Ann. For. Res. 62(1): 3-20, 2019
DOI: 10.15287/afr.2018.1294

ANNALS OF FOREST RESEARCH
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Soil organic carbon storage varies with stand ages and soil depths following afforestation

Guolong Hou[1], Claudio O. Delang[1§], Xixi Lu[2], Lei Gao[3]

Hou G., Delang C.O., Lu X., Gao L., 2019. Soil organic carbon storage varies with stand ages and soil depths following afforestration. Ann. For. Res. 62(1): _-_.

Abstract. Soil organic carbon (SOC) is the largest component of the terrestrial biosphere carbon pool. Afforestation is an effective solution to mitigate Carbon (C) emission and sequester C into soils. However, how and to which extent afforestation influences SOC stock changes are not well understood. This study conducts a quantitative review that synthesizes 544 data points from 261 sites from 90 papers, to examine the impact of afforestation on SOC changes in three soil layers (0-20 cm, 20-40 cm and 40-60 cm). 212 data points are obtained by standardization and/or extrapolationwith high reliability. The results indicate that stand age has significant effects on the SOC stock dynamics under different conditions of previous land use types, plant functional types, temperature or precipitation. The effect is greatest at the topsoil layer of 0-20 cm. Previous land use types significantly influence SOC accumulations, but these effects are not significant in the first 10 years or after 30 years of afforestation. Besides, afforestation on grassland seems to sequester more SOC than that of cropland in the long term. Plant functional types also significantly affect SOC dynamics, with deciduous hardwood reporting a continuous increase of SOC contents at soil depth of 0-60 cm during the whole afforestation period. On the other hand, the accumulation of SOC in evergreen hardwood and evergreen softwood start from the third decades. Higher SOC accumulation rates are observed under evergreen hardwood but no significant differences were found between deciduous hardwood and evergreen softwood for the longer period after afforestation (>20 years). Mean annual temperature and precipitation negatively affect SOC accumulation in the first two decades of afforestation, however, the effects become positive in the later years.We also found that initial SOC stocks did not play a major role in SOC sequestration. In other words, lower SOC soils could also sequestrate a significant amount of SOC after reforestation.

Keywords: carbon sequestration, afforestation, stand age, soil depth

Authors. [1]Department of Geography, Hong Kong Baptist University | [2]Department of Geography, National University of Singapore | [3]Inner Mongolia Key Lab of River and Lake Ecology, Inner Mongolia University
§ Corresponding author: Claudio O. Delang (cdelang@hkbu.edu.hk)

Manuscript received May 15, 2019; revised July 15, 2019; accepted July 16, 2019; online first July 30, 2019.

Introduction

More than 650 billion tons of carbon (C) are stored by forests, with 56% stored in forest litter and soil (FAO 2010). Soil organic carbon (SOC) represents the largest component of the terrestrial biosphere C pool (Scharlemannet al. 2014), and small changes in the SOC stock can influence atmospheric C concentration considerably (Stockmann et al. 2013). Conversion from forest lands to agriculture results in significant soil disturbance, leading to losses of up to 50% of SOC in the first two decades (Lal 2005, IPCC 2005, IPCC 2007, Stockmann et al. 2013). Loss of C from soil is one of the main contributors to climate change, and the contribution of the agricultural sector to increasing global temperature is of great concern (IPCC 2011).

Afforestation is an effective solution to sequester atmospheric C into soils (Berthrong et al. 2009). The area planted with forests has increased from 168 million ha to 278 million ha from 1990 to 2015 owing to afforestation activities in Europe, North America and Asia (Keenan et al. 2015). Although afforestation has increased plantation areas, the contributions and influences of afforestation on SOC stock changes are not satisfyingly documented. A better understanding of SOC stocks and dynamics following afforestation is required to evaluate afforestation programs, to contribute to better C management, and to understand climate change mitigation options.

SOC stock changes are swayed by two processes (Figure 1). First the inputs of soil organic matter through litter fall and roots. The other is the loss of carbon through the decomposition of soil organic matter and leaching (Bonan 2008, Lal et al. 1997, Post and Kwon 2000). Typically afforestation increases the SOC inputs because trees produce more forest litter and have larger roots than crops and grass. However, the amounts of litter or roots vary among tree species. For example, hardwood trees may sequester more carbon than softwood trees because of a higher belowground biomass generated by their larger and more deeply anchored root systems (Strong & La Roi 1983).

Many factors contribute to changes in SOC stock after afforestation (eq. 1):

SOC Sequestration = f [*Climate (MAT, MAP),*
Soils (Initial SOC stock, Soil properties),
Tree species, Time after planting)]

First, climate, mainly annual temperature and precipitation, impacts growth of tress, and also the decomposition of soil organic matter. For example, there is more rapid decomposition of SOC in tropical soils because the climate is better suited to the microorganism which decompose organic matter (Post et al. 1982). Climatic conditions also affect leaching. Dissolved organic carbon is transported by water flows, so greater rainfalls may negatively affect SOC sequestration. Afforestation can mitigate the runoff by increasing soil water holding capacity and by mechanically stabilizing the soil with roots (Fu et al. 2009).

Second is soil conditions, often affected by previous land use. For example, previous land use can significantly affect SOC stock dynamics after afforestation. SOC contents will normally increase in converted cropland while

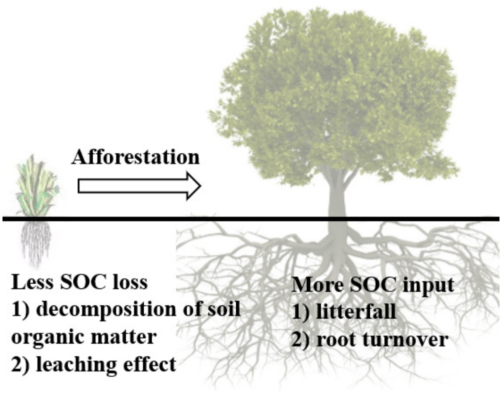

Figure 1 Sources of soil organic carbon stock changes after afforestation

decrease in converted grassland because of the relatively low initial amount of C in cropland soil compared to grassland results in a considerable increase of C after afforestation (Laganiere et al. 2010).

Third is tree species. There is considerable variation among tree species in terms of the quantity of C absorbed and released through decomposition. On the one hand, the decomposition of the roots may result in different SOC inputs due to the different root system of broadleaf (or hardwood) trees and conifers (or softwood) (Strong & La Roi 1983). On the other hand, the input of SOC from litterfall can also be substantially different between deciduous forests and evergreen forests (De Deyn et al. 2008, Laganiere et al. 2010, Pérez-Cruzado et al. 2012).

Another factor that affect SOC stock is stand age. Stand age is a main contributor to SOC change dynamics. However, the relationship between stand age and SOC stock is not necessarily linear. There is a general agreement that SOC stock initially drops following afforestation – due to soil disturbance during the initial stage of land use conversion – and later gradually increases (Li et al. 2012).

These are major factors contributing to SOC change after afforestation. However, considerable uncertainties exist regarding the impact of afforestation on SOC, related to both the original land use and tree species. In terms of the original land use, Poeplau et al. (2011) and Shi et al. (2013) found a decrease in SOC when grassland is reforested, while Laganiere et al. (2010) and Don et al. (2011) reported an increase. Guo & Gifford (2002), Paul et al. (2002), and Bárcena et al. (2014) reported a general decrease in SOC when pastures are reforested. Poeplau et al. (2011), Guo & Gifford (2002) and Laganiere et al. (2010) found an increase in SOC when cropland is reforested. As for tree species, many studies reported higher SOC accumulation with deciduous or broadleaf afforestation (Paul et al. 2002, Laganiere et al. 2010, Bárcena et al. 2014, Liu et al. 2017), whereas a decrease of SOC stock was found for conifer afforestation (Guo & Gifford 2002, Paul et al. 2002, Berthrong et al. 2009). However, hardwoods are usually deciduous in temperate and boreal latitudes, but evergreen in the tropics and subtropics. How the SOC dynamics differ between deciduous hardwood and evergreen hardwood is less understood.

Such gaps in our understanding are likely to arise because of differences in soil types, precipitation, and climatic conditions, but also due to research design, as follows: (i) The soil depth where the carbon is measured. Some studies measure the carbon only at the top layer (0-10 cm or 0-20 cm), some at a much broader layer of 0-40 cm, and some compare across different layers (0-20, 20-40, 40-60, or 0-30, 30-60 cm). These methodological differences make comparison difficult. Analyses with comparison from deeper soil layers are still limited at a global scale (Bárcena et al. 2014, Liu et al. 2017). Ignoring the SOC changes at deeper soil layers may result in under estimating the total SOC storage. (ii) The age of the stand (Jobbágy & Jackson 2000, Paul et al. 2002, Eclesia et al. 2012, Xiong et al. 2014). Stand age is a main influencing factor of SOC dynamics after afforestation (Paul et al. 2002, Bárcena et al. 2014, Deng et al. 2014ab, Laganiere et al. 2010). The interactions between stand age and previous land use, plant types, or climatic conditions changes the effects of afforestation on SOC change dynamics (Jobbágy & Jackson 2000). For example, Eclesia et al. 2012 argued that stand age compensated for SOC losses in humid sites to some extent. (iii) The classification of tree species. Previous studies usually divide plants into hardwood and softwood (Paul et al. 2002, Li et al. 2012) or conifers and deciduous (Bárcena et al. 2014, Morris et al. 2007). However, such categorization does not appropriately account for the differences among deciduous hardwood and evergreen softwood or deciduous softwood (e.g. *Larix*) and evergreen hardwood (e.g. *Eucalyptus*). Moreover, overlaps may occur because species in genera such as *Larix* could be considered both conifers and deciduous and species in *Eucalyptus* could be viewed as broadleaf and evergreen.

Furthermore, previous studies primarily investigate the influences of the main contributing factors, such as previous land use, plant species, plant age, and climatic conditions on SOC stocks and change dynamics individually, with little consideration for the relationship and interactions among different factors (Guo & Gifford 2002, Paul et al. 2002, Laganiere et al. 2010, Li et al. 2012).

The present study aims to address these problems by assessing the impact of stand age on the change of SOC storage after afforestation, considering the effects of influencing factors: previous land use, plant types, temperature and precipitation in different soil layers. In our analysis, we assess the impact of stand age on the SOC dynamics by (i) reviewing C sequestration change at soil-depths 0-20, 20-40, 40-60 cm, while (ii) considering previous land use, plantation type, temperature, precipitation, and (iii) dividing plants in three categories: deciduous hardwood, evergreen softwood and evergreen hardwood. Usually only two categories (hardwood and softwood or deciduous and evergreen) are considered, and the advantages of three categories are (i) someoverlaps can be avoided, (ii) there will be fewer variations among species, (iii) further exploration of SOC dynamics under different tree features can be explored. Our findings contribute to a better knowledge of the mechanisms of SOC stock dynamic after afforestation, and help devise better carbon sequestration strategies.

Materials and methods

Data sources and compilation

The reviewed academic articles included in this quantitative review were retrieved by searching Google Scholar and the Web of Science with the keywords “afforestation” and “soil organic carbon” (cut-off date: 1st June 2018). The following criteria were required to include a study in this research. First,the study had to include at least three C stock data at different depths, so that we could extrapolate the missing values (see below). Also, the deepest layer with reported C value should be close to or deeper than 60 cm because the 0-60 cm layer contains 70%-80% of the SOC stocks found in the first-meter, which is more strongly affected by land use change (Jobbágy & Jackson 2000, Kukal & Bawa 2014).

Second, the study had to include a description of the land use history, at least information of landuse beforeafforestation, and report the initial SOC stocks before afforestation (or afforestation less than 5 years) or the SOC stocks of nearby non-forested sites. Reforestation and afforestation are viewed as the same silvicultural process in this studysince the difference is usually only the length of time during which the land was without forest (IPCC 2007). Third, papers had to statethe tree species andstand age. We only collected data from afforestation sites with single (not mixed) species to avoid the interactiveeffects of different species (Stockmann et al. 2013).

The final dataset comes from 90 peer-reviewed academic articles published between 1990 and 2018, and consists of 261 sites, including 261 topsoils (0-20 cm) and a large number of subsoils (168 from 20-40 cm and 115 from 40-60 cm). In total we obtained 544 datapoints, among which 332 were original data, and 212 were standardized or extrapolated using a polynomial trendline (see below). Apart from SOC data, for each site we recorded all geographical and climatic information, such as latitude, longitude, mean annual temperature (MAT) and mean annual precipitation (MAP) (Table S2, Supporting Information). When temperature or precipitation data were not reported, we obtained values using records from nearby weather stations using http://www.weatherbase.com (Poeplau et al. 2011). Soil taxonomic order was not used in this study because soil texture was not reported in most studies reviewed here. Figure 2 shows the geographic distribution of the study sites.

Sites were divided into groups, as follows: MAT group: ≤10, 10.01-15, 15.01-20, 20.01+ °C; MAP group: ≤500, 500.01-1,000, 1,000.01-1,500, 1,500.01+ mm; stand age group: 0-10, 11-20, 21-30, 31+ years. Previous land uses were classified as cropland and grassland. Plant types were classified into deciduous hardwood, evergreen hardwood and evergreen softwood.

Soil depth standardization and extrapolation

Two sets of data reported in the literature reviewed did not conform with our classification, and we had to estimate the missing data. First, in 151 cases we had to standardize soil depths, because the intervals of soil depths vary among studies. For example, some studies measure the carbon at soil depth of 5 cm, 10 cm, 30 cm and 60 cm, some at much broader layers of 0-30 cm, 0-60 cm and 0-100 cm. In such cases, SOC data were converted from different depths, e.g. 0-5 cm, 5-10 cm, 10-30 cm and 30-60 cm etc., into standard depths 0-20 cm, 20-40 cm, 40-60 cm. Second, in 61 caseswehad to estimate SOC data for deeper layers, for instance, we estimated the data of 40-60 cm layer if we had 0-10 cm, 10-20 cm, and 30-40 cm. 29% of our datapoints are estimated.

The application of such extrapolations needs to fulfill two requirements. First, we only extrapolated data if the studies reviewed reported at least three SOC values. In case the deepest soil layer was shallower than 60 cm, the deeper SOC value should be at least 40 cm deep. The accuracy of this standardization and/or extrapolation in estimating SOC stock was assessed by comparing SOC data predicted by this standardization and/or extrapolation with actual data in the same site. SOC stock predicted by standardization and/or extrapolation was not significantly different to actual data ($P = 0.92$, $n = 368$). We were therefore confident in applying standardization and/or extrapolation to estimate SOC data in this study. Detailed explanation of the standardization and extrapolation method are described in Supporting Information.

SOC estimates

Units of soil carbon or soil organic matter stocks used in the literature, such as "kg m^{-2}", "g m^{-2}", "kg ha^{-1}" and "t ha^{-1}", were transformed to "Mg ha^{-1}". If the samples only reported soil organic matter (SOM) content, the SOC values were calculated using the relation between SOM and SOC with the following eq. 2 (Mann 1986):

$$SOC = SOM \times 0.58$$

Bulk density (BD) is necessary to calculate SOC stocks, and can also affect the sequestration rate (Don et al. 2011, Deng et al. 2014b). To our knowledge no soil bulk density estimation model has

Figure 2 Location of the study sites

been adjusted for soil depth, which may result in an underestimation of SOC stock changes after afforestation (Post & Kwon 2000, Callesen et al. 2003, Don et al. 2011). The observations with missing BD account for 6% of total and 76% of them were located in China, thus BD values were estimated using the equation developed by Wu et al. (2003), whose study is based on the soils of China:

$$BD = -0.1229\ \ln(SOC) + 1.2901 \quad (\text{for } SOC < 6\%)$$

$$BD = 1.3774e^{-0.0413 \cdot SOC} \quad (\text{for } SOC > 6\%)$$

If there was no direct report of SOC stocks in the study, we used the percentage of SOC content concentration or C accumulation, bulk density and sampling depth to calculate SOC storage. As time plays an important role in SOC accumulation, we calculated the SOC sequestration rate, which allows for a comparison across studies at different time scales (Xiong et al. 2014). The SOC stock, SOC stock change ΔCs, and ΔCs rate are calculated using the following equations (Deng et al. 2014b):

$$Cs = (SOC \cdot BD \cdot D)/10$$

$$\Delta Cs = Cse - Csc$$

$$\Delta Cs\ rate = \Delta Cs/A$$

$$\Delta Cs\ rate_{[0\text{-}60\ cm]} = \Delta Cs\ rate_{[0\text{-}20\ cm]} + \Delta Cs\ rate_{[20\text{-}40\ cm]} + \Delta Cs\ rate_{[40\text{-}60\ cm]}$$

where: Cs - SOC stock (Mgha^{-1}), ΔCs rate - the SOC sequestration rate (Mg ha^{-1} yr^{-1}), SOC - SOC concentration (g kg^{-1}), BD - soil bulk density (g cm^{-3}), D - soil depth (cm), Cse - the mean SOC in afforested sites (Mg ha^{-1}), Csc - the mean SOC in the adjacent compared sites (Mg ha^{-1}), and A - stand age (years).

Statistical analysis

Many studies only reported mean values for treatment and control plots without reporting standard deviations or standard error values. In order to include as many studies as possible, we conduct an unweighted quantitative review (e.g. Guo & Gifford 2002, Song et al. 2014). The mean value for each categorical subdivision is calculated with a bias-corrected 95% confidence interval (CI).

We performed a two-way ANOVA to test the main effects and interactions between age groups and previous land use, plant functional types, MAT, and MAP on SOC sequestration rates at different soil layers. We evaluated differences at the 0.05 significance level. We used Pearson's correlation analysis to study the relationships among SOC sequestration rates following afforestation and stand age (SA), MAT, MAP, and initial SOC stocks of all data. We used linear regression analysis to develop the functions of the SOC sequestration potential after afforestation. All statistical analyses were performed using SPSS (version 24 SPSS Inc, Chicago, IL, USA).

Results

Effect of previous land use on SOC storage changes

Previous land uses have significant effects on post-afforestation SOC sequestration ratesin the topsoil layer (0-20 cm) (Figure 3a, Table 1). In general, afforestation on cropland experiences a quicker and greater SOC increase than afforestation on grassland. In addition, the differences in the sequestration rate between converted cropland and grasslandare minimal after 30 years of afforestation. At the top layer, both kinds of land use show decreased SOC in the first 10 years and increased SOC after 30 years (Figure 3a). However, significant differences occurduring the 11 to 30

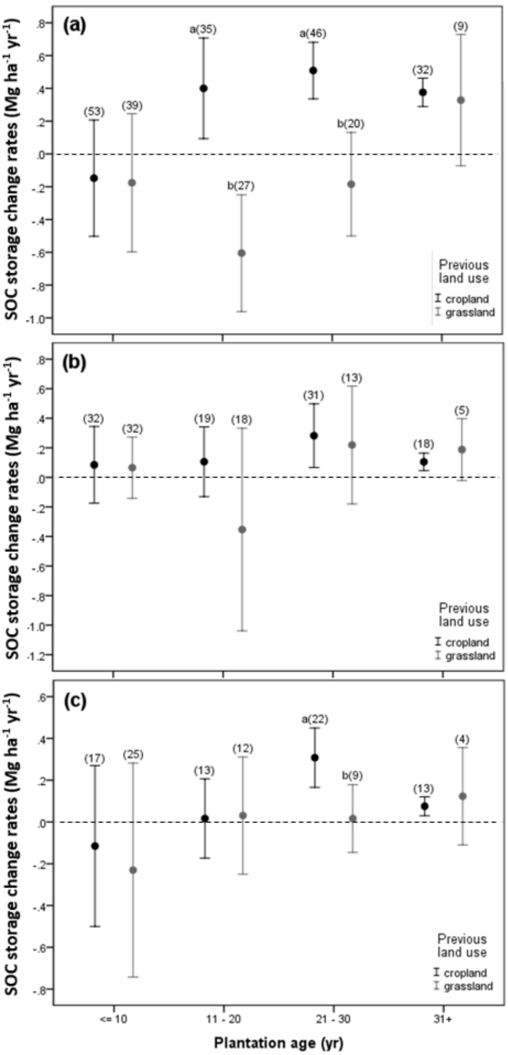

Figure 3 SOC storage change rates in the different stand age groups against different previous land use types at soil depths of 0-20 cm (a), 20-40 cm (b), and 40-60 cm (c). Note. A horizontal line at the zero level indicates no changes of SOC storage. Dots with error bars denote the overall SOC storage change rate and the 95% CI. The number of observations is indicated in parentheses. A different letter at the top of the bars indicates a difference significant at the $P < 0.05$ level.

years of afforestation with SOC sequestration of afforested cropland significantly higher than that of grassland. In the 20-40 cm soil layer (Figure 3b), afforestation on both cropland and grassland show an increase of SOC in the first 10 years, which is different from the upper and deeper soil layers. Over the entire period studied, the SOC sequestration rate of converted cropland peaksbetween 21 and 30 years after afforestation, while for converted grassland, there is generally an upward trend after 10 years of afforestation. Eventually, afforested grassland shows slightly greater SOC sequestration than that of cropland in subsoil layers (20-60 cm) after 30 years of afforestation (Figure 3).

The whole soil depth of 0–60 cm experiences an initial loss and then an increase in C stock (Table 1). However, for grassland, the temporal patterns of SOC sequestration lags behindthat of cropland, with SOC decreasing during the second decade, and increasing after three decades for the whole soil depth (Table 1). Moreover, during the third decade, the subsoil of converted grassland accumulates C, although there is still a loss of C in the topsoil (Table 1).

Effect of plant types on SOC storage

The dynamics of SOC sequestration are remarkably different among plant types at soil layers of 0–20 cm and 20–40 cm (Figure 4). With each plant type, the sequestration capacity varies among soil layers and with time (Figure 4). For the soil layer of 0-20 cm, there is a general upward trend, although this increase is much more pronounced for evergreen hardwood up to 30 years (Figure 4a). Deciduous hardwoods hows a continuous increase of SOC stocks during the whole period. Evergreen hardwood shows an upward trend of SOC sequestration capacity and it surpasses that of deciduous hardwood after two decades of afforestation. Evergreen softwoods show a very low sequestration ability throughout the study period (Figure 4a). For the 20-40 cm soil layer, the pattern of SOC dynamics for two of

Table 1 SOC storage change rates (0–60 cm, Mg ha^{-1} yr^{-1}) of different age groups against various previous land uses and plant types

PA (years)	Previous land uses		Plant types		
	Cropland	Grassland	Deciduous hardwoods	Evergreen hardwoods	Evergreen softwoods
≤10	-0.19 (±0.78)^{b}	-0.34 (±1.04)^{b}	0.20 (±1.71)^{a}	-0.24 (±0.71)^{b}	-1.07 (±1.74)^{c}
11-20	0.53 (±0.73)^{ab}	-0.93 (±1.31)^{b}	0.90 (±1.06)^{a}	-0.29 (±1.91)^{b}	-0.77 (±1.08)^{bc}
21-30	1.10 (±0.54)^{a}	0.06 (±0.84)^{ab}	0.65 (±0.48)^{ab}	2.55 (±1.29)^{a}	0.57 (±0.99)^{b}
31+	0.57 (±0.18)^{a}	0.64 (±0.83)^{a}	0.72 (±0.24)^{ab}	1.40 (±0.81)^{a}	0.39 (±0.24)^{b}

Note. Abbreviations: PA - stand age in years. A different letter at the right top of the figures indicates a difference significant at the $P < 0.05$ level.

the three plant types were similar to that of the top layer; evergreen hardwoods experienced an opposite patternin the first two decades following afforestation compared with the topsoil layer (Figure 4b). At the soil layer of 40-60 cm, all the plant types showed a decrease in SOC stocks in the first 10 years (Figure 4c). For the older plantations in particular the number of observations was very low, so the results can only be considered tentative.

Regarding SOC dynamics of total soil depth against different plant types, deciduous hardwoods and evergreen softwoods follow the same pattern as that of the top layer, but evergreen hardwoods showed a gain in SOC a decade later (Figure 4). For deciduous hardwoods, SOC increased during the entire time, with the SOC sequestration rate varying from 0.2 to 0.9 Mg ha^{-1} yr^{-1} in the whole soil layer. The patterns of SOC change dynamics for ev-

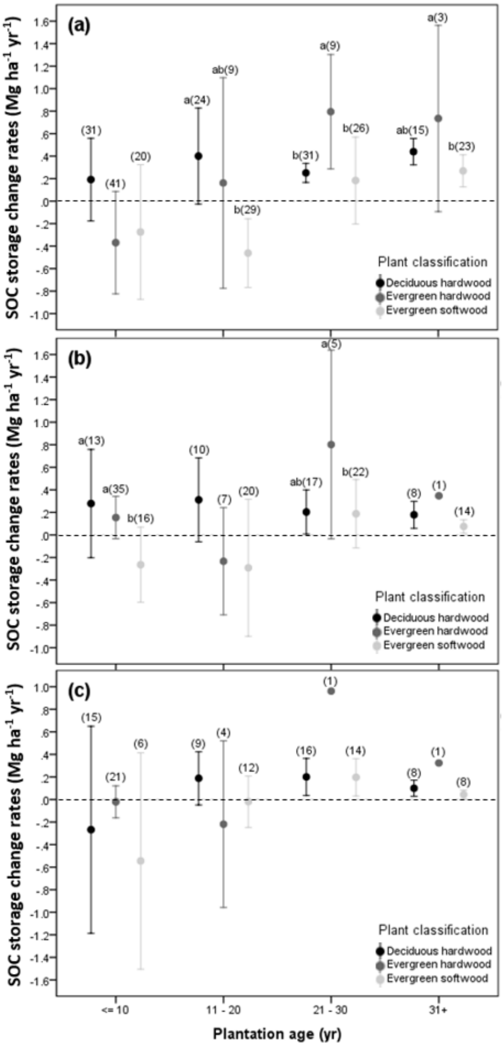

Figure 4

SOC storage change rates in the different stand age groups against different plant functional types at soil depths of 0-20 cm (a), 20-40 cm (b), and 40-60 cm (c).

Note. A horizontal line at the zero level indicates no changes of SOC storage. Dots with error bars denote the overall SOC storage change rate and the 95% CI. The number of observations is indicated in parentheses. A different letter at the top of the bars indicates a difference significant at the $P < 0.05$ level.

ergreen hardwoods and evergreen softwoods are similar at soil depths of 0-60 cm, whereas evergreen softwoods initially show a loss of SOC at greater rates and evergreen hardwoods display much stronger SOC sequestration ability 20 years after afforestation (Table 1).

Effect of temperature on SOC storage changes

Temperature conditions significantly affect the magnitudes and directions of SOC stock changes (Figure 5, Table 2). In the 0-20 cm soil layer, afforested land under 10°C and above 20°C report greater SOC sequestration rates than temperate climate between 10°C and 20°C. In the 20-40 cm soil layer, the SOC sequestration rates in warmer climate (>15°C) tend to increase faster than in the upper soil layer, and are significantly greater than that of the former MAT groups (<15°C). However, in the soil depth of 40-60 cm, the middle temperature groups show higher SOC sequestration abilities. A decrease in SOC contents is found in areas with temperature >20°C for the first time (Figure 5). Comparing the same MAT group in different soil layers, it is interesting to find that extreme climates (with temperature lower than 10°C or higher than 20°C) generally show a decreasing trend of SOC sequestration rate from topsoil to subsoil. However, temperate climate shows an increasing trend of SOC sequestration rates with soil depth (Figure 5).

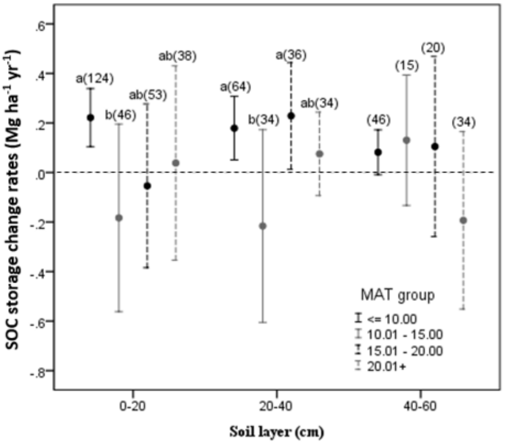

Figure 5 SOC storage change rates against different temperature groups at soil depths of 0-20 cm, 20-40 cm, and 40-60 cm.

Note. A horizontal line at the zero level indicates no changes of SOC storage. Dots with error bars denote the overall SOC storage change rate and the 95% CI. The number of observations is indicated in parentheses. A different letter at the top of the bars indicates a difference significant at the $P < 0.05$ level.

When comparing the SOC dynamics of the top and whole soil layers, the patterns are similar under temperature <15°C (Figure 5, Table 2). However, an opposite trend is found at higher temperatures (Table 2).

Effect of precipitation on SOC storage changes

SOC varies at significantly different rates under different precipitation levels (Figure 6, Table 2 and 3). For the soil layer from 0 to 20 cm, afforested land with a precipitation of 500.1-1,000 mm show a significant increase in SOC contents, while SOC drops with precip-

Table 2 SOC storage change rates (0–60 cm, Mg ha^{-1} yr^{-1}) against different climatic conditions

MAT (°C)	≤ 10	10.01–15	15.01–20	20.01+
ΔCs rate	0.48 (±0.40)^{a}	-0.27 (±1.06)^{b}	0.28 (±0.95)^{a}	-0.07 (±0.93)^{ab}
MAP (mm)	≤ 500	500.01–1,000	1,000.01–1,500	1,500.01+
ΔCs rate	0.38 (±0.58)^{a}	0.54 (±0.42)^{a}	-0.08 (±0.57)^{b}	-0.89 (±1.56)^{b}

Note. Abbreviations: MAT - mean annual temperature, MAP - mean annual precipitation, ΔCs rate - SOC storage change rate.

itation above 1000 mm.For the soil layer between 20-40 cm, a significant decrease in SOC contents is found in areas with rainfall higher than 1,500 mm, whereas afforested land with precipitation <1,500 mm report a significantly greater SOC sequestration capacity. While comparing the same precipitation group in different soil layers, it is interesting to find that groups with lower MAP (below 1000 mm) generally show higher SOC sequestration rates in upper soil layers (0-40 cm). However, the SOC sequestration rate increased with depth for the precipitation group above 1500 mm, with this group displaying the greatest SOC sequestration ability at the soil layer of 40-60 cm.

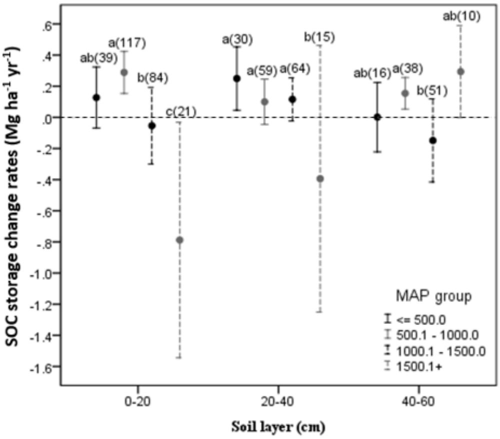

Figure 6 SOC storage change rates against different precipitation groups at soil depths of 0-20, 20-40, and 40-60 cm.

Note. A horizontal line at the zero level indicates no changes of SOC storage. Dots with error bars denote the overall SOC storage change rate and the 95% CI. The number of observations is indicated in parentheses. A different letter at the top of the bars indicates a difference significant at the $P < 0.05$ level.

Precipitation conditions influence the SOC dynamics in a consistent manner at thewhole soil depth (Table 2). The SOC sequestration increases with increasing precipitation in the first two precipitation groups; however, the last two groups report decreasing SOC stocks and a greater rate reduction wasfound with higher precipitation (Table 2).

The influencing factors have more significant effects on the SOC sequestration rate of the topsoil layer than subsoil layers (Table 3). Previous land use and stand age have the most significant influences and their interactions

Table 3 Two-way ANOVA results of SOC storage change rates in the 0-60 cm soil against different previous land uses, plant types, age groups, mean annual temperature, and mean annual precipitation following afforestation

Source	*DF*	0-20 cm		20-40 cm		40-60 cm		Total	
		F	Sig.	*F*	Sig.	*F*	Sig.	*F*	Sig.
PLU	1	16.081	0.000***	2.094	0.150	2.052	0.155	19.422	0.000***
PT	2	4.406	0.013*	3.275	0.040*	0.049	0.952	5.73	0.003**
AG	3	4.343	0.005**	2.000	0.116	2.175	0.095	6.858	0.000***
MAT	3	2.238	0.084	3.023	0.031*	1.404	0.246	3.793	0.010**
MAP	3	8.07	0.000***	2.976	0.033*	2.023	0.115	8.371	0.000***
PLU × AG	3	3.975	0.009**	0.956	0.415	0.263	0.852	4.042	0.007**
PT × AG	6	1.969	0.071	1.238	0.290	0.558	0.763	2.594	0.017*
MAT × AG	9	2.757	0.004**	1.782	0.076	1.020	0.430	4.611	0.000**
MAP × AG	9	2.022	0.038*	3.256	0.002**	1.273	0.266	2.672	0.005**

Note. Abbreviations: PLU - previous land uses, PT - plant types, AG - age groups, MAT - mean annual temperature, and MAP - mean annual precipitation.

also significantly affect SOC dynamics. Precipitation has a greater influence than temperature on SOC sequestration.

Pearson correlation analysis of the change rates for SOC storage shows that the total SOC sequestration rate is positively correlated with plant ages, and the correlation is significant at the topsoil layers. A significantly negative correlation was found with temperature, precipitation, and the initial SOC stocks (Table 4). The correlation is also significantly negative with the initial SOC stocks and precipitation at the second layer, and with temperature at the third layer. For individual age groups, relationships also vary at different soil layers. In the first two decades after afforestation, the relationships between the SOC sequestration rate and temperature, precipitation or initial SOC stocks were always negative, whereas some positive correlations are found after 20 years. The deeper soils show more such positive relationships than the upper soils. However, the relationships between the SOC sequestration rate and stand agesare mostly negative after the first decade of afforestation (Table 4). Functions of the SOC sequestration potential are developed by linear regression analysis (Table 5). The functions developed for the soil layers of 0-20 cm and 20-40 cm can significantly predict the SOC sequestration potential ($P < 0.001$), while the regression for soil layer of 40-60 cm is not statistically significant.

Discussion

Effects of stand ages and soil depths on SOC storage change

There is agreement that previous land use has significant effects on SOC dynamics (Table 3), especially in the upper soil layer (Bárcena et al. 2014, Laganiere et al. 2010, Paul et al. 2002). This is because land use changes

Table 4 Pearson correlation of SOC storage change rates with stand age, mean annual temperature, mean annual precipitation, and initial SOC stocks in different age groups

Soil layers (cm)	AG	PA	MAT	MAP	Initial SOC stocks	*N*
0-20	Total	0.156*	-0.127*	-0.252**	-0.296**	261
	0-10	0.237*	-0.125	-0.294**	-0.269**	92
	10.1-20	-0.026	-0.147	-0.210	-0.404**	62
	20.1-30	-0.131	0.121	-0.061	-0.370**	66
	>30	-0.152	0.128	-0.032	-0.120	41
20-40	Total	0.037	-0.060	-0.172*	-0.413**	168
	0-10	0.126	-0.054	-0.027	-0.272*	64
	10.1-20	0.002	-0.158	-0.338*	-0.608**	37
	20.1-30	-0.079	0.120	0.139	-0.227	44
	>30	-0.354	0.242	0.064	0.391	23
40-60	Total	0.120	-0.185*	-0.075	-0.164	115
	0-10	0.427**	-0.222	-0.143	-0.246	42
	10.1-20	-0.095	-0.352	-0.127	-0.133	25
	20.1-30	-0.266	0.482**	0.433*	0.393*	31
	>30	-0.353	0.431	0.296	-0.305	17

Note. Abbreviations: SA - stand age, AG - age groups, MAT - mean annual temperature, MAP - mean annual precipitation. The level of significance: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

Table 5 Linear regression to develop the functions of the SOC sequestration potential after afforestation

Soil layer (cm)	Equation	R^2	Sig. (*P*)	*N*
0-20	$\Delta Cs = - 4.535 - 0.002 \cdot P + 0.285 \cdot A - 0.097 \cdot I + 8.924 \cdot C + 8.631 \cdot EH$	0.295	0.000***	261
20-40	$\Delta Cs = 7.815 - 0.03 \cdot T + 0.058 \cdot A - 0.288 \cdot I - 0.24 \cdot C - 1.71 \cdot ES$	0.172	0.000***	168
40-60	$\Delta Cs = 0.468 + 0.002 \cdot P + 0.041 \cdot A - 0.087 \cdot I + 2.081 \cdot C - 1.564 \cdot EH - 1.728 \cdot ES$	0.112	0.042*	115

Note. Abbreviations: ΔCs is SOC stock change following afforestation, PLU - previous land uses, PT - plant types, T (°C) - average annual temperature, P (mm) - average annual precipitation, A (year) - plantation age, I (Mg/ha) initial SOC stock. The level of significance: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. None of the regression models presents collinearity of the dependent variables (corresponding VIF values ΔCs0-20: P - 1.963, A - 1.087, I - 1.734, C - 1.623, EH – 1.792, ΔCs20-40: T - 1.191, A - 1.176, I - 1.151, C - 1.216, ES – 1.132, ΔCs20-40: P - 1.37, A - 1.234, I - 1.271, C - 1.313, EH - 1.839, ES - 1.496).

and other perturbations mainly disturb the top layer (Veldkamp et al. 2003). Generally, afforestation ofcroplands has a positive effect on SOC stocks (Liu et al. 2017, Bárcena et al. 2014, Laganiere et al. 2010), whereas it is negative (Bárcena et al. 2014, Laganiere et al. 2010, Paul et al. 2002) or unchanged (Li et al. 2012) for afforestation on grassland. The difference is likely due to the low initial amount of C in cropland soil compared to grassland, and C losses owing to soil disturbance, such as tillage (Laganiere et al. 2010). One explanation is that a higher initial SOC stock is more susceptible to loss by disturbances during seedling (Shi et al. 2013). Another is that higher SOC sequestration rates may result from slower rates of decomposition in more nutrient-poor soils (Vesterdal et al. 2002). The continuous C loss that we found in converted grassland the first three decades at the top soil layers, but only during the first decade for converted cropland, was probably because grassland usually maintains a permanent vegetation cover and high density of fine roots, so it takes longer to match the ongoing decomposition of C for converted grassland (the loss of C happens mainly in the top soil layer rather than subsoil, because the grass roots are shallow). On the other hand, although SOC increases on afforested cropland, it seems to peak earlier. Our analysis shows that afforestation of grassland likelysequesters more C in the long term (Figure 3).

Our synthesis also shows that SOC stocks of the top 60 cm soil layer begin to increase 10 years earlier than that of the top 20 cm soil layer of converted grassland (Table 1). This is probably because roots of replanted trees decomposeand transform into the SOC stocks of subsoil layers (20-60 cm) after two decades of afforestation. Laganiere et al. (2010) also argued the gain of SOC produced by deeper root system of trees is much greater than that of herbaceous plants, so the SOC increase of subsoil layers is more than SOC loss of topsoil. Our results also show an initial SOC loss in afforested cropland (Table 1), which is consistent with results of Deng & Shangguan (2017), possibly a result of site preparation resulting in accelerated mineralization of organic matter and the immediate cessation of agricultural carbon inputs, such as crop residues or manure (Poeplau et al. 2011, Paul et al. 2002). Moreover, in the topsoil layer, the effects of previous land use are significantly different during the second and third decades, indicating that after 30 years of afforestation, the patterns of SOC dynamics are similar for converted cropland and grassland, and both reported an increase in SOC contents (Figure 3a, Table 1). This isconsistent with Paul et al. (2002) and Bárcena et al. (2014). Shi et al. (2013) found negative SOC change rates in each mineral soil depth (0-100 cm with interval of 20 cm) after afforestation on grassland, which is probably because they didn't consider stand age.

Effects of plant types and soil depth on SOC storage change

The tree species planted can influence the magnitude and dynamics of SOC stocks because of the variability in their C inputs (primary productivity and belowground carbon allocation) and potential losses (soil respiration, volatilization of organic compounds, fire and leaching) (De Deyn et al. 2008, Laganiere et al. 2010, Pérez-Cruzado et al. 2012). Many studies report that the highest SOC accumulation occurs in afforestation with deciduous plants (e.g. Paul et al. 2002, Laganiere et al. 2010, Bárcena et al. 2014, Liu et al. 2017), and the effects are larger in thetopsoil layer (Bárcena et al. 2014). This is because the SOM input from litterfall can be higher in deciduous forests than evergreen forests since deciduous trees completely lose their foliage during winter or the dry season (Liu et al. 2017). However, we find that evergreen trees sequester more soil C in later years after afforestation by classifying plant types as deciduous hardwood, evergreen hardwood, and evergreen softwood. Deciduous softwood was not included because of insufficient data. Liu et al. (2017) have a similar classification of plants in their dataset, whereas their results show deciduous hardwood had the greatest SOC sequestration abilities, followed by conifers and evergreen hardwood. This difference from our findings may be attributed to the small scale of arid and semi-arid regions studied by Liu et al. (2017) and also the significant interaction of stand age with the SOC accumulation effects of various plants (Table 3). Deciduous hardwood sequesters more SOC in the first two decades, but evergreen hardwood sequesters more after the first two decades (Figure 4, Table 1). It is probably because mature evergreen hardwoods not only have more litter fall to contribute the C inputs into soils but also maintain a denser foliage during the whole year to reduce the negative effects of high temperature and precipitation on SOC sequestration. Paul et al. (2002) also mentioned the differences of Net Primary Productivity(NPP) are smaller and the advantage of the easily decomposed substrate of broadleaf is not obvious in the initial years of afforestation, the differences become more significant in the later years (Figure 4a).

Pérez-Cruzado et al. (2012) reported a higher loss of SOC in evergreen soft wood soils than in evergreen hardwood soils, which is consistent with our study (Table 1), because of the lower litter decomposition rate and belowground litter input of evergreen softwood. Furthermore, root distributions affected the vertical placement of C in the soil (Jobbágy and Jackson 2000). Deciduous hardwood and evergreen hardwood show greater SOC sequestration abilities than evergreen softwood in deeper soil layers over longer periods (Figure 4b and c, Table 1), possibly owing to a higher belowground biomass generated by the larger and more deeply anchored root systems of hardwood trees (Strong & La Roi 1983, Jobbágy and Jackson 2000), and such differences are greater with increasing stand age (Figure 4). However, it is uncertain whether above - or belowground litter input contributes the most to SOC stocks. Therefore, the processes related to C input and output of plant types should be identified in future work for a better understanding of SOC sequestration by plants (Vesterdal et al. 2013).

Effects of temperature and precipitation on SOC storage change for various stand ages and soil depths

Post & Kwon (2000), Paul et al. (2002) and Laganiere et al. (2010) discuss the influence of climatic zones on SOC dynamics, and find that SOC contents drops in cool temperate zones, and increases in subtropical wet zones, with the highest gains found in regions with high temperature and precipitation.This is becausetrees grow fast and produce more forest litter in tropical and subtropical regions, which can be a source of SOC input (Post et al. 1982). However, Zhang et al. (2010) found lower rate of SOC sequestration at higher temperature and precipitation, which may be attributed to the rapid decomposition of SOC in tropical soils with higher temperature (Post et al. 1982). Furthermore, the contradictions may be the result of different effects of temperature or precipitation on the SOC sequestration rate during different time periods (Table 4). The present study suggests both effects of temperature and precipitation on SOC sequestration are significantly influenced by stand again the topsoil (Table 3). Specifically, in the first two decades of afforestation, both temperature and precipitation have negative effects on SOC accumulation capacities, whereas positive correlations are detected after 20 years (Table 4), which is likely because the gain in SOC promoted by biomass inputs of older plants exceeds the increase of decomposition of SOC under warmer and more humid climate (Xiong et al. 2014).

Eclesia et al. (2012) also argued the SOC decreases were counter balanced by the effect of stand age, as plantations increased their SOC stocks with age in humid areas. However, at the topsoil layer, higher precipitations reduce the SOC sequestration rate regardless of stand age (Table 4). One probable reason is that soil erosion and leaching effects caused by high rainfall contribute to the SOC loss of the topsoil layers (Jobbágy & Jackson 2000; Gao et al. 2013). In addition, SOC stocks were significantly reduced under high MAP (>1500 mm) at the topsoil, but increased in the deep soil layer (40-60 cm) (Figure 6). This may be the result of more organic matter leaching into deeper layers, and soil erosion in the top layers introduced by higher precipitation (Jobbágy & Jackson 2000, Gao et al. 2013).

Uncertainties in the analysis

Not all studies we include report the information we need for this quantitative review. In order to include as many studies as possible, some missing values are extrapolated or calculated. We apply standardization and extrapolation to estimate the missing values within each specific site (see Supporting Information for further explanation).We extrapolate 19.7% of subsoil data, which may add inaccuracy to our conclusions. The accuracy of each site's polynomial trendlines (order 2) with the observed data is high ($P = 0.92$, $n = 368$), so we are confident that our data are sufficiently accurate. We suggest that future study include more observations of SOC data from subsoil layers. The uneven distribution of various plant types may also result in uncertainties. Finally, some inaccuracies may result from using SOM values to estimate SOC values, and from using estimated BD values to estimate SOC values. However, only 9% of the SOC values are calculated based on SOM value and estimated BD values in this study. We trust that the results we obtain are accurate. One limitation of this study is that 95% of the studies we reviewed had no long-term (more than 50 years) observations of the SOC stock change after afforestation.

Conclusions

The results of this study show stand age has significant effects on SOC stock dynamics under different conditions, especially at the topsoil layer (0-20 cm). Previous land use significantly influences SOC accumulation, whereas the largest differences exist in the middle stand age (10-30 years), indicating that the effects of previous land use are limited after three decades of afforestation. Besides, afforestation on grassland seems to sequester more C than that of cropland in the long term. Plant types also significantly affected SOC dynamics, with deciduous hardwood reporting a continuous increase in SOC contents at soil depths (0–60 cm) during the whole afforestation period. The accumulation of SOC lags behind nearly two decades for evergreen hardwood and evergreen softwood. Higher SOC accumulation rates are observed under evergreen hardwood, and no significant differences are found between deciduous hardwood and evergreen softwood for forests older than 20 years. SOC dynamics differ significantly under different temperature or precipitation conditions, and age plays a significant role in the upper soil layers. Generally, temperature and precipitation affected SOC accumulation negatively in the first two decades of afforestation; however, the effects become positive in later years.The initial higher SOC stocks did not play a major role in SOC sequestration. Lower SOC soils did not affect SOC sequestration after reforestation.

In this quantitative review, we emphasize that analysis of SOC dynamics should consider the temporal patterns of different influencing factors and soil depths, otherwise the results may result in inconsistent findings across studies. However, due to insufficient data available, we did not consider the effects of soil properties, including pH, clay content, soil types,the influence of plant density, and plant genera on the changing dynamics of SOC.

Acknowledgements

The work described in this paper has been fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (project no. 12305116).

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Supporting Information

The online version of the article includes Supporting Information:

Supp. Info. 1. Depth functions developed by Jobbagy & Jackson (2000)

Supp. Info. 2. Polynomial trendline (order 2)

Supp. Info. 3. Assessment of accuracy

Supp. Info. 4. References of the dataset