest management, conservation, and reforestation (UNEP 2018b). To realize this potential, it is imperative to embark on actions that mitigate climate change both by increasing forest sinks through improved land management while reducing emissions from land-use activities. A recent global assessment of the potential of 20 land-based climate mitigation pathways identified reforestation as the single most important option with the potential to sequester and store ~50% of the total mitigation potential of 23.8 PgCO$_2$e yr^{-1} by 2030 (Griscom et al., 2017). It is therefore welcome news that the United Nations General Assembly has declared the 2020s as the "UN Decade on Ecosystem Restoration", aimed at massively scaling up the restoration of degraded and destroyed ecosystems, as a proven measure to fight the climate crisis and enhance food security, water supply and biodiversity.

Decades of tropical deforestation has resulted in large areas of deforested or degraded landscapes. In 2000, the International Tropical Timber Organization (ITTO) classified 60% of the world's tropical forests to be either degraded or categorized as secondary forests. Secondary forests commonly develop naturally on land abandoned after shifting cultivation, settled agriculture, pasture, or failed tree plantations (ITTO, 2002). While large portions of these deforested lands will spontaneously recover and develop into secondary forests without human intervention (Guariguata et al., 1997; Finegan & Delgado, 2000; Aide et al., 2001; Lwanga, 2003; Letcher & Chazdon, 2009; Chazdon, 2014; Chazdon and Guariguata, 2016; Poorter et al., 2016), significant portions will require some form of human intervention (Chazdon, 2003).

Reforestation strategies vary from low-intensity interventions, such as natural regeneration, assisted natural regeneration, and enrichment planting, to more intensive interventions such as forest plantation establishment by planting and intensive management including rigorous weeding, pre-commercial thinning, and pruning. Forest plantations are established for a variety of reasons or objectives and they vary in composition, structure, and management intensity (Cossalter & Pye-Smith, 2003; Stanturf et al., 2014). Several tropical forest studies have endorsed forest plantations as a viable option for reforesting or rehabilitating deforested landscapes, especially where invasive grasses or ferns pose a barrier to natural regeneration (Lugo, 1997; Campoe et al., 2010). This is primarily due to their generally rapid growth, high biomass accumulation (Omeja et al., 2011; Brancalion et al., 2019), and inherent ability, in many cases, to facilitate the regeneration of native tree species in their understories through modification of both physical and biological site conditions (Keenan et al., 1997; Parrotta et al., 1997; Butler et al., 2008; Baatuwie et al., 2011; Ashton et al., 2014; Pryde et al., 2015; Amazonas et al., 2018). These two forest types (plantations and secondary forests) are increasingly widespread and the dominant forms of tropical reforestation, thus stimulating comparison of their respective values (Bonner et al., 2013; Gilman et al., 2016), especially their relative climate change mitigation potential (Griscom et al., 2017).

A growing number of tropical reforestation studies have been published in recent years. However, most of these have been based in the Neotropics and Asian tropics, with very few published studies from the African tropics, especially West Africa. Most of the study sites are additionally usually less than 20 years old (Bonner et al., 2013). This poses a key challenge, as the later development of such early successional studies, which would be important for estimating the climate change mitigation potential, cannot be predicted with much certainty. There are only a few well-designed tropical reforestation projects that are old enough to support the needed fine-tuning between ecological theory and practice (Temperton, 2007; Weiher, 2007). Even fewer comparative studies of forest plantations and secondary forests have been published within the tropics. In their recent seminal global meta-analysis of secondary forests and monoculture forest plantations in the tropics and subtropics, Bonner et al. (2013) compiled over 140 studies

but ended up with a dataset of 48 studies from 42 sites (19 plantations, 23 secondary forests) after data quality screening. Out of the 42 sites, only 4 (1 secondary forest, 3 forest plantations) were in Africa, with only 1 plantation site in West Africa. Out of the 42 sites, 7 (4 in Asia, 3 in South America) had paired in-country plantation–secondary forest sites to allow for good comparative analysis. These findings unequivocally demonstrate the apparent paucity of previous research in this area. In addition, in reviewing available literature, no tropical forestry study was found that quantitatively estimated the standing timber volumes and timber stumpage values of secondary forests and forest plantation sites and compared these with primary forest sites.

In this study, we assessed the climate change mitigation potential of old (42–47 years) unmanaged timber plantations and secondary forests of similar ages and relative distances from surrounding secondary remnant forests, by comparing their basal areas and above-ground carbon stocks to those of nearby primary forests. Additionally, we estimated and compared the timber volumes and values of these three forest types.

The specific objectives of the study were to (i) assess and compare above-ground carbon stocks and basal areas of old timber plantations, naturally regenerated secondary forests, and primary forests, (ii) estimate and compare timber volumes and timber stumpage values of plantation, secondary, and primary forests, (iii) estimate and compare above-ground carbon stocks between two forest zones (wet and moist), and (iv) assess and compare the relative contribution of naturally regenerated woody perennials i.e. woody recruits (trees, shrubs and lianas) to above-ground carbon stocks, basal area, timber volume, and value within the plantations and compare these with secondary forests.

We hypothesized that (i) above-ground carbon stocks, basal area, timber volume, and timber value will be higher in plantations than in secondary forests of similar ages (Lugo, 1992; Holl & Aide, 2011; Zahawi et al., 2013; Holl & Zahawi, 2014; Gilman et al., 2016), as forest plantation establishment practices, such as seed collection, raising nursery seedlings, site preparation, and planting, circumvent some of the ecological filters that inhibit seedling establishment during natural regeneration (Holl & Aide 2011, Brancalion, 2012a). Additionally, the purposeful planting of high-value timber species is expected to lead to relatively higher production of timber volume and value within the plantations. (ii) Above-ground carbon stocks, basal area, and timber volume will be higher in primary forest than in secondary forests and timber plantations; however, timber value is expected to be higher in the plantations than the primary and secondary forests; (iii) in the secondary forests, above-ground carbon stocks, basal area, timber volume, and value will be higher than those of the woody recruits within the plantations due to expected high competition between colonizing plants and fast-growing planted trees, resulting in a trade-off between the growth of planted trees and woody recruits (Lamb et al., 2005; Catterall et al. 2005; Zimmerman et al., 2007) in addition to initial management interventions such as removal of understorey competition during the first 3–4 years. We further hypothesized that accumulated above-ground carbon stocks will be higher in the wet forest zone compared to the moist zone following a precipitation gradient (Poorter et al., 2016).

2. Methods

2.1. Study sites

This study was carried out across eleven sites located within five forest reserves (permanent forest estates), which are managed and protected by the Forest Services Division (FSD) of the Forestry Commission, Ghana. These reserves are located within the wet and moist forest zones in southern Ghana (Fig. 1) with elevations generally below 300 masl.

Seven of the sites (coded W-AK, W-TU, W-CO, W-TI, M-AK, M-TI, M-CO) are old (42–47 years) monoculture timber plantations of native and
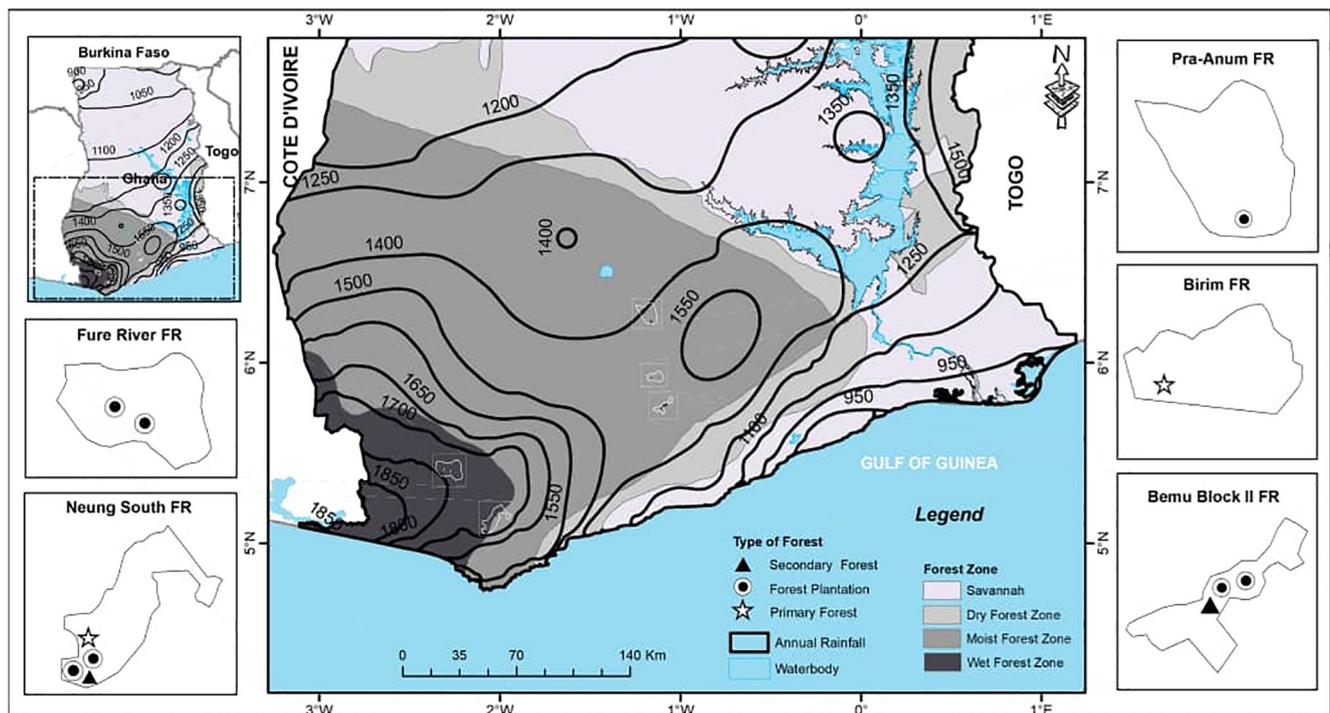
Fig. 1. Map of Ghana highlighting the locations of the five (5) Forest Reserves and 11 study sites.

Table 1
Description of the 11 study sites.

Forest Reserve (Gross area in km²)	Forest Zone[a]	Site Code	Site / Forest Type	Year Planted	Latitude/ Longitude	Area of Study Site (ha)	No. of sample plots (20 × 20 m)	Mean Annual Rainfall[b] (mm)	Mean No. of Dry Months/Yr[c]	Mean Annual Temperature[b] (°C)
Neung South (113)	Wet Evergreen	W-AK	*Aucoumea klaineana* plantation (exotic)	1971	05°03′51.7″ N 02°05′32.8″ W	2.48	7	1706	1	26.1
Neung South (113)	Wet Evergreen	W-HU	*Tarrietia utilis* (syn. *Heritiera utilis*) plantation (native)	1971	05°03′54.0″ N 02°05′26.3″ W	6.37	8	1706	1	26.1
Neung South (113)	Wet Evergreen	W-SF	Secondary Forest	1972*	05°03′46.8″ N 02°05′36.0″ W	10.22	9	1706	1	26.1
Neung South (113)	Wet Evergreen	W-RF	Primary Forest	N/A	05°05′53.7″ N 02°04′42.3″ W	25.48	10	1722	1	26.0
Fure River (158.2)	Wet Evergreen	W-CO	*Cedrela odorata* plantation (exotic)	1976	05°24′17.1″ N 02°18′22.7″ W	2.32	7	1779	1	26.3
Fure River (158.2)	Wet Evergreen	W-TI	*Terminalia ivorensis* plantation (native)	1971	05°23′48.4″ N 02°17′21.0″ W	7.24	9	1779	1	26.3
Pra-Anum (123.3)	Moist Semi-deciduous	M-AK	*Aucoumea klaineana* plantation (exotic)	1971	06°13′19.2″ N 01°09′34.1″ W	2.95	8	1459	2	26.3
Bemu Block II (43.8)	Moist Evergreen	M-CO	*Cedrela odorata* plantation (exotic)	1974	05°45′41.5″ N 01°05′15.7″ W	7.4	9	1569	2	26.0
Bemu Block II (43.8)	Moist Evergreen	M-TI	*Terminalia ivorensis* plantation (native)	1974	05°46′16.2″ N 01°04′38.4″ W	2.93	8	1573	2	26.0
Bemu Block II (43.8)	Moist Evergreen	M-SF	Secondary Forest	1976*	05°45′41.5″ N 01°05′27.4″ W	4.96	8	1569	2	26.0
Birim (39.1)	Moist Semi-deciduous	M-RF	Primary Forest (Reference)	N/A	05°54′11.3″ N 01°10′32.6″ W	37.33	10	1521	2	26.2

[a] Forest Zone classification based on Hawthorne and Abu-Juam (1995).
[b] Interpolated average rainfall and temperature data: 1970–2000 (WorldClim, version 2)
[c] Dry month (< 60 mm rainfall per month) in accordance with the Köppen Climate Classification System for Tropical climates
* Year site was reported abandoned

exotic species, two of the sites (W-SF, M-SF) are secondary forests of similar ages as the plantations, and two are primary lowland forests (W-RF, M-RF). The first letter of the codes indicates the forest zone, wet or moist, and the subsequent letters refer to planted tree species, or whether they are secondary or primary in the case of the natural forests. The forest zones form distinctive biophysical environments ranging from wet evergreen forests to moist semi-deciduous forests with mean annual rainfall (1970–2000) at the study sites ranging between 1706

and 1779 mm in the wet zone and 1459 and 1573 mm in the moist zone (Table 1), with an average temperature ranging from 26.0 °C to 26.3 °C (Table 1). The soils of the two forest zones are quite similar in chemical characteristics. The soils of the six sites in the wet forest zone are predominantly Xanthic Ferralsols, which are deeply weathered acid soils with low nutrient content and low cation exchange capacity (CEC), with a clay assemblage dominated by low-activity clays (mainly kaolinite and sequioxides) and low in base cations. The soils of the five moist sites are predominantly Haplic Acrisols; strongly weathered acid soils with a sandy-loamy surface soil and accumulation of low-activity clay with low base saturation and low nutrient availability (FAO, 1988; WRB, 2015).

Details of the sites geographical locations, climate, planted tree species (plantations), forest type (primary forest, secondary forest, and forest plantation), and forest zones are provided in Table 1. A total of 93 sample plots (20 × 20 m), with one smaller 5 × 5 m sample plot nested at the center of each, were involved in the study. The distribution of sample plots was as follows: plantations (56), secondary forests (17), and primary forests (20). A total of fifty 20 × 20 m plots were in the wet forest zone and forty-three in the moist forest zone (Table 1).

2.1.1. Land-use history

Land-use history was gleaned from available records of the Forestry Commission, Ghana and through semi-structured interviews conducted by authors with a few retired former workers of the erstwhile Forestry Department who played key roles in the establishment and maintenance of the forest plantations.

Around the early 1970s, the former Forestry Department (now Forest Services Division of the Forestry Commission) embarked on several timber species plantation trials and community-based forest plantation programmes using both native and exotic timber species within selected timber production forest reserves in the various forest zones of Ghana. The seven timber plantations covered under this study were established between 1971 and 1976 under these initiatives.

Prior to establishment of the plantations, the seven sites were degraded natural forest stands that had undergone several logging cycles. Once selected for conversion, loggers were permitted to harvest all remaining economic timber trees. Residual large trees were either felled with chainsaws or girdled and arboricide was applied. Axes and machetes were used for lopping and slashing residual vegetation to prepare the land for planting. The debris was burnt in all the moist forest zone plantation sites (M-CO, M-TI, M-AK) but not in the wet forest zone (except W-CO), where the generally wetter conditions made burning difficult. Land preparation was carried out by casual workers engaged by the Forestry Department.

In the case of *Cedrela odorata* plantation sites (M-CO, W-CO), farmers were brought in to cultivate the land by planting food crops, such as plantain, cocoyam, maize, and vegetables, under the Taungya System, a form of agro-forestry where farmers from forest-fringe communities are granted access to degraded forest reserve lands to cultivate short-term food crops while assisting the Forestry Department to establish and maintain timber tree plantations. The farmers then planted tree crops while cultivating their food crops for a period of three to four years, after which the farmers left the plantations. No further tending was carried out in M-CO; however, Forestry Department workers carried out strip weeding and complete weeding in W-CO at least once a year for an additional eight years. W-CO was thus the only plantation stand in the study where weeding was carried out beyond four years. No further silvicultural treatments were administered thereafter.

At the other five plantation sites (M-TI, M-AK, W-AK, W-TU, W-TI), strip and complete undergrowth weeding and cutting of vines and creepers that could smother young trees was undertaken by workers of the Forestry Department twice or thrice a year for a period of three to four years and then stopped. No further silvicultural treatments were administered thereafter.

The cases of the two secondary forests (M-SF, W-SF) were similar.

M-SF, which adjoins M-CO, was prepared for plantation establishment concurrently in 1974 and farmers were brought in under the Taungya System. However, due to general downsizing of the Forestry Department field workers in the early 1970s, there was inadequate supervision of the farmers, leading to a complete failure of the planted tree crop. Apart from the poor supervision, farmer apathy and, in some cases, reported willful destruction of the tree seedlings to ensure continued farming opportunities on the land were important reasons that contributed to the failure. Despite being prepared, the site was reportedly likely never planted with tree seedlings and was only used for food crop farming. The plantation project thus failed and was discontinued. The farmers were made to leave the site around 1976 and the land was left to fallow. In the case of W-SF, which adjoins W-AK and W-TU, the site was cleared and prepared in 1971, around the same time as W-AK and W-TU. However, though *Terminalia ivorensis* was reportedly planted in W-SF, due to staff downsizing, the stand was poorly maintained and by the end of 1972 was adjudged as a completely failed plantation site and has been abandoned since.

In the case of the two primary forests, the portion of Neung South Forest Reserve, where study site W-RF is located, is under permanent protection (Globally Significant Biodiversity Area) with good forest condition (i.e. Condition Score 2; Hawthorne and Abu-Juam, 1995). The Birim Forest Reserve is a production forest, but Compartment 23, where our study site is located, has no record of logging. The study site was purposefully selected within a segment of Compartment 23 that had no signs of logging or recent anthropogenic disturbances (e.g. charcoal on the ground, presence of stumps or coppiced trees) and was in good forest condition (Forest Condition Score 2; Hawthorne and Abu-Juam, 1995).

2.1.2. Plantation establishment

Planting materials used in establishing the plantations came from varied sources; some were raised in nearby temporary tree nurseries (M-CO, W-CO, W-TI), supplied from the Mesewam Central Nursery near Kumasi (M-TI, M-AK, W-AK), or were harvested wildlings from the same forest reserve (W-TU).

Planting was carried out during the major rainy season (April–June) and initial spacing was reported to be 16ft × 16ft (4.88x4.88 m), i.e. 420 seedlings ha^{-1}. Replacement of dead seedlings (beating up) was carried out during the minor rainy season (September–October) of the planting year. The main tending operations carried out were weeding of competing grasses and shrubs and cutting or removal of vines. Weeding in the non-taungya sites was conducted either along planted strips or in the whole area. In the taungya sites (M-CO, W-CO), farmers undertook complete regular weeding for the period of food crop cultivation (usually three to four years).

2.2. Site selection and biomass data collection

2.2.1. Site selection

The seven timber plantation sites (W-AK, W-TU, W-CO, W-TI, M-CO, M-AK, and M-TI) are located within Production Forest Reserves. A search through the forest plantation database of the FSD at the time of the study revealed that the seven timber plantation sites were the only remaining old timber plantations that had not previously been thinned and not allocated for logging. These 'unthinned' plantation sites were selected to be comparable with the secondary forests and to avoid complications in estimating removals during previous thinning operations that did not always follow standard procedures and regimes, and usually impacted by the skill, compliance level, and type of logging equipment used by individual private operators. The two secondary forest sites (W-SF, M-SF) were selected based on their proximity to selected plantation sites and the similarity of their ages and land-use histories. The timber plantation and secondary forest sites were within proximity (~500 m) to remnant secondary forest stands. The two primary forests (W-RF and M-RF) were selected based on their relative

proximity to selected forest plantations and secondary forest sites, and their near pristine condition (forest condition score 2. Hawthorne and Abu-Juam, 1995) with minimal levels of anthropogenic disturbances. The only noticeable disturbance was the presence of hunters' trails in certain portions of the selected compartments.

2.2.2. Biomass data collection

A systematic random sampling design was employed. Grid lines were drawn across the sites and points of intersection selected as plot positions. We established a total of 93 plots (20 m × 20 m) each with a subplot (5 m × 5 m) nested within the centre, making a total of 186 sample plots.

Within the large plots (20 m × 20 m), all woody perennials (trees, shrubs and lianas) with diameter at breast height (DBH) ≥ 10 cm (1.3 m above ground level or above buttress) were identified, tagged, and DBH measurements taken using diameter tapes or Spiegel Relaskop (for buttressed trees). The heights of all timber trees (DBH ≥ 30 cm) were measured up to a top diameter of 20 cm (equivalent to minimum sawlog top-end diameter over-bark) using a Nikon Forestry Pro laser rangefinder and Spiegel Relaskop. Total tree height was measured using a Nikon Forestry Pro laser rangefinder with the sine method (Larjavaara and Muller-Landau, 2013). Within the sub-plots (5 m × 5 m), all trees with DBH between 2 and 9.9 cm were identified, tagged, and DBH measurements taken using diameter tapes or digital calipers. Total tree height was measured using a Nikon Forestry Pro laser rangefinder and linear tapes. All trees of the respective planted species with DBH ≥ 10 cm were considered 'planted', all others including lianas and shrubs were considered woody recruits. In the case of lianas, diameter measurements were taken 1.3 m from the main rooting position (i.e. point where stem goes into the soil) and only lianas rooted within the sample plots were measured (Pearson et al., 2005; Gerwing et al., 2006).

2.3. Data analysis

In view of the limitation caused by the lack of other old unmanaged timber plantation sites with similar ages and associated natural regeneration sites across the landscape for the study, we considered randomly sampled plots within sites as treatment replicates in our experimental design (Griscom et al. 2011; Amazonas et al., 2011; Garcia et al., 2016).

2.3.1. Biomass and carbon stocks

We used the tree inventory data (DBH and total height) to estimate the above-ground biomass (AGB). The AGB was estimated following the allometric equation of the Chave et al. (2014) pantropical model using three variables, i.e. DBH, total tree height, and wood density:

$$AGB = 0.0673 \times (\rho D^2 H)^{0.976}$$

where D is diameter at breast height (cm), H is total tree height (m), ρ is wood density (g cm^{-3}), and AGB is the estimated above-ground biomass (kg).

Wood density (ρ) figures for tree species were sourced from available databases (Kryn and Fobes, 1959; Lavers, 1983; Reyes et al., 1992; Zanne, et al., 2009; Carsan et al., 2012).

For certain small-sized trees, shrubs, and lesser-known tree species for which no information on wood densities could be found in the available databases, we estimated AGB following the allometric equation of Henry et al. (2010), which was developed from studies conducted in the moist tropical forests of Ghana:

$$AGB = 0.30 \times D^{2.31}$$

In the case of lianas, we used the allometric equation of Schnitzer et al. 2006:

$$AGB = \exp[-1.484 + 2.657 \ln(D)]$$

We converted estimated AGB to carbon mass (carbon stocks) by applying the carbon fraction of dry matter conversion factor of 0.465 recommended for tropical angiosperms (Martin et al. 2018).

2.3.2. Basal area

We used tree DBH measurements to calculate basal area within each plot (20 m × 20 m).

2.3.3. Timber volume

A stump height of 0.5 m, or buttress height, was deducted from merchantable height values obtained from the inventory.

Timber volume (V_t) was determined as (Forestry Commission, Ghana):

$$V_t = (0.00007857 \times D^2) \times H_m \times 0.6093$$

where H_m is merchantable height (less stump/buttress height).

2.3.4. Timber stumpage value

In Ghana, the Timber Resources Management and Legality Licensing Regulations, 2017 (LI 2254) prescribes a formula for calculating stumpage fees or value based on timber prices, market conditions, and inventory levels of timber species. Therefore, stumpage value (StV) was determined as:

$$StV = 0.35 \times FOB \times StR \times V_t \quad (LI2254, 2017),$$

where the factor 0.35 represents the average sawlog - lumber recovery rate; FOB is the free-on-board value of air-dried lumber (September 2018), these prices are published quarterly by the Forestry Commission; StR is Stumpage Rate and refers to a factor (20% - high-demand species, 10% - moderate-demand species, and 5% low-demand species or lesser-known species) related directly to the market demand and inventory levels or resource life of the timber species.

2.3.5. Statistical analyses

Plot means were computed for all 93 plots within the 11 sites and used to run one-way between-subjects factorial ANOVA for the following dependent variables: above-ground biomass, basal area, timber volume, and timber value across forest types (plantation, secondary, and primary forests) and forest zones (moist and wet). Post-hoc analyses were carried out using the Games-Howell test, as the Levene statistic computed for each of the dependent variables confirmed unequal error variances. Two-way factorial ANOVA was conducted to simultaneously study the effect of the two independent variables (forest type and forest zone) on four dependent variables (above-ground biomass, basal area, timber volume, timber value).

Independent-samples t-test was conducted to compare plot means of woody recruits within the plantation and the secondary forest sites for the four dependent variables: above-ground biomass, basal area, timber volume, and timber value.

All statistical analyses were carried out using IBM SPSS Statistics v.25.

3. Results

3.1. Forest type

The one-way between-subjects ANOVA conducted to compare the effect of forest type (forest plantation, secondary forest, primary forest) on four dependent variables (above-ground carbon stocks, basal area, timber volume, timber value) showed mixed responses (Table 2).

No significant differences were found in mean AGCs between plantations and primary forest types, but both primary and plantation forests had significantly higher AGCs compared to secondary forests. In the case of tree basal area and timber volume, the plantation was similar to the primary forest. However, the primary forest did not differ from the secondary forest with respect to basal area and timber volume.

Table 2
Mean above-ground carbon stocks, basal areas, timber volumes, and values of the three forest types in the study.

	Forest Type		
	Plantation	Primary	Secondary
Above-ground carbon stocks (Mg ha^{-1})			
Mean	159.7[b]	173.0[b]	103.4[a]
Std. error of mean	14.3	25.1	12.3
Basal area (m^2 ha^{-1})			
Mean	37.8[b]	34.0[a,b]	24.8[a]
Std. error of mean	2.7	3.4	1.9
Timber volume (m^3 ha^{-1})			
Mean	338[b]	294[a,b]	167[a]
Std. error of mean	41	50	38
Timber value (US$ ha^{-1})			
Mean	8577[b]	3112[a]	1870[a]
Std. error of mean	1441	809	548

Letters qualitatively indicate Games-Howell post-hoc test results comparing tree growth and timber value variables between forest types: means with the same letters are not significantly different (α = 0.05).

On the other hand, the timber plantation had significantly higher tree basal area and timber volume compared to the secondary forest (Table 2). Timber value was significantly higher in the plantations than in the primary and secondary forests. However, though the primary forest had a higher timber value compared to the secondary forest, this difference was not statistically significant.

3.2. Forest zones

The distributions and levels of carbon stock accumulation for each of the three forest types across the two forest zones are presented in Fig. 2. The distribution of AGC in the wet zone plantations show a strong positive skew, suggesting a higher frequency of high value scores, and therefore the mean score is much higher than the median, while contrastingly the primary forest data from the moist and wet zones show the opposite.

To determine the effect of forest zone (wet, moist) on carbon accumulation within the forest types, we compared the AGC levels of their plot means. AGC levels for each of the forest types was generally higher in the wet forest zone compared to the moist zone, and a one-way between-subjects ANOVA conducted showed a marginally significant effect of forest zone (α = 0.05) on AGC levels, for the forest types [F(1,87) = 2.287, P = .053]. However, Games-Howell post hoc multiple comparisons of specific forest types across the two forest zones showed
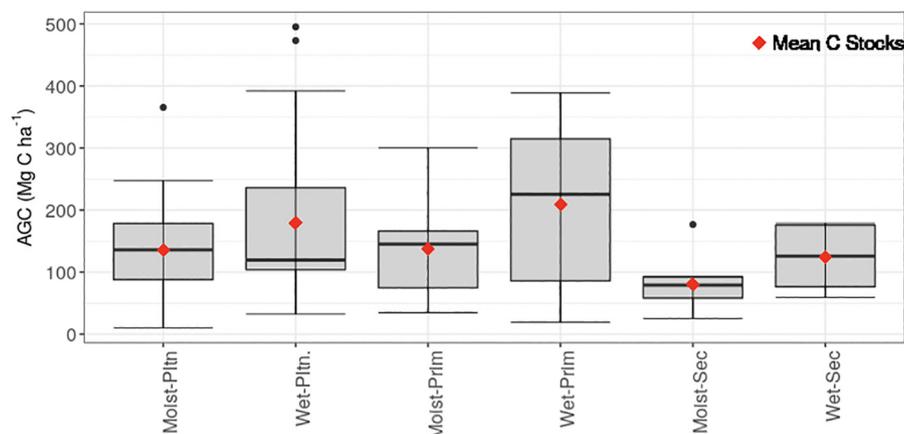
Table 3
Summary ANOVA for effect of forest zone × forest type interaction on carbon stocks, basal area, timber volume, and value.

Dependent Variable	Sum of Squares	df	Mean Square	F-value	P-value
Above-ground carbon stocks (Mg ha^{-1})	3172.29	2	1586.14	0.161	0.851
Basal area (m^2 ha^{-1})	86.66	2	43.33	0.135	0.874
Timber volume (m^3 ha^{-1})	80940.98	2	40470.49	0.541	0.584
Timber value (US$ ha^{-1})	25106225.50	2	12553112.80	0.165	0.848

no significant difference.

3.3. Forest type × Forest zone

A two-way factorial ANOVA was conducted to simultaneously study the effect of the two independent variables (forest type and forest zone) on the four dependent variables (AGC, basal area, timber volume, timber value).

The results show that the interaction (forest type × forest zone) was not significant (α = 0.05) for all four variables (Table 3).

3.4. Woody recruits

3.4.1. Relative contribution of woody recruits to stand parameters in forest plantations
Fig. 3 shows the relative contribution of planted and recruited trees to AGC levels, tree basal areas, timber volumes, and standing timber values within the forest plantation stands.

Overall, woody recruits contributed more to stand AGC (60%) and basal area (62%) compared to planted trees, while planted trees contributed more to stand timber volume (55%) and timber value (68%). However, individual plantation species showed differences in the relative contribution of planted trees and woody recruits to the various stand variables.

3.4.2. Comparison of woody recruits in plantations with secondary forests
Table 4 compares above-ground carbon stocks, basal areas, timber volumes, and values of woody recruits within plantations with secondary forests (which are all recruits).

A comparison between woody recruits within plantations and secondary forests using the independent student *t*-test showed no significant differences in AGC stocks, basal area, timber volume, and value. These results suggest that contrary to the expected trade-off between planted trees and recruits within the plantations, their
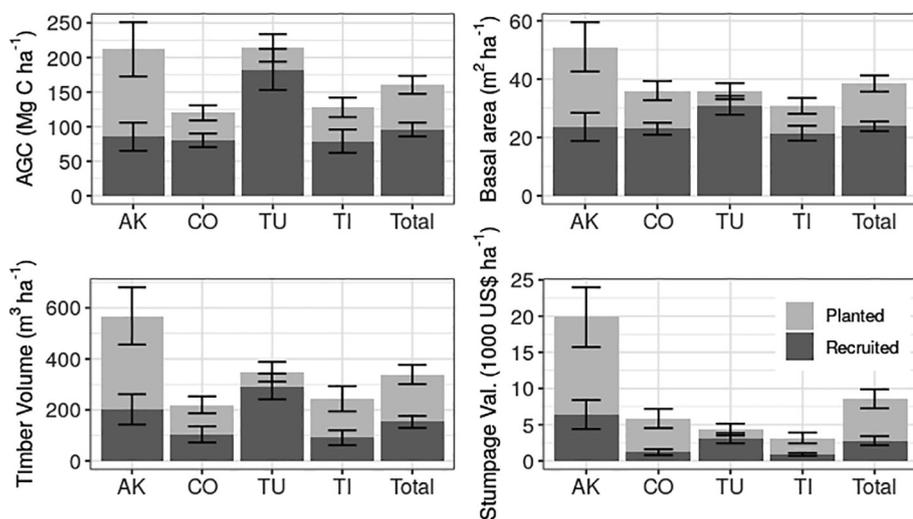

Fig. 2. Distribution and levels of above-ground carbon stocks (AGC) between the two forest zones for the three forest types.

Fig. 3. Relative contribution of planted and naturally regenerated trees (woody recruits) to mean stand total AGC, basal areas, timber volumes, and timber values for the four timber species plantations in the study (Species code: AK – *Aucoumea klaineana*; CO – *Cedrela odorata*; TI – *Terminalia ivorensis*; TU – *Tarrietia utilis*; 'Total' represents the overall mean across the four plantations [AK, CO, TI, TU], Error bars represent 1 SE).

Table 4

Summary of independent *t*-test and means comparing above-ground carbon stocks, basal areas, timber volumes, and values of woody recruits within plantation and secondary forest sites.

	Forest Type		T-value	P-value
	Plantations	Secondary		
Above-ground carbon stocks of woody recruits (Mg ha^{-1})				
Mean	95.9	103.6	0.398	0.692
Std. error of mean	10	12.3		
Basal area of woody recruits (m^2 ha^{-1})				
Mean	23.84	24.86	0.312	0.756
Std. error of mean	1.69	1.98		
Timber volume of woody recruits (m^3 ha^{-1})				
Mean	153.2	168.46	0.323	0.747
Std. error of mean	23.27	38.23		
Timber value of woody recruits (US$ ha^{-1})				
Mean	2780.32	1900.33	0.742	0.460
Std. error of mean	629.5	543.59		

performance relating to the four dependent variables in the study was comparable to that of the naturally regenerating secondary forests.

4. Discussion

Our study presents a unique dataset from old unmanaged timber plantations abandoned 3–4 years after establishment due to unforeseen socio-economic and management challenges, rather than by design. These plantations aptly fit into Lugo's (1997) concept of "self-design", a strategy to balance human intervention with ecosystem self-design. Where for example; an unmanaged plantation is allowed to change through the natural invasion of its understorey by trees and other plant species. The timber plantations in this study are therefore not representative of the majority of commercial timber plantations in the country and possibly within the tropics, which are usually intensively or semi-intensively managed for the production of industrial timber in usually 15–25-year rotations; or the fast-grown Eucalypts, Acacias, and Pines that are grown in much shorter rotations (usually 5–10 years), mainly for the production of pulp and wood chips. However, we expect that old reforestation sites, which have persisted without human intervention for close to 40 years and have successfully facilitated colonization of their understories by a mix of native plant species, some of which currently occupy mid and upper canopy positions, could serve as models. They hold a treasure trove of information, which may be gleaned to provide valuable lessons for guiding the design and

implementation of future reforestation efforts in the tropics. Projects that may likely benefit from this knowledge include restorative plantings, watershed restoration, carbon offsets, or long-rotation forest plantations with both commercial and conservation goals. Our comparative study therefore assessed the climate change mitigation potential of these unique forest plantations, naturally regenerated secondary forests of similar ages and distance from remnant forests patches, and nearby primary forests. Additionally, the timber volumes and values of the three forest types were also assessed.

4.1. Above-ground carbon stocks

As predicted, AGC levels were significantly higher in plantations compared to secondary forests and higher in primary forests compared to secondary forests. However, contrary to our expectation, the values for primary forests were not significantly different from those of the plantations. Few quantitative tropical studies have been published concerning AGB in paired old plantations and secondary forests (e.g. Han et al., 2010; Otuoma et al., 2016) and some sub-tropical studies (Jordan & Farnworth, 1982; Lugo, 1992), albeit with mixed results. In contrast to our findings, certain earlier studies in Puerto Rico (Aide et al., 2001; Marín-Spiotta et al., 2007) found higher or similar AGB levels in 80-year-old secondary forests compared to primary forests, with the latter study attributing their findings to the gradual replacement of woody tree species in the primary forests with palms, which have much lower biomass accumulation ability. Similar observations were made by Letcher & Chazdon (2009) in Costa Rica, where secondary forests attained similar AGB as old-growth forests 30 years after abandonment. Contrary to our findings, in a meta-analysis of natural regeneration and active restoration in the tropics, Crouzeilles et al. (2017) reported higher biomass accumulation in natural regeneration sites compared to actively restored sites after controlling for four biotic and abiotic factors. Previous early tropical successional studies, however, show higher standing AGB in forest plantations compared to secondary forests (Sang et al., 2013; Bonner et al., 2013; Holl & Zahawi, 2014). Recent non-empirical studies assessing the climate change mitigation potential of various reforestation methods have produced mixed results. While Bastin et al. (2019) contend that extensive tree planting in large areas of the tropics provides one of the most cost-efficient ways to mitigate climate change; Lewis et al. (2019a), on the other hand, argue that natural forest regeneration is the most effective forest landscape restoration strategy to mitigate climate change and that natural regeneration is 40 times more effective at storing carbon compared to forest plantations . The study by Bastin et al. (2019) has since come under a barrage of criticism by several scientists based on

perceived technical and ecological flaws (e.g. Friedlingstein et al., 2019; Lewis et al., 2019b; Veldman et al., 2019). The Lewis et al. (2019a) study also contains certain inherent weaknesses in the model that render their conclusions as quite controversial, especially the underlying assumption of their analysis that forest plantations will be harvested within a maximum of 10 years and that most of the wood will be used for short-life products, such as paper and woodchips, thus releasing the carbon stored soon after harvest. However, they conceded that if forest plantations are managed on longer rotations and the timber harvested converted into long-life products, then their contribution to climate mitigation may be higher than estimated in their study. In addition, their assessment of forest plantations included agricultural tree crop plantations, such as cocoa, coconut, apple, and cashew, which have much lower carbon-sequestering ability compared to forest trees. In contrast, our study analyses long-rotation high-value timber plantations, which, if harvested, will likely mainly be converted into long-life harvested wood products such as furniture, construction lumber, flooring, etc. Long-life harvested wood products consequently increase the volume of carbon sequestered in these products and positively impact the estimation of carbon balances in forest systems, and therefore play an important role in climate mitigation (Ji et al., 2016; Brunet-Navarro et al. 2017; Parobek et al., 2019). In this study, AGC within the timber plantation stands was contributed to by both planted trees and woody recruits that were well represented both in the under- and overstorey. The relatively higher AGC accumulation in timber plantations compared to naturally regenerated secondary forests may likely be attributed to e.g. the purposeful selection of fast-growing exotic and native timber tree species, which are mainly long-lived pioneers. Furthermore, another factor may have been the active establishment in monocultures at relatively wide spacing (5 m × 5 m), which supported stem radial and apical growth, thus enabling the seedlings to circumvent initial biotic and abiotic hurdles to establishment, likely to be encountered by the naturally regenerating secondary forest stands. Additionally, the four selected tree species (*Cedrela odorata, Aucoumea klaineana, Terminalia ivorensis, Tarrietia utilis*) appeared to have facilitated the colonization of their stands by ameliorating and causing spatial and temporal variability in site conditions through early canopy formation and shading out of competing light-demanding grasses and shrubs, thus serving as nurse crops for colonizing woody recruits (Parrotta, 1992; Ashton et al., 1997; Keenan et al., 1997; Lugo, 1997; Parrotta et al., 1997; Chapman & Chapman, 1999; Otsamo, 2000; Zanne & Chapman, 2001; Janzen, 2002; Butler et al., 2008; Farwig et al., 2009; Viani et al., 2010; Griscom and Ashton, 2011; Baatuwie et al., 2011; Omeja et al., 2011; Appiah, 2012; Ashton et al., 2014; Pryde et al., 2015; Viani et al., 2015a,b; Brancalion & van Melis, 2017; Brancalion et al., 2019), which contributed to overall stand AGC. Trees that provide medium shade or have dispersed crowns with rapidly decomposing leaf litter generally tend to create understorey micro-conditions suitable for germination and establishment of woody recruits, and thus serve as good nurse trees (Otsamo, 2000). Such trees should be considered during species selection for reforestation interventions. The four timber plantation species in this study closely fit the description.

4.2. Basal area

Both the timber plantation and the secondary forest stands have tree basal areas similar to those of the primary forests. Our results demonstrate that basal area was restored to primary forest levels within the timber plantations and secondary forests 42 years after establishment. These findings are consistent with earlier tropical forest restoration studies (Aide et al., 2001; Liebsch et al., 2008; Letcher & Chazdon, 2009). However, basal area of the timber plantations was significantly higher than that of the secondary forests (Lugo 1992; Garcia et al., 2016). Some previous early successional studies in the tropics have also observed greater tree basal areas in planted compared to secondary

forests (Butterfield & Mariano, 1995; Bonner et al., 2013; Holl & Zahawi, 2014; Gilman et al., 2016). Contrary to our findings, Otuoma et al. (2016) reported that after 70 years of growth, mixed-species forest plantations and secondary forests had significantly lower basal areas compared to disturbed primary forests in western Kenya. They also found the basal areas of the mixed-species plantations to be slightly higher than those of secondary forests of comparable age, though not statistically different. We found mean basal area of the plantations in our study (37.8 ± 2.7 m^2 ha^{-1}) to be comparable to those of the 70-year-old mixed-species plantations in the previously mentioned Kenyan study (39.0 ± 3.2 m^2 ha^{-1}).

4.3. Timber volume and value

Timber plantations are established and managed primarily to optimize timber volumes and value. However, the monoculture plantations of the four studied timber species (*Aucoumea klaineana, Cedrela odorata, Tarrietia utilis, Terminalia ivorensis*), were left unmanaged (i.e. no removal of understorey competition, thinning, pruning, etc.) three or four years after planting. Estimated timber volume did not differ significantly between the primary forest and the secondary forests and timber plantations. However, timber volume was significantly higher in the timber plantations compared to the secondary forests (table 2). It is interesting to note that whereas the primary forest had higher AGC levels compared to the timber plantations, though not significantly different, the plantations accrued higher timber volume. This is likely a result of the primary forest 'spreading' stand AGB across more smaller-diameter trees (note that timber trees were defined as those with dbh ≥ 30 cm) compared to the forest plantation.

Mean timber stumpage value per hectare was significantly higher in the timber plantation ($8555 ha^{-1}) compared to the primary forest ($3112 ha^{-1}) and secondary forest ($1870 ha^{-1}). The timber stumpage values used in the analysis are those paid by logging companies to the Forestry Commission for harvested natural forest timber trees on state-managed lands, and are usually 40–50% lower than what is charged by private landowners for planted timber trees. The purposeful planting of high-value timber tree species, which constituted the majority (55%) of timber volume within the timber plantation stands, mainly accounted for the significantly higher timber value compared to the primary and secondary forests. At a discount rate of 2% per annum over the 40-year period, and establishment and maintenance costs for the planted forest and secondary forests estimated at $2300 ha^{-1} and $0 ha^{-1} over the first three years, respectively (Zahawi and Holl, 2009; Brown and Kollert, 2017), the net present value (NPV) is $1641 ha^{-1} and $863 ha^{-1} for timber plantations and secondary forests respectively. However, at higher discount rates (≥3%) the secondary forest yields a higher NPV. The highest standing timber value of $51 499 ha^{-1} was recorded within plot 1 in the A. klaineana stand (W-AK1), where the ten timber trees valued within the 20 m × 20 m plot (i.e. 250 stems ha^{-1}) were all A. klaineana. This gives an indication of the potential value that could accrue from a 40-year-old well-managed, widely-spaced A. klaineana plantation. In the case of the secondary forest, the best standing timber value of $7740 ha^{-1} was realized in M-SF2. Using a 2% discount rate and the same establishment cost for planted and secondary forests, the NPV is $21955 ha^{-1} and $3575 ha^{-1} for timber plantation and secondary forests, respectively. Increasing the discount rate to 5% per annum while maintaining other costs as in the earlier scenario, NPV decreases to $5787 and $1154 for planted and secondary forest, respectively. However, here too the secondary forest gives a higher NPV at much higher discount rates (≥9%) provided secondary forest costs are maintained at $0. Other studies, however, have assigned varying costs for passive reforestation, such as monitoring and protection from fire and cattle, during the early years of establishment (Janzen, 2002; Birch et al., 2010; Zahawi et al., 2014). These NPV figures compare favourably with findings from economic studies on forest landscape restoration conducted under Initiative 20x20, a

country-led effort to bring 20 million hectares of land in Latin America and the Caribbean under restoration efforts by 2020 (Vergara et al., 2016). These results demonstrate that timber plantations established with initial wide spacing (e.g. 5 m × 5 m) to provide a conducive microclimate for the regeneration of native woody recruits both in the under- and overstorey, may additionally provide good financial returns. The outcome of the financial analysis makes a good business case for long-term passive restoration, especially in areas that would not require any financial investments for monitoring and protection during early stand establishment, such as moist and wet forest areas where wildfires may be rare and locations far from human settlements. It further re-inforces the need for the provision of long-term financing at concessionary rates for reforestation projects to make them attractive as financially viable land-use options for landowners (Brancalion et al., 2012b); the viability of which will be significantly improved when payments for forest ecosystem services (i.e. carbon sequestration, watershed protection, biodiversity conservation, etc.) are included.

4.4. Woody recruits

Observing that woody recruits contributed 45% of the timber volume and 32% of the value within the plantations was surprising. Contrary to our expectations, this study did not find a significant difference between woody recruits within the plantations and secondary forest values for AGC, basal area, timber volume, and value. Forest plantations are well documented to provide shelter and facilitate the recruitment of a diverse understorey. However, we were surprised to find that in the long run, planted trees did not outcompete the native recruits. Our data do not indicate a trade-off between planted and re-cruited trees, as no correlation between the AGC of planted and re-cruited trees seems to occur. Similar observations have been reported, albeit at a young plantation age (Gilman et al., 2016), and in one case a positive correlation was observed between AGC stock accumulation and woody species regeneration (Brancalion et al., 2019), a win–win case for climate mitigation and local biodiversity conservation. We can infer from our findings that close proximity of the reforestation sites to remnant forest patches and a low-intensity management regime of the plantations that excluded active removal of understorey competition, pruning, thinning, and other silvicultural interventions after three years of growth supported the significantly high contribution of woody recruits to stand biomass and carbon stocks.

The relatively higher contribution of woody recruits to AGC (60%) and basal area (62%), and the relatively higher contribution of planted trees to standing timber volume (55%) and value (68%) indicate that a majority of such timber trees could be harvested for financial return in such long-rotation timber plantations. This can be done using reduced-impact logging practices while leaving a fairly stocked heterogenous residual stand predominantly composed of native tree species. The removal of the mature planted trees is expected to open canopy gaps that may facilitate the establishment of new woody recruits while releasing suppressed wildlings (Duncan & Chapman, 2003; Kansenene, 2007), especially shade bearers. However, Otsamo (2000) questioned the effectiveness of this method in protecting understorey woody recruits during timber harvesting. Duncan & Chapman (2003) on the other hand found no adverse effect on residual stems after logging in low-density forest plantations.

Therefore, where there is an objective to gain commercially from future timber harvesting while having long-term conservation goals, then high-value timber tree species may be established in plantations at wide initial spacing or low stocking (400–625 trees/ha) under low-intensity management regimes. Lower stocking has been reported to increase drought resistance and resilience within forest stands (D' Amato et al., 2013), thus making them more resilient to climate change impacts.

4.5. Forest zone

As expected, AGC was higher in the wet zone compared to the moist zone for each of the three forest types (Poorter, et al., 2016). However, these differences were not statistically significant. On an individual-species level, *A. klaineana* and *T. ivorensis* stands accumulated higher AGB levels in the wet zone. However, in the case of *C. odorata*, AGB was higher in the moist zone, possibly indicating a preference for the more mesic conditions of the moist zone.

4.6. Study limitations

This study is limited by the lack of additional old plantation and secondary forest sites of similar ages, to allow a more rigorous replication. However, the robust statistical package employed in the analyses minimizes confounds and maximizes statistical independence of the data points (Schank & Koehnle, 2009; Freeberg & Lucas, 2009). The scope of the study was further limited by a lack of discussion concerning other ecosystem services that are potentially impacted by the different forest types, especially biodiversity. The lack of destructively sampled data for derivation of biomass and carbon values was substituted using mainly a widely used pantropic allometric equation (Chave et al., 2014), where total tree height, DBH, and wood densities of trees are known, and a locally derived allometric equation (Henry et al., 2010) is used for tree species whose wood densities are unknown. Notwithstanding these limitations, the study of such old, relatively successful reforestation sites, which are rare in the West African tropics, provides a clearer picture of the 'end game'. Additionally, such empirical tropical studies provide useful data to guide the development of more accurate and realistic algorithms for global estimates of carbon uptake potential under various reforestation options.

5. Conclusions

Our study has demonstrated that reforestation by planting trees led to higher biomass accumulation, carbon sequestration, and timber value in both the moist and wet zones compared to natural regeneration. Thus, we suggest that forest plantations managed on long rotations have higher climate mitigation potential compared to naturally regenerating secondary forests of similar ages. The higher biomass accumulation and carbon stocks were contributed by both planted trees and colonizing woody recruits, contrasting our third hypothesis that suggests a trade-off between the growth of planted trees and colonization of the understories of forest plantations by native recruits. Although Lewis et al. (2019a) criticized forest plantations as an inefficient option for climate change mitigation, our study suggests that long-rotation forest plantations developed on deforested or degraded lands under low-intensity management regimes, using long-lived forest tree species, are efficient for carbon sequestration and storage. In addition, as long-rotation forest plantations may have reasonably high timber values they offer multiple potential pathways combining carbon sequestration with timber production, thus making them an attractive land-use option for landowners. Under scenarios where selective logging is not desired, such tropical forest plantations may provide a "fast track" for attaining carbon stocks similar to primary forests. We need further ecological and economic analysis to understand how long-rotation forest plantations may contribute to the reforestation of deforested and degraded tropical landscapes, their impact on biodiversity, and the contribution of sequestered carbon in harvested wood products to carbon balance estimates. Future research should consider other ecosystem services provided by reforestation projects and the potential impact of payment for ecosystem services on such 'green' investments.

CRediT authorship contribution statement

Hugh C.A. Brown: Conceptualization, Methodology, Investigation,

Supervision, Formal analysis, Writing - original draft, Writing - review & editing, Funding acquisition. **Frank A. Berninger:** Conceptualization, Methodology, Writing - review & editing. **Markku Larjavaara:** Writing - review & editing. **Mark Appiah:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118236.

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