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RESEARCH ARTICLE

Variation in above and below ground carbon storage in a *Eucalyptus grandis* plantation established in a grassland with a chronosequence of age

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Abstract

Plantation forests are one of the major carbon sinks. However, knowledge is scarce regarding the short- and long-term carbon sequestration potentials of plantation forests grown in tropical grasslands. Therefore, the changes in aboveground carbon stocks (AGC) and soil carbon stocks in a chronosequence of *Eucalyptus grandis* plantations (4, 10, 19, and 27 years) established on grasslands in mid-elevational areas of Sri Lanka were studied in the present study. An adjacent grassland was studied as the control. Carbon stock of understory significantly decreased with stand age ($p = 0.000$) while carbon stock of litter layer significantly increased with stand age ($p = 0.001$). Total AGC stocks and soil carbon stocks in *E. grandis* plantation forests were significantly higher than that of the grassland ($p < 0.05$). Moreover, soil carbon stocks in *E. grandis* plantations increased significantly with increasing stand age ($R^2 = 86.8\%$). With the increasing depth, soil carbon stock had significantly decreased ($p < 0.05$). There was a 56% increase in overall ecosystem carbon stock after 27 years and approximately 20 times higher ecosystem carbon stock than the grassland, which was their previous land use. Therefore, the study suggests that stand age plays a major role in carbon storage in plantation forests and the use of *E. grandis* as a plantation crop would be a beneficial option for rapid carbon sequestration in grass-dominated ecosystems in the tropics. In the long run, this could be a good solution for rebalancing the ecosystem that has been severely impacted. Further, this study provides valuable information in deciding the thinning age of Eucalyptus plantation forests in the tropics based on the C sequestration potential.

Keywords Above Ground Carbon stock · Carbon sequestration · *Eucalyptus grandis* · Grassland · Soil Carbon stock · Stand age

Introduction

Human intervention in the environment over the past several centuries has created a significant impact on the atmospheric concentration of CO_2, in particular through the burning of fossil fuels (Khan 2017; Mahowald et al. 2017). The average CO_2 concentration in the atmosphere increased up to 405 ppm in 2017. The temperature rises caused by the high CO_2 levels in the atmosphere had led to climate changes causing various drastic effects on earth such as storms, drought, rising sea levels and melting glaciers (Chakraborty et al. 2016; Sony et al. 2018). Therefore, global attention has turned more toward carbon pools where carbon can be stored to rebalance damaged ecosystems (Lal 2008).

In the global carbon cycle, forest ecosystems are one of the key carbon storage systems (Pan et al. 2011 ; Behera et al. 2017). According to Soepadmo (1993), the total storage of organic carbon in the tropical rainforest is approximately 3.93×10^{11} tons, of which the vegetation accounts for 58%, soil for 41%, and litter for 1%. Organic carbon content in an ecosystem is a crucial factor in deciding its fertility, especially soil organic matter (SOM) (Russell 1977). A high Soil Organic Matter (SOM) concentration can provide plants with additional nutrients and improve water availability, which raises soil fertility and increases ecosystem productivity (Johns 2017). Although natural forests are considered to be the major biological carbon-sequestering units, plantation

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forests which are expanding at a rate of 2% annually (van Dijk and Keenan 2007) also significantly contribute to carbon sequestration (Richards et al. 2007; Chen et al. 2015). As mentioned by Chen et al. (2011, 2015) fast-growing species tend to store more carbon due to their higher photosynthetic rates, high biomass accumulation, and high carbon storage capacity. Therefore, being one of the most commonly planted fast-growing tree species in the world, Eucalyptus species have become a potential contender to reduce global atmospheric CO_2 levels (Rockwood et al. 2008).

The total land area under Eucalypt plantations in the world is estimated over 7% of the total area of plantation forests (20 million hectares) (FAO 2015). The high growth rate of the species, yielding a quick monetary return (as timber and firewood), resistance to environmental stresses, short rotation period, high stand density per unit area and the need for less post-plantation care are among the reasons for the popularity of growing Eucalyptus species (Pereira et al. 1994; Barros and Novais 1996; Lambert and Turner 2000). Further, according to Sang et al. (2013), Eucalyptus species produce commercially desirable timber and firewood and they are tolerant to a broad range of soil conditions including low soil fertility. Most importantly, Eucalyptus plantations may also involve both above-ground and below ground carbon sequestration (Ribeiro et al. 2015).

However, it is still controversial whether they increase or decrease carbon sequestration with their stand age. Whereas some studies report afforestation with Eucalyptus species had increased soil carbon stocks (Kaye et al. 2000; Epron et al. 2009; Maquere et al. 2008) while some other studies report a decrease (Lebenya et al. 2018) or stabilization (Turner and Lambert 2000) or no effect (Fialho and Zinn 2014) in soil carbon. Therefore, to clarify this matter, it is important to find carbon sequestration potentials under tropical Eucalyptus forests. Further, stand age is found to be a crucial factor that decides the carbon sequestration potential of these plantation forests (Berthrong et al. 2012; Powers et al. 2012; Ming et al. 2014; Li et al. 2015). A study reported a decrease in soil C stock after eight years of afforestation in South Africa which was established in a sub humid grassland (Lebenya et al. 2018). Further, Berthrong et al. (2012) found that soil carbon stock increased with stand age in Eucalyptus plantation forests (aged between 10 and 45 years) which were established on a grassland in Argentina. Epron et al. (2009) also reported an increase in soil carbon after 14 years in a Eucalyptus forest established in savannah, Congo. However, all these studies were done only for soil carbon and had not been studied until the Eucalyptus plantation reached its usual optimal rotation length (25–27 years). Therefore, information on both above and below-ground carbon sequestration in Eucalyptus plantation forests, established in tropical grasslands, and their long-term variation (until reaching their maximum rotation length) are still lacking.

Thus, this research is aimed at studying the effect of increasing stand age on the carbon sequestration capacity of Eucalyptus plantations established in tropical grasslands, to determine whether the establishment of Eucalyptus plantations is an environmentally friendly option for accelerating carbon sequestration until maximum rotation length is reached. Further, the information would be important in determining the maximum felling age after the plantation sequestered more carbon. Here we measured carbon stocks in aboveground vegetation as well as the soil in *E. grandis* plantation forests established on a montane grassland at mid-elevation lands of Sri Lanka, across an age sequence of *E. grandis* plantations. Our aim was to reveal how the stand age may affect above- and below-ground carbon reserves. This study discloses the changing pattern of carbon stocks with the age of the forest and compares it with an adjacent montane grassland. We hypothesized that planting *E. grandis* in degraded underutilized tropical montane grasslands would be a feasible mechanism for promoting carbon sequestration and improving the ecosystem in such sites.

Methods

Study area

This study was carried out on four *E. grandis* plantation forests of different ages and a montane grassland (locally known as 'Patana') located in the upcountry intermediate zone of Sri Lanka (5° 54′ N–9° 52′ N and 79° 39′ E–81° 53′ E). The study area is characterized by a tropical monsoon climate (Mapa et al. 2005) with the mean annual temperature of the region varying between 19 and 23 °C while the mean annual rainfall of the area is 2245 mm, of which 60% is received between October to February (Tea Research Institute, 2019) from the north-eastern monsoon. The soil is representative of typical Haplohumults fine loamy, acidic, non-calcareous, and isohyperthermic soils (Mapa et al. 2005). The topography is generally hilly to steeply dissected with sandy clay loam surface and subsurface soils. Healthy *E. grandis* plantation forests with ages of 4, 10, 19, and 27 years and adjacent montane grassland were selected for the study (Fig. 1). All these selected sites were located within a radius of 8.5 km, spreading over an area with rugged topography at an elevation that ranged from 700 to 1300 m (Table 1) with modest slopes (< 4–6%). *Cymbopogon nardus* was the dominant species in the selected grassland.

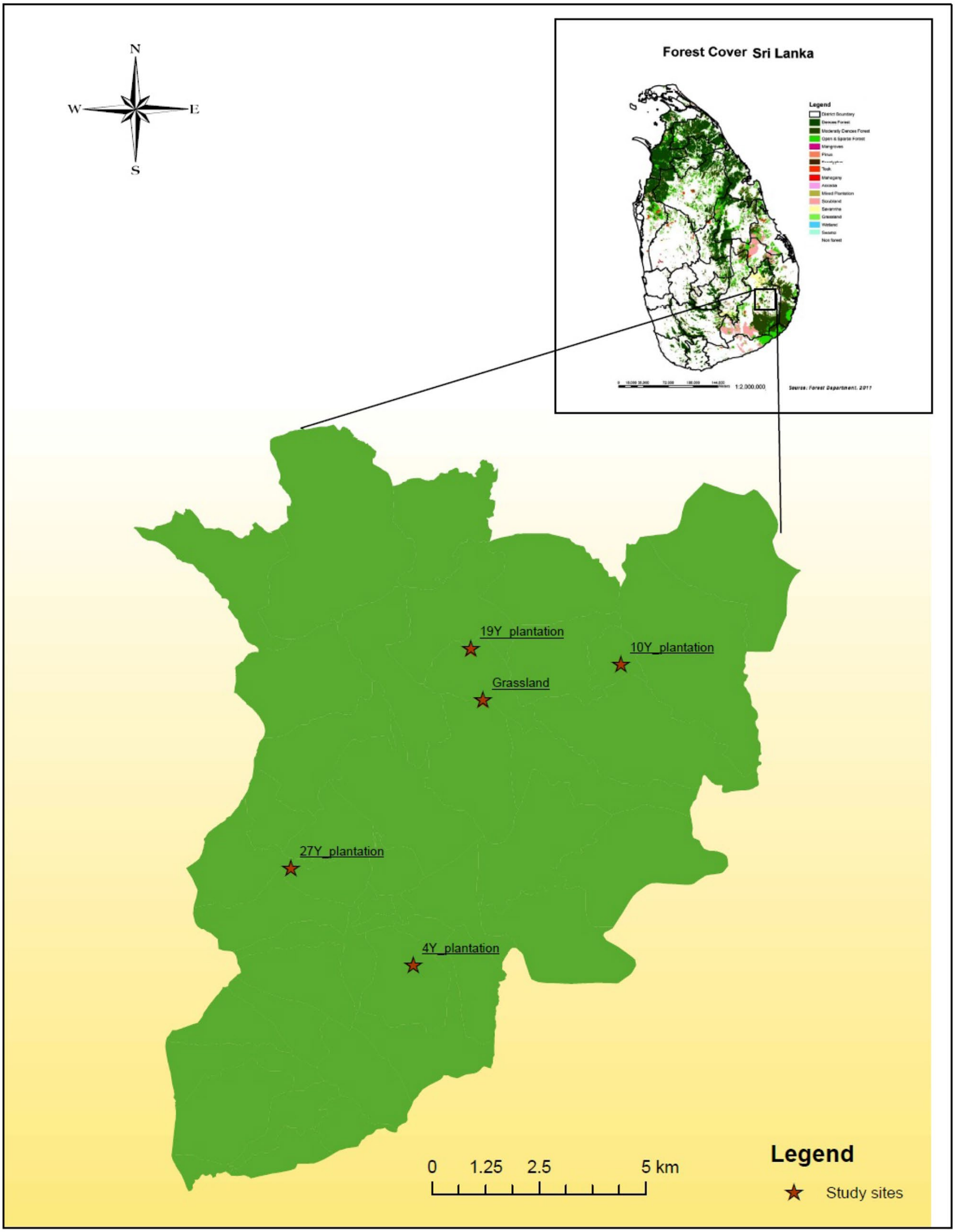

Fig. 1 Study sites in the upcountry intermediate zone of Sri Lanka

Table 1 Characteristics of Eucalyptus grandis forests and grassland in the study (values are means ± SD)

	4-year-old plantation	10-year-old plantation	19-year-old plantation	27-year-old plantation
Stand density (trees ha^{-1})	1562 ± 241 a	822 ± 87 b	342 ± 72 c	289 ± 41 c
Tree height (m)	7.00 ± 0.68 c	9.64 ± 1.12 a	9.68 ± 1.45 b	10.51 ± 1.99 a
DBH (cm)	14.12 ± 2.68 c	17.42 ± 3.4 c	21.21 ± 4.19 b	30.18 ± 5.24 a
Crown width (m)	4.180 ± 0.96 c	3.250 ± 0.75 d	6.350 ± 1.22 b	9.540 ± 2.90 a
Basal Area (m^2 ha^{-1})	25.30 ± 9.19 a	20.31 ± 8.38 a	12.54 ± 5.12 b	22.18 ± 8.41 a

Different letters indicate significant differences between mean values (Tukey's HSD, $p < 0.05$)

History and the silviculture of *E. grandis* plantations

Before the establishment of plantation forests, the selected sites had been covered with grasslands dominated by *Cymbopogon nardus*. Considerable site preparation with the removal of shrubs and weeds before reforestation had been carried out in these sites. Eucalyptus seedlings were planted with 2.5 m × 2.5 m space between plants and about 50 g/plant of fertilizer has been added as base fertilizer (Nitrogen: Phosphorus: Potassium (N:P:K) = 9:11:9) at the time of the establishment of the plantation. Approximately 32–40 trees were in each plot which varied along with the age. Thinning of forest stands was carried out usually at, 3–4 years, 7–8 years, 13 years, 18 years, and 25 years after the establishment of the plantation. However, no thinning measures have been performed in the selected plantation forests during this study.

Establishment of experimental plots

Experimental plots were established in selected forests and grassland, according to a stratified random sampling approach. Six 20 × 20 m^2 experimental plots were established in each selected Eucalyptus forest stand and the grassland in randomly chosen locations. Each plot was then divided into four equal subplots of 10 m × 10 m.

Measurements of stand characteristics

The stem diameter of trees (whose heights were taken) was measured at breast height (at 1.3 m height) using a diameter tape. The number of trees (which had trunk diameters greater than 10 cm) in each plot was enumerated and the tree density per site was calculated. The total heights of all the trees (whose diameter at breast height was greater than 10 cm) in each plot were measured using a Suunto clinometer. Tree crown widths were measured by projecting the edges of the crown to the ground and measuring the length along one axis from edge to edge through the crown center using a tape (Condit 2008).

Vegetation and litter sampling, preparation, and measurement of the dry mass of the understory

The experimental plot was divided into 4 subplots, the quadrat (1 m^2) was thrown into four random places in each subplot and understory plant species with their roots within the quadrats were collected separately, species wise into plastic bags. In the laboratory, the collected understory plants were carefully wrapped in papers and dried in a preheated oven at 65 °C, for 24 h and the dry mass was measured.

Litter

Litter on the forest floor was collected into properly labelled polyethylene bags in four randomly chosen quadrats (1 m × 1 m) in each plot. A total of 24 samples were collected from each site. Sampled litter was dried at 65 °C to constant weight and the final dry mass was measured with an electronic balance.

Montane grassland

At each plot of the grassland, three quadrates (each with an area of 1 × 1 m^2) were sampled for aboveground biomass (AGB). The plants were clipped from the ground, and fresh weight was taken. Then three 100 g subsamples were oven-dried at 85 °C for 48 h and the dry weight was measured.

Soil sampling and sample preparation

Soil samples were taken from 3 randomly selected points in each subplot using a hand auger (50 mm diameter) and pooled to have one composite sample. Soil samples were obtained from two depth levels; depths of 0–15 cm (upper soil layer) and 15–30 cm (lower soil layer). Thus, a total of 72 composite soil samples were collected from each site for each layer. Selected points were > 0.5 m away from the nearest tree and > 5 m away from each other. The litter layer was removed before sampling. Collected soil samples were placed in properly labeled air-tight polyethylene bags and were transported to the laboratory.

Collected soil samples were sieved using a 2 mm sieve to remove stones and roots. Soil pH, soil moisture content, and microbial biomass carbon in fresh soil were analyzed using the standard protocols given below. The remaining soil was air dried and ground into a powder of < 0.15 mm using M 20, IKA, WERKE® grinder before further analyses.

Soil analysis

Soil carbon content was determined by automated dry combustion using a CHN analyzer (Elemental analyzer, Perkin-Elmer 2400 series II). Initially, a portion of the air-dried and sieved soil samples (0.15 mm mesh size) was again ground into a homogenous powder and sieved through a 10 µm mesh sieve. About 1.0–1.5 mg of, this soil sample was used to analyze C content using a CHN analyzer.

Statistical analysis

All data were averaged across the plots in each site to generate site-level values for analysis. Carbon stocks in aboveground vegetation and soil carbon stocks were analyzed via the General Linear Mixed Model at a 0.05 significance level using SAS 9.1.3 portable version. The model examined all interactions between the stand ages and carbon stocks, thereby eliminating pseudo-replication in the experimental design. The data of basal area (BA), Aboveground biomass (AGB), Aboveground carbon content (AGC), Aboveground carbon per tree, and soil C stock were transformed to Log or Antilog values to approximate a normal distribution. Other variables were tested without transformation. Pearson correlation was used to investigate the relationships between variables. Simple linear regression analyses or polynomial regression analyses were also performed to test the relationships between the measured variables. Selection criteria for the regressions were based on R^2 and p-value. All statistical tests other than the mixed model ANOVA was conducted using Minitab (19.2 0) Software.

Calculation of above ground biomass and tree carbon stock

Plantation forest The basal area (BA) was calculated from measurements of the diameter (DBH in cm) for each measured tree (Eq. 1). Aboveground biomass (AGB) was estimated based on previously developed allometric equations (De Costa and Suranga 2012), as allometric equations for Sri Lankan *E. grandis* forest stands were not available. Then, merchantable wood volume was calculated using Eq. 2.

$$\mathrm{BA} = \pi\,(\mathrm{DBH})^2/40000 \tag{1}$$

$$\mathrm{V} = \mathrm{f\ g\ h} \tag{2}$$

where V represents the merchantable wood volume per tree (m^3) and g and h refer to basal area per tree (m^2) and tree height (m) respectively and f, is the 'form factor' which is unique for the tree species. The value, 0.335 was taken as the form factor of *E. grandis* (De Costa and Suranga 2012). The merchantable wood volume calculated was converted to above-ground biomass per tree using the following relationship (Cost et al. 1990).

$$\begin{aligned}&\text{Above-ground tree volume}\left(\mathrm{m}^3\right)\\&= 1.67 \times \text{Merchantable wood volume}\left(\mathrm{m}^3\right)\end{aligned} \tag{3}$$

The factor 1.67 represent the biomass contained in leaves, branches and other aboveground parts, which were excluded when merchantable wood volume was calculated. Therefore, according to Birdsey (1992) and De Costa (2012), following Eq. (4) was used to convert the above ground tree volume (m^3) to AGB per tree (kg) assuming a wood density for *E. grandis* as 490 kg m.$^{-3}$ Thereafter, AGB Mg per hectare was calculated by the Eq. 5 below.

$$\begin{aligned}\text{AGB per tree (kg)} &= \text{above} - \text{ground tree volume}\left(\mathrm{m}^3\right)\\&\times \text{ wood density}\left(490\ \mathrm{kg\ m}^{-3}\right)\end{aligned} \tag{4}$$

$$\text{AGB} = (\text{AGB per tree}/1000) \times \text{Stand density (per hectare)} \tag{5}$$

Using AGB per hectare, aboveground carbon stock (AGC) was calculated by using the Eqs. 6 and 7 while assuming that the carbon content of biomass to be 50% (Sampson 1992).

$$\begin{aligned}&\text{Aboveground C stock per hectare}\left(\mathrm{Mg\ C\ ha}^{-1}\right)\\&= \text{AGB per hectare}\left(\mathrm{Mg\ C\ ha}^{-1}\right) \times 0.5\end{aligned} \tag{6}$$

$$\text{Above ground C per tree (kg)} = \text{AGB per tree (kg)} \times 0.5 \tag{7}$$

Using a conversion factor developed by Birdsey (1992), the total tree C stocks per hectare were calculated by the Eq. 8 below.

$$\text{Total tree C stock per hectare} = \text{AGC per hectare} \times 1.3054 \tag{8}$$

where the factor 1.3054 represents the root biomass of trees (De Costa and Suranga 2012).

Understory and litter The C stocks in the understory vegetation and litter were determined by multiplying dry mass per unit area by carbon fraction. (0.47) (Goslee et al. 2010).

Grassland Above ground biomass was calculated using following equations (UNDP 2014).

$$\text{Total dry weight}\left(\text{kg m}^{-2}\right) = \text{Total fresh weight (kg)} \times \text{Subsample dry weight (g)} \times \text{Sample area}\left(\text{m}^{2}\right) / \text{Subsample fresh weight (g)} \tag{9}$$

$$\text{Above ground biomass}\left(\text{AGB}_{\text{grass}}\right) = \text{Total dry weight} \times 0.47 \tag{10}$$

Here it is assumed that the carbon content of biomass to be 50% (Sampson 1992).

$$\text{Aboveground C stock}_{\text{grassland}}\text{ per hectare}\left(\text{Mg C ha}^{-1}\right) = \text{AGB per hectare}\left(\text{Mg C ha}^{-1}\right) \times 0.5 \tag{11}$$

Results

Carbon stocks in trees of the plantation

Figure 2a depicts carbon stocks in trees for the plantation forests of different ages. The average carbon stock in trees was highest in the 27-year-old plantation (30.15 Mg C ha^{-1}) while the lowest was found in 4-year-old plantation (17.37 Mg C ha^{-1}). However, these carbon stocks did not differ significantly among stands of different ages (Mix model ANOVA, $p > 0.05$) and did not correlate with stand age ($p > 0.05$).

C stocks in the understory and litter layer

The C stocks in the understory of the studied plantations (Fig. 2b) had shown a negative correlation with the stand age of the plantation (Pearson correlation = − 0.736, $p = 0.000$). However, the C stocks of the litter layer had significantly increased with the stand age (Pearson correlation = 0.705, $p = 0.001$) (Fig. 2c). This is approximately 1.5 times higher than the carbon stock of the understory.

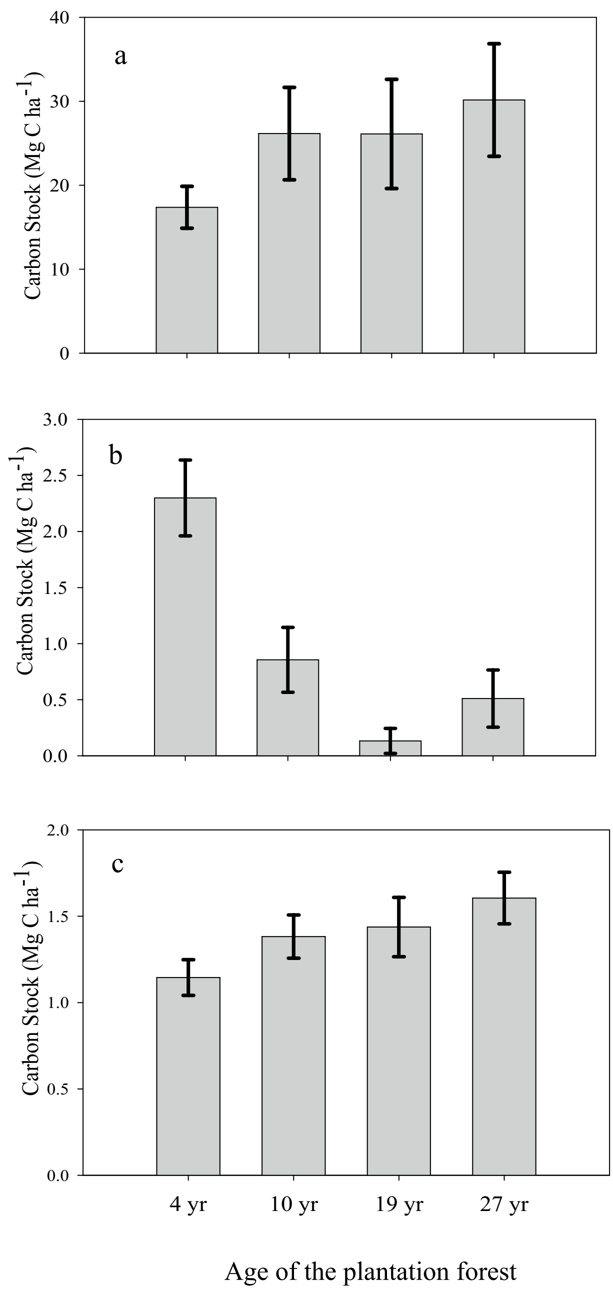

Fig. 2 Variation of carbon stocks in **a** trees of plantation, **b** understory, **c** litter layer with stand age in *Eucalyptus grandis* plantation forests

Total above-ground carbon (AGC) stock

Total AGC stock was highest in the 27-year-old plantation (32.27 ± 10.83 Mg C ha^{-1}) whereas the lowest was recorded in the youngest or the 4-year-old plantation (20.83 ± 5.67 Mg C ha^{-1}). Although there was no

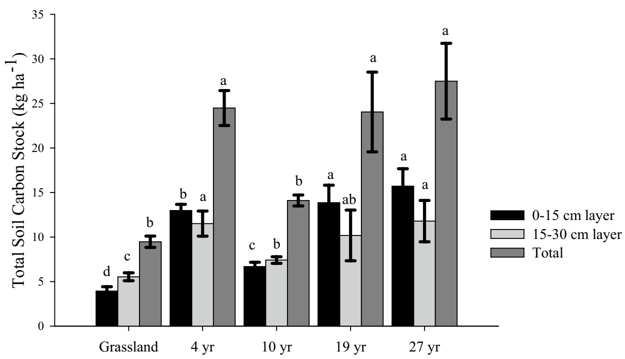

Fig. 3 Variation of carbon stocks in soil layers with stand age in *Eucalyptus grandis* forest plantations and grassland (Different letters indicate significant differences between mean values; Tukey's HSD, $p < 0.05$)

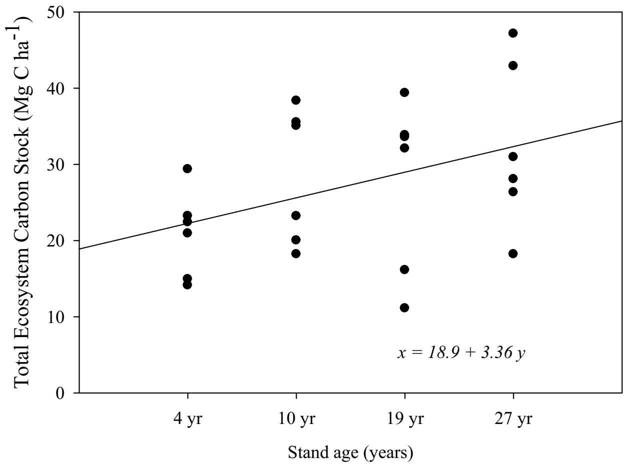

Fig. 4 Variation of total ecosystem carbon stocks of *Eucalyptus grandis* plantation with stand age

significant relationship between the stand age and AGC stock, the total AGC had shown an increasing trend with the stand age. Compared to grassland (1.64 ± 0.06 Mg C ha^{-1}) there was an approximately 20-fold increase in total AGC stock in 27 year-old of plantation.

Carbon stocks in soil

As depicted in Fig. 3, the soil carbon stocks in all plantation forests and the grassland in the study were significantly different (Mix model ANOVA, $p < 0.05$). Moreover, carbon stocks changed with increasing soil depth in the studied sites ($p < 0.05$), showing a significant decrease with increasing depth ($p = 0.000$). Carbon stocks in the upper soil layer (0–15 cm layer) in *E. grandis* plantations increased significantly with increasing stand age ($p = 0.000$; $R^2 = 86.75\%$; Pearson correlation = 0.739) while the carbon stocks in the 15–30 cm layer showed a comparatively weak non-significant relationship with the increasing stand age ($p > 0.05$). However, the total soil carbon stocks in the plantations changed significantly with increasing stand age ($p = 0.000$; Pearson correlation = 0.868). Moreover, total soil carbon stocks in *E. grandis* plantations had significantly higher carbon stocks ($p < 0.01$) compared to the grassland (Table 2). The soil carbon stock in the 27-year-old plantation forest was 2.6 folds higher than that of the grassland.

Total ecosystem carbon stocks

Total plantation forest carbon stocks in plantation forests varied significantly and they correlated positively with the stand age (ANOVA, $p = 0.000$, Pearson Correlation = 0.722, = 0.000) (Fig. 4). There was a 56% increase in overall forest carbon stock after 27 years when compared to the 4-year-old plantation. Further, there are around 20-fold higher total carbon stocks in the 27-year-old plantation compared to the grassland (Table 2). AGC stock contributed more to the total ecosystem carbon when compared with below-ground carbon stocks (Table 2). The contributions by litter and understory to the total ecosystem carbon were 5.1% and 3.5% respectively. The highest contribution was from plantation stand (91.4%) while the lowest was from the soil (0.08%). However, compared to plantation forests grassland had very low total ecosystem carbon stock (Table 2).

Table 2 Total ecosystem carbon in *Eucalyptus grandis* plantations forests with different stand ages (values are means ± SD

Stand age (yrs)	Total Above Ground Carbon (Mg C ha^{-1})	Total Below ground Carbon $\times 10^{-3}$ (Mg C ha^{-1})	Total Ecosystem Carbon (Mg C ha^{-1})
4	20.83 ± 5.67 a	24.48 ± 1.96 a	20.85 ± 5.66 a
10	28.39 ± 8.88 a	14.10 ± 0.61 b	28.40 ± 8.88 a
19	27.68 ± 11.28 a	24.03 ± 4.47 a	27.71 ± 5.66 a
27	32.27 ± 10.83 a	27.49 ± 4.25 a	32.29 ± 10.8 a
Grassland	1.64 ± 0.06 b	9.46 ± 1.63 b	1.65 ± 0.06 b

Different letters indicate significant differences between mean values (Tukey's HSD, $p < 0.05$)

Discussion

Carbon stocks in above-ground vegetation

Many factors can affect carbon storage in trees of forests (Ryan et al. 2010; Lin and Zhao 2018). Among them, stand age strongly affects the carbon sequestration ability in trees of plantation forests (Cheng et al. 2014; Chen et al. 2015; Köhl et al. 2017). Although the relationships were not statistically significant, we noticed that AGC stocks showed an increasing tendency with stand age across the four studied *E. grandis* plantations. Cheng et al. (2014) also observed a significant increase in AGC stock of a *Pinus tabulaeformis* plantation in Shanxi, China, while Chen et al. (2015) observed a decrease in above-ground carbon in a *Eucalyptus urophylla* plantation. However, the latter study by Chen et al. (2015) was on plantations that are younger than 10 years. In our study, we observed a comparatively lower AGC stock in the 19-year-old plantation forest. The reason for this could be their lower BA, which is mainly due to the low stand density caused by thinning practices. The AGC stock results of the present study fall within the lower ranges according to the values reported across Eucalyptus plantations and some other plantations worldwide (Binkley and Ryan 1998; Ming et al. 2014) and this could be probably due to low nutrient contents in our study sites. However, further studies are required to clarify this discrepancy.

Interestingly, AGC stocks of all the studied plantation forests were higher than the estimated C stocks of the original grassland. Richards et al. (2007) also observed a similar trend when comparing Hoop pine plantations and pastures, in Australia. The main reason could be lower biomass compared to plantation forests.

Although not significant, the understory and litter layer had contributed sufficiently to the carbon sequestration in the studied plantation forests (5.1% and 3.5% respectively). Ming et al. (2014) also observed similar contributions from understory and litter under a *Mytilaria laosensis* plantation. We detected a significant negative relationship between the carbon stock of the understory and the stand age of the plantation forest. However, these were in contrast to the findings of Ming et al. (2014) who observed a positive relationship between understory carbon stock and stand age in a *Mytilaria laosensis* plantation in China. It has been found that Eucalypt trees contain allelopathic chemicals which either could be emitted by leaves or mixed with soil via litter and root exudates which influence negatively the understory vegetation (Souto et al. 2001). Moreover, a study done on Chinese Fir reported an increase in the production of allelochemicals with stand age (Chen and Wang 2012). Therefore, an increase in allelochemicals might have reduced the understory vegetation with stand age which led to a reduction of understory contribution to total ecosystem carbon stock. However, in our study the carbon stock of the litter layer showed a significant positive relationship with stand age which was similar to the results of Ming et al (2014) and Yue et al. (2018) for a Spruce plantation in China. Nevertheless, our average values were lower than the values for the *Mytilaria laosensis* plantation and Spruce forest in those studies. As revealed by Xiong and Nilsson (1999), the increasing litter layer could have negatively affected the growth of understory vegetation as well).

Carbon stocks in soils of plantation forest

Our results suggest that soil depth affects the soil carbon stocks in *E. grandis* plantations. Further, it was observed that the soil carbon stocks gradually decrease with increasing depth. This could be linked to the reduction in fine roots with depth in forest ecosystems as mentioned by Rovira and Vallejo (2007). Soil C stock of both soil layers in the present study increased with increasing stand age of the forest, agreeing with the observations made by Trouve et al. (1994) for a Eucalyptus hybrid plantation in savannas in Congo (up to 19 years), by Chen and Shrestha (2012) for Boreal forests in Canada (up to 203 years). However, the results of this study contradict the results of Turner and Lambert (2000) who observed, a stabilization in soil organic carbon with some indication of an increase after 20 years of establishment of *E. grandis* plantation forest in eastern Australia. This increase in soil carbon could support plant growth and improve water availability, which leads to soil fertility and productivity. Furthermore, it supports soil structural stability by encouraging aggregate formation.

The slowdown in the decomposing rates with stand age might have contributed to the increase in carbon accumulation of studied plantation forest soil with stand age. Moreover, the accumulation of more leaf litter on the forest floor with the increase in stand age could also result in an increase in carbon in the soil. Compared to plantations, the grassland had a lower amount of soil C stock in both layers. This could be linked to the mineralization processes in soils. Further, it has been found that under the Eucalyptus plantations, the decomposition of litter is slow (Barlow et al. 2007). This may be due to various inhibiting factors such as soil acidity and antimicrobial compounds that are found in Eucalyptus soils which slow down microbial activities, reducing decomposition rates (Zimmer et al. 2005; Soumare et al. 2015) which result in, a higher amount of soil C stock under Eucalyptus plantations, compared to grassland.

However, the higher carbon stock in 4-year-old plantations compared to a 10-year-old plantation could be due to the accumulated carbon in previous grassland vegetation. A similar observation was recorded by Justin et al. (2015). Since the growth rate of Eucalyptus is high (Almeida et al.

2007) they might have used up most of the organic carbon in the soil, which might have led to the lower soil C stock in the 10-year-old plantation. However, after 10 years, with the accumulation of litter, root exudates and other organic substances soil carbon stocks might have increased.

Total ecosystem carbon stock

The distribution of the total ecosystem carbon stock peaked in the 27-year-old plantation. It was approximately 20 times higher than the values obtained for grassland. Similarly higher values were reported by du Preez for *E. nitens* plantation, after eight years of establishment in a grassed catchment. Compared to grassland, a significant relationship was observed between total ecosystem carbon and stand age. Similar results were observed in a study on *Mytilaria laosensis* plantation in China (Ming et al. 2014). Overall, Eucalyptus plantations had sequestered sufficient ecosystem carbon to replenish grassland ecosystem carbon stocks that were lost after clearing.

Conclusion

Standage is one of the major factors that determine the carbon stock in *E. grandis* plantation forest according to the present study. The carbon stock of the litter layer significantly increased with stand age while the carbon stock of the understory significantly decreased up to 27 years. Both above-ground and below-ground carbon stocks had increased until the trees reached their maximum rotation length. The present study also revealed that soil carbon stock decreases with the soil depth in *E. grandis* plantation forests. Further, AGC stock contributed more to the total ecosystem carbon, when compared to below-ground carbon stock. The total ecosystem carbon had increased significantly with the increasing stand age in *E. grandis* plantation forests, and at 27 years it was approximately 20 times higher than the carbon stocks of grassland, which was their previous land use. Therefore, the maximum rotation length for *E. grandis* plantation forests can be extended up to 27 years, to increase carbon sequestration in these forests. This study suggests that consideration of *E. grandis* as a plantation species would be more beneficial since they support maximization of carbon sequestration and therefore would lead to soil fertility and productivity, resulting in an improved ecosystem. Furthermore, planting *E. grandis* would be a feasible mechanism for promoting carbon sequestration and improving the soil quality of tropical grasslands. According to the results, the total carbon stock was the highest in 27 years old plantation forests. Therefore, by increasing the age of the final felling of the plantation we can sequester more carbon. Further, this study has provided clear information to resolve the controversy on the carbon sequestration potential of *E. grandis* on degraded soils such as montane grasslands. Additionally, since the stand age plays a major role in carbon storage in plantation forests, it is an important factor to consider when calculating carbon sinks and sources in an ecosystem.

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References

Almeida AC, Soares JV, Landsberg JJ, Rezende GD (2007) Growth and water balance of Eucalyptus grandis hybrid plantations in Brazil during a rotation for pulp production. For Ecol Manage 251:10–21

Ambagahaduwa IM, Prasad N, Gunatilleke IAUN, Seneviratne G, Gunatilleke CVS (2009) Estimation of above ground biomass of a Pinus caribaea Morelet stand in lower Hantana. J Natl Sci Found Sri Lanka 37:195–201

Anderson JM, Ingram JSI (1993) Tropical soil biology and fertility, a hand book of methods, 2nd edn. CABI International, Wallingford

Bandaratillake H M (1996) Eucalyptus plantations in Sri Lanka: environmental, social, economic and policy issues. Conservator of Forests, Sri Lanka, FAO Corporate Document Depository. Available from http://www.fao.org/docrep/005/ac772e/ac772e0l.htm (Accessed on 23 July 2012)

Barlow J, Gardner TA, Ferreira LV, Peres CA (2007) Litter fall and decomposition in primary, secondary and plantation forests in the Brazilian Amazon. For Ecol Manage 247:91–97

Barros NF, Novais RF (1996) Eucalypt nutrition and fertilizer regimes in Brazil. In: Attiwill PM, Adams AM (eds) Nutrition of Eucalypts. CSIRO Publishing, Melbourne, pp 335–355

Behera SK, Sahu N, Mishra AK, Bargali SS, Behera MD, Tuli R (2017) Aboveground biomass and carbon stock assessment in Indian tropical deciduous forest and relationship with stand structural attributes. Ecol Eng 99:513–524

Berthrong ST, PIneiro G, Jobbágy EG, Jackson RB (2012) Soil C and N changes with afforestation of grasslands across gradients of precipitation and plantation age. Ecol Appl 22(1):76–86

Binkley D, Ryan MG (1998) Net primary production and nutrient cycling in replicated stands of *Eucalyptus saligna* and *Albizia facaltaria*. For Ecol Manage 1121:79–85

Birdsey RA (1992) Changes in forest carbon storage from increasing forest area and timber growth. In: Sampson RN, Hair D (eds) Forests and global change. American Forestry Association, Washington, pp 23–39

Chakraborty A, Joshi PK, Sachdeva K (2016) Predicting distribution of major forest tree species to potential impacts of climate change in the central Himalayan region. Ecol Eng 97:593–609

Chen HY, Shrestha BM (2012) Stand age, fire and clearcutting affect soil organic carbon and aggregation of mineral soils in boreal forests. Soil Biol Biochem 50:149–157

Chen LC, Wang SL (2012) Allelopathic behaviour of Chinese fir from plantations of different ages. Forestry 86:225–230

Chen DM, Zhang CL, Wu JP, Zhou LX, Lin YB, Fu SL (2011) Subtropical plantations are large carbon sinks, evidence from two monoculture plantations in South China. Agric for Meteorol 151:1214–1225

Chen Y, Liu Z, Rao X, Wang X, Liang C, Lin Y, Zhou L, Cai X, Fu S (2015) Carbon storage and allocation pattern in plant biomass among different forest plantation stands in Guangdong, China. Forests 6:794–808

Cheng X, Han H, Kang F, Song Y, Liu K (2014) Variation in biomass and carbon storage by stand age in pine (*Pinus tabulaeformis*) planted ecosystem in Mt. Taiyue, Shanxi, China. J Plant Interact 9:521–528

Condit R (2008) Methods for estimating aboveground biomass of forest and replacement vegetation in the tropics. Center for Tropical Forest Science Research Manual. (Available from: http://ctfs.arnarb.harvard.edu/Public/pdfs/CarbonInventoryMethods.pdf (Accessed on 14 August 2021)

Cost ND, Howard J, Mead B, McWilliams W, Smith W, Van Hooser D, Wharton E (1990) The forest biomass resource of the United States. In: The forest biomass resource of the United States. United States Department of Agriculture Forest Service, General Technical Report WO-057. https://www.srs.fs.usda.gov/pubs/gtr/gtr_wo057.pdf

De Costa WAJM, Suranga HR and Ranasinghe DMSHK (2009) Estimation of carbon stocks in the forest plantations of Sri Lanka. In: Proceedings of the National Forestry Research Symposium, 12 – 13 March, 2009, Kandy, Sri Lanka. pp 12–13

De Costa WAJM, Suranga HR (2012) Estimation of carbon stocks in the forest plantations of Sri Lanka. J Natl Sci Found 40:9–41

du Preez CC, Lebenya RM and van Huyssteen CW (2021) Change in total carbon stocks eight years after afforestation of a sub-humid grassland catchment with Pinus and Eucalyptus species. New Forests 1–18

Epron D, Marsden C, M'Bou AT, Saint-André L, d'Annunzio R, Nouvellon Y (2009) Soil carbon dynamics following afforestation of a tropical savannah with Eucalyptus in Congo. Plant Soil 323:309–322

Fialho RC, Zinn YL (2014) Changes in soil organic carbon under eucalyptus plantations in Brazil: a comparative analysis. Land Degrad Dev 25:428–437

Food and Agriculture Organization of the United Nations (2015) Global forest resources assessment 2015: How are the world's forests changing? Food and Agriculture Organization of the United Nations

Goslee K, Walker SM, Grais A, Murray L, Casarim F, Brown S (2010) Leaf Technicial guidance series for the development of a forest carbon monitoring system for REDD+: module C-CS: calculations for estimating carbon stocks. Winrock International, Morrilton, AR, USA

Johns C (2017) The role of carbon in promoting healthy soils. Strategic Analysis Paper, Future Directions International, 10. Retrieved from https://www.futuredirections.org.au/publication/role-carbon-promoting-healthy-soils/

Kaye JP, Resh SC, Kaye MW, Chimner RA (2000) Nutrient and carbon dynamics in a replacement series of Eucalyptus and Albizia trees. Ecology 81:3267–3273

Khan MZA (2017) Causes and consequences of greenhouse effect and its catastrophic problems for earth. Int J Sustain Manage Inform Technol 3:34

Köhl M, Neupane PR, Lotfiomran N (2017) The impact of tree age on biomass growth and carbon accumulation capacity: a retrospective analysis using tree ring data of three tropical tree species grown in natural forests of Suriname. PLoS One 12:e0181187

Lal R (2008) Carbon sequestration. Philos Trans Roy Soc B 363:815–830

Lambert M, Turner J (2000) Commercial forest plantations on saline lands. CSIRO Publishing, Melbourne

Lebenya RM, Van Huyssteen CW, Du Preez CC (2018) Change in soil organic carbon and nitrogen stocks eight years after conversion of sub-humid grassland to Pinus and Eucalyptus forestry. Soil Research 56:318–330

Li T, Ren B, Wang D, Liu G (2015) Spatial variation in the storages and age-related dynamics of forest carbon sequestration in different climate zones—evidence from black locust plantations on the Loess Plateau of China. PLoS One 10:e0121862

Liu G, Zhao Z (2018) Analysis of carbon storage and its contributing factors—a case study in the Loess Plateau (China). Energies 11:1596

Mahowald NM, Randerson JT, Lindsay K, Munoz E, Doney SC, Lawrence P, Schlunegger S, Ward DS, Lawrence D, Hoffman FM (2017) Interactions between land use change and carbon cycle feedbacks. Global Biogeochem Cycles 31:96–113

Mapa RB, Daasanayake AR, Nayakekorale HB (2005) Soils of the Intermediate zone of Sri Lanka, 1st edn. Soil Science society of Sri Lanka

Maquere V, Laclau JP, Bernoux M, Saint-Andre L, Gonçalves JLM, Cerri CC, Piccolo MC, Ranger J (2008) Influence of land use (savanna, pasture, Eucalyptus plantations) on soil carbon and nitrogen stocks in Brazil. Eur J Soil Sci 59:863–877

Ming A, Jia H, Zhao J, Tao Y, Li Y (2014) Above-and below-ground carbon stocks in an indigenous tree (*Mytilaria laosensis*) plantation chronosequence in subtropical China. PLoS One 9:e109730

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire D, Piao S, Rautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. Science 333:988–993

Pereira JS, Linder S, Araujo MC, Tome M, Madeira MV, Ericsson T (1994) Biomass production with optimized nutrition in *Eucalyptus globulus* plantations. In: Pereira JS, Pereira H (eds) The State of the art. CSE, ISA, Lisbon, pp 13–30

Perera LSA and DMSHK Ranasinghe (2013) Carbon sequestration potential of privately managed swietenia macrophylla plantations in the wet and intermediate zones of Sri Lanka. In: Proceedings of international forestry and environment symposium, September 2013. University of Sri Jayewardenepura, Colombo, pp 27–28. https://doi.org/10.31357/fesympo.v18i0.1946

Powers MD, Kolka RK, Bradford JB, Palik BJ, Fraver S, Jurgensen MF (2012) Carbon stocks across a chronosequence of thinned and unmanaged red pine (*Pinus resinosa*) stands. Ecol Appl 22:1297–1307

Ribeiro SC, Soares CPB, Fehrmann L, Jacovine LAG, von Gadow K (2015) Aboveground and belowground biomass and carbon estimates for clonal Eucalyptus trees in Southeast Brazil. Revista Árvore 39:353–363

Richards AE, Dalal RC, Schmidt S (2007) Soil carbon turnover and sequestration in native subtropical tree plantations. Soil Biol Biochem 39:2078–2090

Rockwood DL, Rudie AW, Ralph SA, Zhu JY, Winandy JE (2008) Energy product options for Eucalyptus species grown as short rotation woody crops. Int J Mol Sci 9:1361–1378

Rovira P, Vallejo VR (2007) Labile, recalcitrant, and inert organic matter in Mediterranean forest soils. Soil Biol Biochem 39:202–215

Russell EW (1977) The role of organic matter in soil fertility. Philos Trans Roy Soc Lond B 281:209–219

Ryan MG, Harmon ME, Birdsey RA, Giardina CP, Heath LS, Houghton RA, Robert Jackson RB, McKinley DC, Morrison JF, Murray BC, Skog KE, Pataki DE (2010) A synthesis of the science on forests and carbon for US forests. Issues Ecol 13:1–16

Sampson RN (1992) Forestry opportunities in the United States to mitigate the effects of global warming. Water Air Soil Pollut 64:157–180

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

Soepadmo E (1993) Tropical rainforests as carbon sinks. Chemosphere 27:1025–1039

Sony RK, Sen S, Kumar S, Sen M, Jayahari KM (2018) Niche models inform the effects of climate change on the endangered Nilgiri Tahr (*Nilgiritragus hylocrius*) populations in the southern Western Ghats, India. Ecol Eng 120:355–363

Soumare A, Manga A, Fall S, Hafidi M, Ndoye I, Duponnois R (2015) Effect of *Eucalyptus camaldulensis* amendment on soil chemical properties, enzymatic activity, Acacia species growth and roots symbioses. Agrofor Syst 89:97–106

Souto XC, Bolano JC, Gonzalez L, Reigosa MJ (2001) Allelopathic effects of tree species on some soil microbial populations and herbaceous plants. Biol Plant 44:269–275

Subhasinghe U (2009) Plantation forestry in Sri Lanka. Forest Management Practices-Sri Lanka. Available from http://www.sci.sjp.ac.lk/upul/forestmanagementlanka/history.html (Accessed on 16 May 2017)

Tea Research Institute (2019) Monthly rainfall and temperature data. Available from the Monthly rainfall and temperature database of Tea Research Institute, Passara

Trouve C, Mariotti A, Schwartz D, Guillet B (1994) Soil organic carbon dynamics under Eucalyptus and Pinus planted on savannas in the Congo. Soil Biol Biochem 26:287–295

Turner J, Lambert M (2000) Change in organic carbon in forest plantation soils in eastern Australia. For Ecol Manage 133:231–247

UNDP (2014) Grassland carbon stock calculation and preparation of water balance model for vashlovani protected areas. United Nations Development Programme, Final Report, 12–13. https://www.undp.org/sites/g/files/zskgke326/files/migration/ge/GE_UNDP_EE_Grassland_Carbon_Stock_Calculation.pdf

van Dijk AIJM, Keenan RJ (2007) Planted forests and water in perspective. For Ecol Manage 251:1–9

Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass. Soil Biol Biochem 19:703–707

Xiong S, Nilsson C (1999) The effects of plant litter on vegetation: a meta-analysis. J Ecol 87(6):984–994

Yue JW, Guan JH, Deng L, Zhang JG, Li G, Du S (2018) Allocation pattern and accumulation potential of carbon stock in natural spruce forests in northwest China. PeerJ 6:e4859

Zimmer M, Oliveira R, Rodrigues E, Graça MA (2005) Degradation of leaf litter phenolics by aquatic and terrestrial isopods. J Chem Ecol 31:1933–1952