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Carbon accumulation in soil layers under degraded, intact and planted forest cover types in tropical semi-deciduous and moist evergreen forests

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Abstract

Tropical forest soils can contribute significantly to mitigating climate change by sequestering and storing carbon in their layers. However, in West Africa, knowledge of how much carbon is stored in deeper soil layers of various forest cover types and protected from further release into the atmosphere remains scanty. We quantified the carbon (C) and nitrogen (N) contents of tropical soils in Ghana at 0–20 cm and 20–50 cm, by comparing a degraded forest and an intact forest in the semi-deciduous forest zone, and intact forest, degraded forest, and agroforestry plantations in the moist evergreen forest zone. In semi-deciduous forests, C concentration was significantly higher for intact forest than degraded forest, but total C content of soils from the intact forest was not greater than the degraded forest due to compensating differences in bulk density. C content differed by depth for the two forests, with values at 0–20 cm of 48.1 vs 38.4 Mg ha^{-1} and at 20–50 cm of 20.6 vs 26.5 Mg ha^{-1}, for degraded and intact forests respectively. In moist evergreen forests, soil C concentrations were similar between intact forest, degraded forest and plantations, yet, differed between the depths. Among the three, soils under plantations had the highest C content due to higher bulk density. For N, differences among cover types and soil depths followed similar patterns as those for C. Our results suggest the potential for formerly disturbed or degraded forests to gain more C lies primarily in live forest biomass, not in soil, especially if forests have maintained vegetative cover of some type since disturbance. The potentially large capacity for deeper soil layers to store C, and their reduced susceptibility to forest disturbance makes them an important soil carbon pool to further quantify and preserve.

Keywords C content · Soil depth · Degraded forest · Intact forest · Plantation · Semi-deciduous forest · Moist evergreen forest

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Introduction

Tropical forests greatly contribute to the global C cycle as they contain about half of the world's biomass C as well as 14% of the world's soil C (IPCC 2000). Forty percent of the terrestrial biosphere's C is estimated to exist in tropical forests, and 41% of this is reported to be stored in soils (Sampson et al. 1993; Watson et al. 2000; Lewis et al. 2009). Restoration of degraded tropical forests soils therefore may potentially contribute to climate change mitigation through sequestration and C storage in upper and deeper soil layers. In assessing C storage impacts of land-use change and ecosystem succession, soils have become a point of interest due to their potential ability to sequester large amounts of C (Post et al. 1982; DeGryze et al. 2004). However, in tropical forests, C assessments have focused primarily on living biomass with little emphasis on soil C storage (Chiti et al. 2010). Assessment of tree biomass C is assumed to be of equal or greater importance than litter layer and soil compartments, as it can accumulate large amounts of C (Cairns et al. 1996; Bauhus et al. 2002; Balboa-Murias et al. 2006).

The amount of C stored in soils depends mainly on surface vegetation and land use type (Arrouays et al. 2001). Powers (1989) indicated that forest productivity is directly linked to soil organic matter content, and therefore soil C may increase or decrease depending on the potential site productivity. Powers et al. (2012) and Law et al. (2004) explained that undisturbed forests with high productivity will generally have greater total ecosystem C stocks of living biomass, forest floor material (organic soil horizons), and mineral soil C. While undisturbed forests or forests with little disturbance may appear to have greater potential to store C in their soils, soils of disturbed forests are seen to transform from C sinks to C sources (Van der Werf et al. 2009; van Straaten et al. 2015). However, the problem of disturbed forest sites becoming atmospheric C sources could be countered through afforestation of previously degraded sites and resultant long-term accumulation of C in both plant biomass and soil (Laganiere et al. 2010).

Due to land-use change, secondary forests have been increasing throughout the tropics for decades (Brown and Lugo 1990) with Ghana being no exception. Over the years, Ghana has lost most of its primary forests in the high forest zone as results of intensive anthropogenic activities including timber harvesting and slash-and-burn agriculture (Opoku et al. 2005; FAO 2010), leaving only several remnant forest patches and large amounts of degraded forest lands. Afforestation or plantation development is now being adopted to rehabilitate degraded forest, with the aims of providing timber and other wood products, improving rural livelihoods and economic development, as well as contributing to climate change mitigation by sequestering C in biomass and soils (Appiah 2003; Zhang and Owiredu 2007; Foli et al. 2009). In Ghana, while the capacity of forest biomass to sequester C may be known (Adu-Bredu et al. 2010; Opuni-Frimpong et al. 2013; Yeboah et al. 2014), the potential of soils in afforestation projects and degraded forest lands to sequester C is not well understood.

Davidson et al. (2000) highlighted the need to study soil C dynamics to understand the C balance in forests and their response to future global change. Thus, the assessment of soil C storage capacity under different forest cover types and the quantities of C stored in deeper layers need to be factored into decision making on forest management and conservation, including efforts for climate change adaptation and mitigation. Both single and mixed species afforestation have great potential to contribute to C sequestration (Siry et al. 2005; Hodgman and Munger 2009). However, the amount of C these plantations sequester into their soils remain poorly understood, and their potential to increase soil C has been questioned (Sartori et al. 2007; Don et al. 2011; Neumann-Cosel et al. 2011; Brahma et al. 2018). Harper et al. (2012) emphasized this, by reporting similar soil C content under planted tree stands and adjacent farmland soils. Upper layers of soils are reported to hold about 60% of soil C, hence they have gained much attention for assessment (Albaladejo et al. 2013). On the other hand, the studies of C content in deeper soil are on the periphery (Szopka et al. 2016), despite their capacity to sequester additional C (Wan et al. 2019).

In this study, we try to unearth the potential capacity of soils under different forest cover types to sequester C by quantifying the C content of tropical soils of Ghana from two depths (0–20 cm and 20–50 cm) in two forest zones (semi-deciduous and moist evergreen). Specifically, we tested if: (1) soils under intact forests, plantations and degraded forests had similar carbon contents; and (2) deeper layers accumulated as much carbon as surface layers under different forest cover types. We also assessed soil N content to determine if past disturbance caused reductions in the site capital of this essential plant nutrient.

Methods

Site descriptions

The study was conducted in three forest reserve areas in different forest zones in Ghana (Fig. 1). The forest reserves included Pamu-Berekum forest reserve in the dry

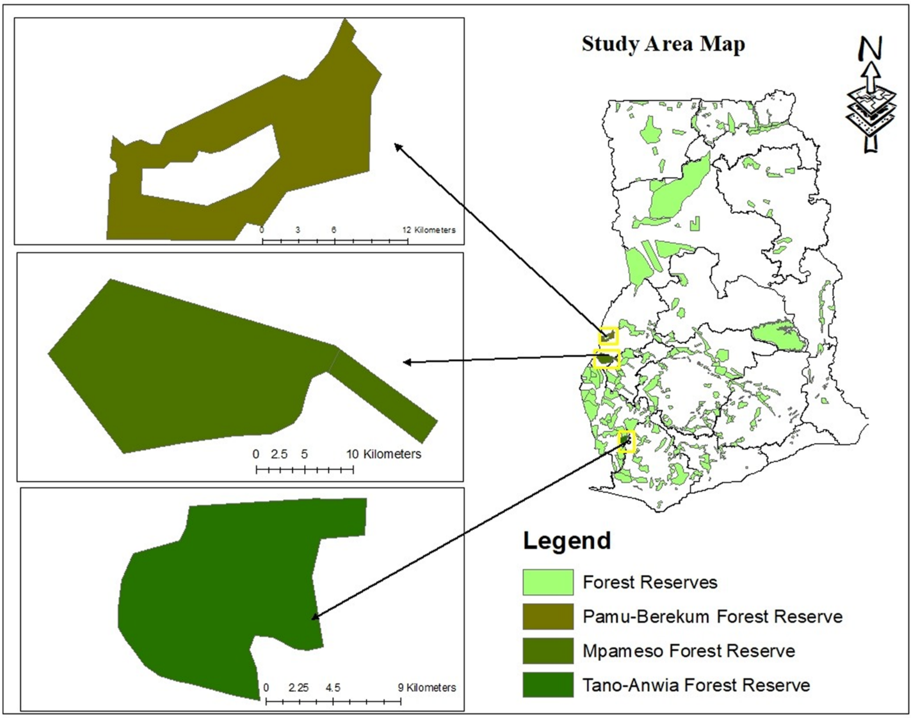

Fig. 1 Study site locations: Pamu-Berekum forest reserve, Mpameso forest reserve, Tano-Anwia forest reserve

semi-deciduous zone, but also extending into moist semi-deciduous zone, and Mpameso forest reserve in the moist semi-deciduous zone. The two zones have the most plant diversity of economic importance and were originally described as highly stocked closed canopy forests (Blay et al. 2009). The third is the Tano-Anwia forest reserve found in the moist evergreen forest zone, which once occupied about 8.2% of the total forest area of Ghana (Wagner et al. 2008).

The *Pamu-Berekum* forest reserve (7°25′ N latitude and 3° 56′ W longitude) covers an area of 189 km^2 (Hawthorne and Abu-Juam 1995). It receives rainfall between 1100 and 1200 mm per annum and is highly vulnerable to fires owing to prolonged dry seasons (Derkyi 2012). Dry seasons typically last from November to March with mean monthly rainfall of ~ 44 mm and mean daily temperature of over 27 °C. Generally, soils are classified as oxysols and ochrosols (Hall and Swaine 1981). The occurrence of catastrophic wildfires in the 1980s (Swaine 1992) and subsequent anthropogenic disturbances rendered the forest reserve highly degraded with only a few intact forests in riparian areas. Current vegetation is mostly grass and shrubs, with patches of *Tectona grandis* (teak) plantations and several areas under agricultural activities.

Mpameso (7°5′ N latitude and 3°53′ W longitude) occupies an area of 323 km^2 (Hawthorne and Abu-Juam 1995) with a mean annual rainfall of 1200–1500 mm and exhibits the deciduous habit during the dry period. The length of dry season and its characteristics are similar to those of Pamu-Berekum forest reserve. *Celtis mildbraedii, Entandrophragma utile, Khaya anthotheca, Khaya ivorensis, Nesogordonia papaverifera, Pericopsis elata, Terminalia ivorensis, and Triplochiton scleroxylon* are among commercial timber species that characterize the area. Soils belong to the forest ochrosol great soil group (Martin 1982). This reserve has also experienced frequent fires and disturbances from other anthropogenic activities, yet has over 30% remaining in intact forest cover (IUCN 2014).

Tano-Anwia forest reserve (6°50′ N latitude and 2°35′ W longitude) has an area of 253 km^2 and receives rainfall between 1500 and 1700 mm per annum. The forest and its surroundings experience short dry periods from December to February with average monthly rainfall of ~ 50 mm and fairly constant temperature of around 27 °C throughout the year. Though the reserve is affected by logging and other disturbances, it is considered to be in good condition due to untouched compartments that are not easily accessible (BirdLife International 2020). Tree species of interest in the area include *Percopsis elata*, *Triplochiton scleroxylon* and *Aningeria* spp. Its surroundings in off-reserve areas have seen forest cover drastically reduced to shrubs, grass and/or woodlands with few scattered timber tree species due to human population increase, excessive logging and agricultural farm expansion. A portion of formerly degraded lands in the off-reserve areas have been restored through afforestation projects, including the Oda-Kotomso community afforestation project (OCAP) established in the late 1990s.

Sample collection

The sites were generally categorized into two main forest zones: semi-deciduous forest (SD) and moist evergreen forest (ME). This was done to enable comparison of forest cover types (degraded, intact, plantations) in reserves with relatively similar climatic conditions and composition. As such, the Pamu-Berekum and Mpameso forest reserves were placed under the SD forest, while Tano-Anwia forest reserve and its surroundings were placed under ME. Soils for SD were then sampled from Pamu-Berekum forest reserve (degraded forest, Fig. 2a) and Mpameso forest reserve (intact forest). In ME, samples included an

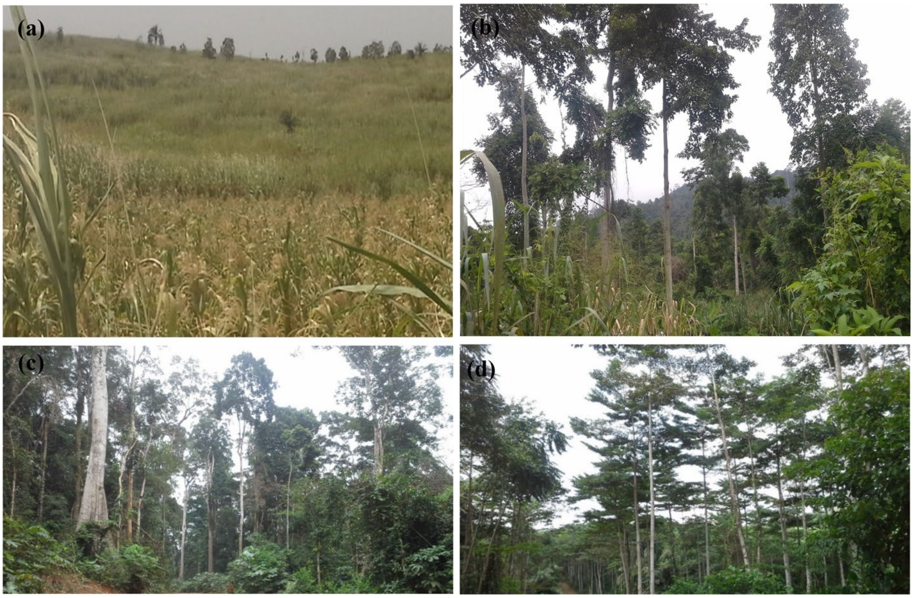

Fig. 2 Photos of degraded forest in the semi-deciduous forest zone (**a**), and degraded forest (**b**), intact forest (**c**) and single species plantation (**d**) in the moist evergreen forest zone

on-reserve Tano-Anwia forest (intact forest, Fig. 2c), an off-reserve Tano-Anwia forest (degraded forest, Fig. 2b) and agroforestry plantations established in formerly degraded Oda-Kotomso community lands (OCAP plantations, Fig. 2d). OCAP consisted of mixed or single species stands of about 23 indigenous and exotic species. OCAP plantations used in this study were single species stands of *Cedrela odorata*, *Triplochiton scleroxylon, Ceiba pentandra, and Nauclea diderrichii* with initial average planting density of 1600 trees ha^{-1} for each. Mixed stands had initial average planting density of 1111 trees ha^{-1} and were comprised of mixtures of species including *Aningeria robusta, Antiaris toxicaria, Ceiba pentandra, Entandrophragma angolense, Heritiera utilis, Khaya ivorensis, Mammea africana, Milicia excelsa, Pycnanthus angolensis, Terminalia ivorensis, Terminalia superba and Triplochiton scleroxylon*. No specific tree inventory was conducted but from observations during soil sampling, species that dominated in mixed species stand included *Aningeria robusta*, *Mammea africa*, *Khaya ivorensis*, *Pycnanthus angolensis*, *Entandrophragma anogolense* and *Triplochiton scleroxylon*. At the time of sample collection, trees within OCAP plantation stands were between 7 and 14 years old.

At all sites, soil core samples were collected in June 2013 from two depths in the mineral soils, 0–20 cm and 20–50 cm, using a 1.90 cm inner diameter stainless steel soil sampler. With the exception of OCAP plantations where plots were sited based on plantation type, a 400 m wide diagonal strip of ~ 1 km^2 was laid in each forest type to encompass the variation in soils and landform within, and the strip was subdivided into 5 plots, each approximately 0.2 km^2. Three plots were then randomly selected. Plots were located approximately 300 m inside each forest from a referenced point (either from a road or a path). Selection of sample locations was informed on recommendation from Forest Service personnel responsible for managing the respective reserves. The intact forest sample plots were located in areas that have not been commercially logged in the last 40 years as required by harvesting cycle in natural forests for reentry in Ghana. Within each plot, soil samples were collected at least 100 m apart using a simple random technique. For OCAP plantations, three plots consisting of two pure stands (~ 1 ha for each stand) and a mixed stand (~ 1 ha) were treated as individual sample plots and a simple random technique employed for sampling in each of these plots. Thus, the combination of single and mixed stands represented OCAP plantations with at least ten sample points in each plot. We chose a sample size of at least ten sample points for each treatment as we had difficulty in some sites getting soil below 15 cm depth due to compacted soils, high gravel content of soils and accessibility of sites. A total sum of 191 samples were used in this study (Table 1). Samples collected were tightly sealed in zip lock bags and stored refrigerated (< 2 °C) at the Forestry Research Institute of Ghana (FORIG), until transported to the Soils & Plant Laboratory at Michigan Technological University in Houghton, MI, US, for further processing and analysis.

Laboratory procedures and elemental analysis

Samples were oven dried (65 °C for > 48 h) and weighed. Bulk density of the samples was determined by dividing the dry weight of bulk soil (before sieving) by the volume of soil—volume was obtained by multiplying the cross-sectional area of the sampling probe by the depth of soil increment. Coarse fragments were then sieved (2 mm screen) and samples reweighed to determine fine fraction mass. The fine fraction was ground with a mortar and pestle and finely ground dry samples were analyzed for C and N concentrations (g kg^{-1}) with an elemental analyzer (4010 ECS system, Costech Analytical Technologies, Valencia, California, US). Carbon and nitrogen contents (Mg ha^{-1}) were calculated by multiplying concentrations by fine fraction mass and dividing by the cross-sectional area of the sampling probe.

Statistical analysis

A two-way analysis of variance was used to assess the differences in soil C and N concentrations and contents among the different forest cover types and different soil depths within

Table 1 Number of samples from each location used in analysis

Forest cover types/sampling sites	Number of samples for depth		
	0–20 cm	20–50 cm	Total
Semi-deciduous forest			
Degraded forest	20	21	41
Intact forest	20	20	40
Total	40	41	81
Moist evergreen forest			
Intact forest	10	10	20
Degraded forest	10	10	20
Plantations	34	36	70
Total	44	56	110
Grand total	84	97	191

each of the two forest zones. When an ANOVA resulted in a *p*-value of less than 0.05, comparisons between forest cover types and/or depths were conducted using Tukey's post-hoc test. All statistical analyses were conducted in IMB SPSS Statistics 26.0.

Results

Semi-deciduous forest (SD)

Carbon and N concentrations were significantly greater in the intact forest than degraded forest for both soil depths ($p < 0.05$ for both C and N; Table 4). The effect was much greater for deeper soils, where intact forest had concentrations nearly three times those in degraded forest (Fig. 3a). In surface soils, intact forest concentrations were about 1.4 times those in

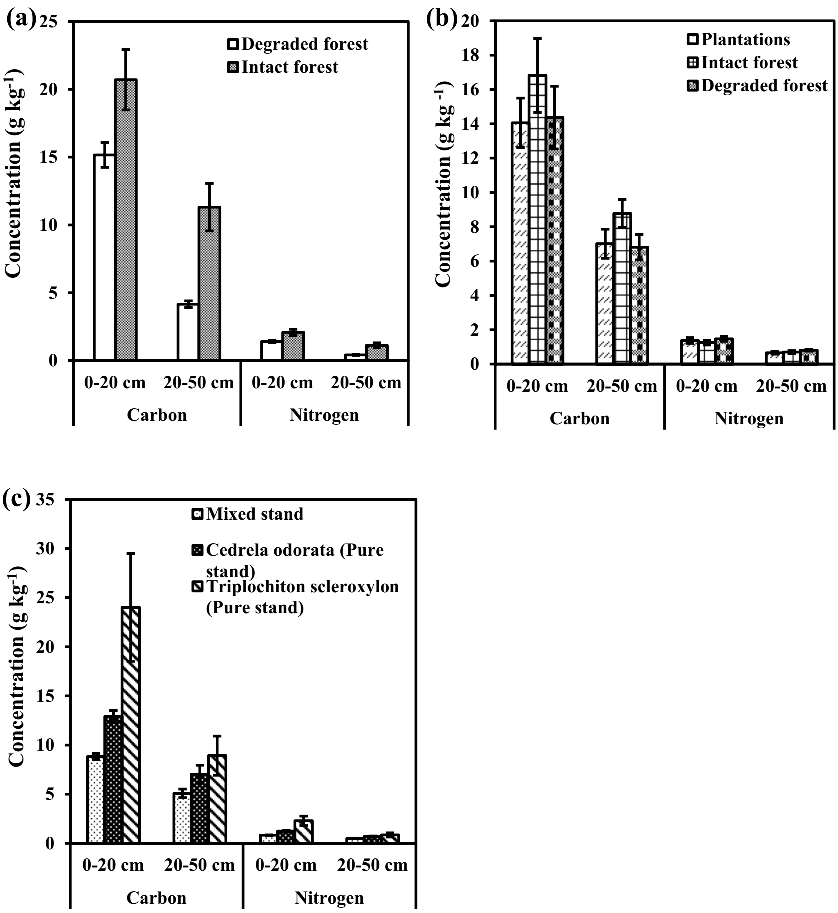

Fig. 3 Soil C and N concentration of intact and degraded forests in the semi-deciduous forest zone (**a**), and intact, degraded and plantation forests (**b**) and single and mixed species stands (**c**) in the moist evergreen forest zone. Values are means ± standard errors

Table 2 Total C and N content of soils to a 50 cm depth under the different forest cover types

Forest cover types	C (Mg ha^{-1})	N (Mg ha^{-1})
Semi-deciduous forest		
Degraded forest	68.6 ± 4.8	6.5 ± 0.4
Intact forest	64.8 ± 6.3	6.5 ± 0.6
Moist evergreen forest		
Intact forest	46.6 ± 6.4	4.3 ± 0.6
Degraded forest	48.2 ± 4.4	4.4 ± 0.4
Plantations	56.7 ± 3.2	5.4 ± 0.3
Mixed species stand	49.4 ± 3.2	4.7 ± 0.3
Cedrela odorata (single species/pure stand)	68.7 ± 9.6	6.7 ± 0.8
Triplochiton scleroxylon (single species/pure stand)	56.7 ± 6.7	5.4 ± 0.6

Values are means ± standard errors

Table 3 Soil bulk density and fine fraction density of the different forest cover types

Forest cover types	Bulk density (g cm^{-3})		Fine fraction density (g cm^{-3})	
	0–20 cm	20–50 cm	0–20 cm	20–50 cm
Semi-deciduous forest				
Degraded forest	1.64 ± 0.05	1.99 ± 0.14	1.61 ± 0.06	1.94 ± 0.14
Intact forest	1.26 ± 0.07	1.36 ± 0.09	1.06 ± 0.08	1.08 ± 0.11
Moist evergreen forest				
Intact forest	1.22 ± 0.10	1.01 ± 0.11	1.07 ± 0.12	0.91 ± 0.10
Degraded forest	0.93 ± 0.09	1.28 ± 0.09	0.86 ± 0.09	0.98 ± 0.09
Plantations	1.44 ± 0.06	1.45 ± 0.08	1.38 ± 0.07	1.39 ± 0.09

Values are means ± standard errors

degraded forest. Despite differences in soil C and N concentrations, soil C and N contents to 50 cm did not differ between the two forests (Table 2), as intact forest had lower bulk density and fine fraction density than degraded forest (Table 3). Nonetheless, differences were observed between the two soil depths ($p < 0.05$, Table 4), where degraded forest had higher C content than intact forest for the 0–20 cm depth (48.1 vs 38.4 Mg ha^{-1}) and lower values than intact forest for the 20–50 cm depth (20.6 vs 26.5 Mg ha^{-1}) (Fig. 4a).

Moist evergreen forest (ME)

In this forest, soil C and N concentrations did not differ among intact forest, degraded forest and plantations ($p > 0.05$ for both C and N), but differences were observed between 0–20 and 20–50 cm depths ($p < 0.05$, Table 4) in all cover types, with concentrations at 0–20 cm approximately twice those at 20–50 cm (Fig. 3b). Furthermore, within the plantations, differences in soil C and N concentrations were observed among single species stands and mixed-species stands ($p < 0.05$) and between soil depths ($p < 0.05$) (Table 4).

Table 4 Summary of analysis of variance (ANOVA) outputs for measured parameters of soils under different forest cover types in semi-deciduous and moist evergreen forest zones

Forest types	C concentration		N concentration		C content		N content	
	F value	*p* value	F value	*p* value	F value	*p* value	F value	*p* value
Semi-deciduous forest								
Forest cover types	18.519	< 0.001	20.707	< 0.001	0.430	0.514	0.000	0.984
Soil depths	47.713	< 0.001	41.769	< 0.001	47.507	< 0.001	44.336	< 0.001
Moist evergreen forest								
Forest cover types	0.753	0.473	0.358	0.700	3.051	0.052	5.057	0.008
Soil depths	20.825	< 0.001	18.861	< 0.001	15.406	< 0.001	11.986	0.001
Plantations								
Forest cover types	10.145	< 0.001	11.402	< 0.001	6.183	0.004	6.158	0.004
Soil depths	17.118	< 0.001	4.3200	< 0.001	11.973	0.001	12.834	0.001

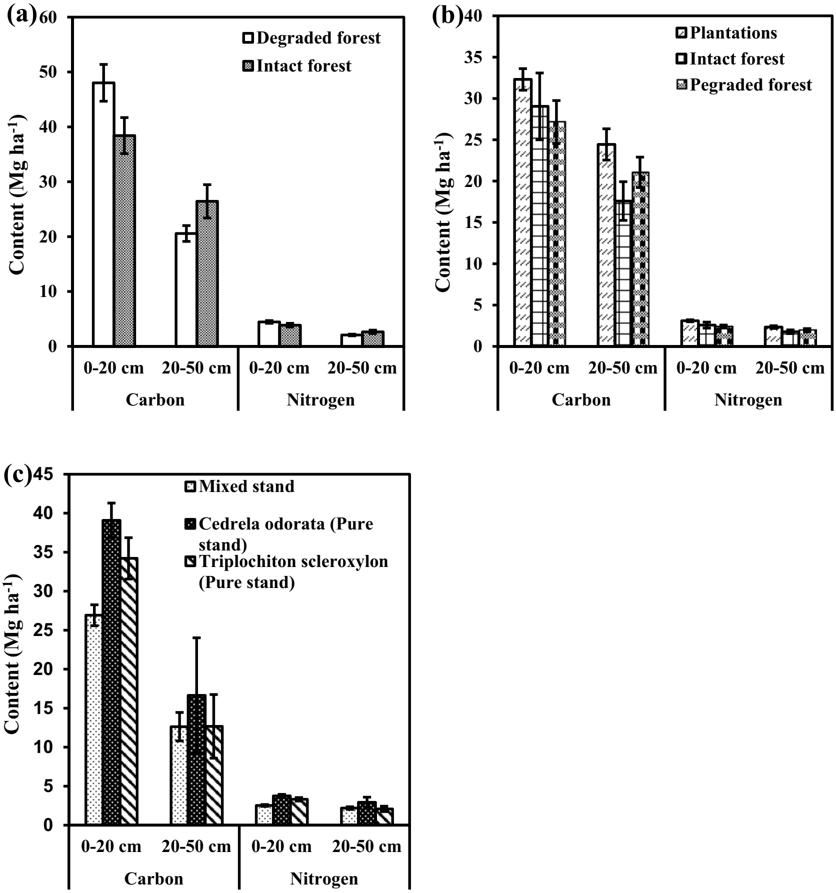

Fig. 4 Soil C and N content of intact and degraded forests in the semi-deciduous forest zone (**a**), and intact, degraded and plantation (**b**) and single versus mixed species stands (**c**) in the moist evergreen forest zone. Values are means ± standard errors

Mixed-species plantations had lower C and N concentrations in both 0–20 cm and 20–50 cm depths than for either of the pure (single species) stands (Fig. 3c).

In terms of C contents, plantations had highest values among the three forest cover types, though the observed significant difference was only marginal ($p = 0.05$, Table 4). Additionally, differences did exist between 0–20 and 20–50 cm depths ($p < 0.05$, Table 4). Total C and N contents to 50 cm were highest for plantations, with values for intact forest and degraded forest being lower and similar to each other (Table 2). Moreover, plantations recorded higher bulk density and fine fraction density than both intact and degraded forests (Table 3). Within the plantations, soil C content did differ among different stands ($p < 0.05$) and also between the two soil depths ($p < 0.05$). The mixed-species plantations had a lower C content than the single species stands in the 0–20 cm depth (Fig. 4c). At 20–50 cm, the highest C content was found in the *Cedrela odorata* pure stand, with lower and similar values for the *Triplochiton scleroxylon* pure stand and mixed species stand (Fig. 4c).

Discussion

Soil C content under semi-deciduous forest cover types

In forest ecosystems, the amount of C stored in soil layers can be greatly influenced by forest cover type, past land use and disturbance. In the present study, soil C varied among the different forest cover types and between soil depths at the semi-deciduous and moist evergreen forest types. Similar findings have been reported by related studies which investigated soil C storage dynamics under different vegetation covers (Pradhan et al. 2012; Ming et al. 2014; Berihu et al. 2017; Kendie et al. 2019). When we compared degraded forest and intact forest in the semi-deciduous forest zone, the soil C concentration was higher for intact forest than degraded forest in both soil depths. Despite lower C concentration, degraded forest accumulated as much C in its soils as intact forest. This was due to higher bulk density and fine fraction density for degraded forest, which compensated for the lower C and N concentrations. The similarity in C contents for intact forest and degraded forest does not corroborate reports by Pradhan et al. (2012), Nang (2016) and Brahma et al. (2018), who found natural forested soils hold higher amounts of C than those of degraded lands. The maintenance of total soil C storage for degraded forest in this study could be attributed to the C accumulation near soil surface which offset the reduced C amount in lower depths. We suspect that the continual presence of grasses and shrubs for the three decades since the forest cover was lost to severe fire in the 1980s promoted the accumulation of much C in their upper soil layers, due to shallow root systems and retention of litter near the soil surface. The greater bulk density and lower C and N concentrations in the surface soil of the degraded forest are consistent with the soil having lower organic matter concentration (Ping et al. 2013) and being somewhat compacted, which could lead to difficulties for regeneration of some species.

Though intact forest accumulated less C in the upper layer (0–20 cm), it accrued more in lower depths (20–50 cm), which might not be surprising. The very high amount of C accumulated in the lower depth of intact forest could be an indication of organic C from root decomposition. Root turnover has been suggested to control the movement of organic matter into the soil and as such plays critical role in allocation of C to the soil profile (Jobbágy and Jackson 2000; Setälä et al. 2016). In spite of a lower amount of soil C stored in lower depths by degraded forest compared to intact forest, the quantity is still fairly large.

Prior to forest degradation, degraded forest was occupied by large trees whose dead roots could have contributed to deeper soil layers, where it may have been protected from fast release into the atmosphere.

Recently, it has been suggested that accurate comparisons of soil C and nutrient contents in response to land management or global change should be performed using equivalent soil mass rather than fixed soil depths (Wendt and Hauser 2013; FAO 2019; IPCC 2019; Smith et al. 2020; von Haden et al. 2020). Due to much lower soil bulk density and fine fraction density for intact forest, the mass of soil sampled to 50 cm was only 71% of that for degraded forest, and the fine fraction mass was only 58% of that for degraded forest. This suggests the intact forest would have a greater soil C content for equivalent soil mass, but the exact degree of the difference cannot be determined without data from even deeper soil depths for intact forest.

That said, the total soil C contents we have measured to 50 cm (65–69 Mg C ha^{-1}) suggest that the far greater opportunity to sequester C in degraded forest land resides in the re-establishment of tree biomass. Overstory biomass in intact SD forests can be as high as 152–596 Mg ha^{-1} (Brown and Lugo 1984; Gautam and Pietsch 2012; Brown et al. 2020), which is far greater than the < 40 Mg ha^{-1} (Hofstede et al. 1995; Gibbon et al. 2010; Oliveras et al. 2014) estimated to exist in the nearly treeless degraded forest areas (Fig. 2a). This is not to say that soil C storage is far less than overstory C. In fact, Chiti et al. (2010) report similar C stocks in overstory biomass and soil to 1 m for a mixed deciduous rainforest in Ghana. Rather, for the types of disturbance experienced by degraded sites in this study, the amount of soil C lost was either small or was gradually replenished over the past three decades, in contrast to the near complete loss of aboveground biomass C. In areas that have suffered more severe degradation, such as conversion to agriculture followed by years of cultivation, greater loss of soil C (Guo and Gifford 2002; Murty et al. 2002; Wei et al. 2014) would create opportunities for soil C gain in restoration that do not exist at our degraded forest location.

Soil C content under moist evergreen forest cover types

To further elucidate the C storage capacities of soils under natural stands and plantations, this study also compared intact forest, degraded forest, and plantation forest in the ME zone. Soil C concentrations were similar for all, but differences occurred between the two soil depths sampled. The similar C concentrations could mean all three forest cover types received similar mass C inputs, for example litter fall. Likewise, the estimation of C content values did not differ among the intact and degraded cover types, though plantations recorded the highest C content in both soil depths. Intact forest had the second highest C content value at 0–20 cm but the least at 20–50 cm.

The lack of significant differences between intact and degraded forest and the rather high C content of soil under plantations contradict the suggestions of consistently higher soil C in natural forest stands than plantations (Bewket and Stroosnijder 2003; Adu-Bredu et al. 2010; Bessah et al. 2016; Brahma et al. 2018). A report from Nti (2012) indicated an average tree volume of 4.6 to 29.2 m^3 ha^{-1} for OCAP plantations at about age 9. At this stage, OCAP trees in combination with dense undergrowth (Fig. 2d) might have provided sufficient above and belowground litter inputs to maintain a soil C content generally similar to natural forests. Prior to plantation establishment, the forest cover had not experienced a total clear-cut, but rather was reduced to shrubs, grass and/or woodlands with a few scattered timber tree species. No tillage occurred. As such, we believe as long as former forest lands retain natural vegetative cover, even if it is grass and shrubs, they do not experience large declines in soil C content. Both intact and degraded forests continue to experience some degree of disturbance, particularly in degraded forest where small plot farming occasionally occurs, which might result in continuous loss of some soil C (Houghton and Hackler 2000; Nyssen et al. 2008; Berry 2011). Due to agricultural expansion and timber harvesting, degraded forest is sparsely vegetated, has about 10% forest cover with shrubs mostly dominating.

The large amount of C stored in soils under OCAP plantations only seems to emphasize the large capacity of plantations to store C in their soils as suggested by Ming et al. (2014), Schlesinger and Lichter (2001) and He et al. (2013). Furthermore, whilst, this study seems to suggest that on average, both intact and degraded forests accumulated similar amount of C irrespective of depth, other studies such as (Berihu et al. 2017) have reported higher C content in dense natural forest than open forest in the same climate zone. This situation might have resulted from frequent anthropogenic disturbances coupled with the possibility of biomass production reduction in intact forest due to its recovery from previous commercial felling.

In the plantation settings, there were significant differences in soil C concentration among single- and mixed-species plantations and between soil depths. This translated into significant differences in C content between single- and mixed-species plantations in both depths. It was further observed that soil under pure plantation of *Cedrela odorata* (an exotic species) had accumulated more C than pure plantation of *Triplochiton scleroxylon* (a native species) and the mixed-species plantation, with *Triplochiton scleroxylon* also accumulating more soil C than the mixed-species stand (Table 2). In general, the single-species (pure) plantations accumulated more C in their soils than the mixed-species. In contrast, soil C storage of mixed-species plantations in sub-tropical China was greater than that of single-species plantations (He et al. 2013), and soil under mixed-species stands of *Eucalyptus* and *Acacia* was reported to be higher in C than single-species stands (Forrester et al. 2013). In Ghana, the exotic species *Cedrela odorata* is faster growing (Opuni-Frimpong et al. 2013) than indigenous species, and hence soil under it might have received larger C inputs from above- and belowground litter, coupled with slow litter decomposition from modified microclimate due to a closed canopy. *Triplochiton scleroxylon* is also fast growing compared to other native species, and thus might have similar ability to produce more C inputs than trees in the mixed plantations. Mixed stands included both slow and fast growing species and competition for resources (moisture, light, nutrients) among species in the stand might have resulted in overall lower productivity of mixtures (Petit and Montagnini 2006; Piotto 2008). This could have resulted in lower production of soil C inputs. Irrespective of this finding, the mixed-species plantation still showed promising potential to store C in its soil particularly in the 20–50 cm layer where it stored as much as the *Triplochiton scleroxylon* pure plantation.

Soil layers

Generally, the study revealed that C content of soil under all forest cover types decreased with increasing depth (Table 3). Similar trends with depth have been suggested by other studies who also reported relatively higher C content values in the upper layers of soils compared to the lower layers (Grüneberg et al. 2010; Ming et al. 2014; Zádorová et al. 2015; Bessah et al. 2016; Berihu et al. 2017; Gross and Harrison 2019). The proportion of soil C content to 50 cm stored in the 0–20 cm depth was about 64.8%, 58.4% 57.2%

for SD forests, ME forests and ME plantations, respectively compared to 35.2%, 41.6%, 42.8% in the 20–50 cm depth. The soil C concentrations were much higher in 0–20 cm depth in all the study sites. Peichl and Arain (2006) and Zhang et al. (2012) demonstrated that higher C content in upper soil depth is due to production of organic C near the ground surface as result of decomposition of litter and root systems. However, due to susceptibility of upper layer of soils to forest disturbance, huge amounts of C can be released in the event of disturbances such as fire, harvesting or tillage. Notwithstanding the high C content in upper soil depth, we agree with Harper and Tibbett (2013) that lower soil depths are very important C pools as they help in preserving soil C for hundreds to thousands of years, hence some attention and emphasis must be placed on them. The significant amount of soil C existing at 50 cm suggests the need for sampling regimes that sample much deeper (up to several meters) to truly understand the impact of disturbance to intact, mature forests on total soil C storage and the potential to regain C upon reforestation.

Soil N contents

While the main focus of this paper was to assess the effects of forest cover and degradation on soil C storage, we also analyzed N to determine if forest disturbance had led to a loss in total soil N capital. Patterns of N concentrations and contents were similar to those of C, with C:N ratios generally in a very narrow range (10.1–11.0). The degraded forests had similar total soil N content to the intact forests, suggesting any temporary declines in total soil N after disturbance were minor and/or recovered rapidly due to the maintenance of the sites in a vegetated state.

Conclusion

The study showed variations in soil C content among the different forest cover types as well as soil depths, thus demonstrating the potential for soils under different forest cover to store C in their layers. Soils of degraded forest lands held as much C as those of intact forest, partly due to the large accumulation of C in the upper layers. Contrary to other reports, soils under plantations appeared to store as much or more C than nearby intact and degraded natural forests. The lack of tillage combined with the maintenance of vegetative cover on plantation lands after their initial disturbance, mostly shrubs, grass and/or woodlands with few scattered timber tree species, likely played a role in their ability to contain large amounts of soil C. Single species plantation stands also appeared to accrue more C in soil than mixed species stands, however, over the years, we anticipate a similar capacity for both. These findings suggest that if disturbed forests are not tilled and are kept or returned to a vegetated state for a sufficient period of time, they are able to maintain soil C content similar to that of undisturbed forests. Thus, in the longer term, the potential to sequester C in such disturbed or degraded forests resides primarily in re-establishing live forest biomass. The study further revealed that forest degradation does appear to alter surface soil quality (lower C and N concentrations and higher bulk density in degraded forests), which may cause some issues during initial phases of reforestation efforts. Notwithstanding the large capacity for upper soil depth to accumulate C, this study highlights the potential capacity for deeper soil layers to store C. Their reduced susceptibility to forest disturbance makes them an important soil C pool, especially in forests with deep-rooted species. This study provides primary information on soil C content of different forest covers which is needed for C budgeting in Ghana and tropical areas with similar forests. It thus also supplements the efforts to add to the existing knowledge base for C assessment and to provide in-depth understanding of C balance in forests and their potential response to future global change. However, extensive and contemporary soil sampling protocols will be needed to further provide insights to soil C storage capacities of different forest cover types and to deeper soil depths in tropical Africa.

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