A systematic analysis and review of the impacts of afforestation on soil quality indicators as modified by climate zone, forest type and age

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Abstract

This global systematic analysis and review investigate the impacts of previous land use system, climate zone, forest type and forest age on soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP) stock, soil bulk density (BD) and pH at soil layers 0-20, 20-60 and 60-100 cm, following afforestation. Data came from 91 publications on SOC, TN and TP stock changes, covering different countries and climate zones. Overall, afforestation significantly increased SOC by 46%, 52% and 20 % at 0-20, 20-60 and 60-100 cm depths, respectively. It also significantly increased shallower TN stocks by 28% and 22% at 0-20 and 20-60 cm depths, respectively, but had no overall impacts on TP. Previous land use system had the largest influence on SOC, TN and TP stock changes, with greater accumulations on barren land compared to cropland and grassland. Climate zone influenced SOC, TN and TP stock changes, with greater accumulations for moist cool than other climate zones. Broadleaf forests were better than coniferous forests for increasing SOC, TN and TP stocks of the investigated soil profile (0-100 cm). Afforestation for <20 years accumulated SOC and TN stocks only at the soil surface (0-20 cm), whilst afforestation for >20 years accumulated SOC and TN stocks to 100 cm soil depth. Changes to SOC and TN stocks were positively correlated at depths down to 100 cm under all forest age groups, demonstrating that an increase TN could offset progressive N limitation, and maintains SOC accumulation as forests age. TP stock decreased significantly in topsoil (0-20

cm) for <20-year-old forest and did not change for >20-year-old forest, suggesting that it may become a limiting factor for carbon sequestration as forests age. Following afforestation, soil BD decreased alongside significant increases in SOC and TN stocks to 100 cm depth, but had no relationship with TP.

Keywords: Land use change, Climate, Soil organic carbon, Afforestation, Soil nitrogen, Soil phosphorus

1. Introduction

Land-use change is one of the major driving forces behind changes in soil organic carbon (SOC), so it could contribute to potential strategies for mitigating the consequences of climate change (Guo and Gifford, 2002; Hooker and Compton, 2003). Afforestation on non-forest lands has been suggested as a mitigation strategy, but its potential is uncertain due to poor predictions and data availability. Better assessments of SOC changes following afforestation could reduce the considerable uncertainty in estimating carbon sequestration and emissions in terrestrial ecosystems and provide empirical evidence for the development of climate change mitigation strategies to be used in forest management policy making. However, previous published regional/global assessment reviews (Berthrong et al., 2009; Bárcena et al., 2014; Shi et al., 2016; Liu et al., 2018) have mainly focused on soil depths limited to less than 30 cm. An increasing number of field studies suggest that SOC contents in the deeper soil profile (i.e. below 30 cm soil depth) are more sensitive to land use change compared to those near to the soil surface (Chang et al., 2012; Shi et al., 2013; Deng et al., 2014). Leaving out deep soil layers in predictions of SOC storage following afforestation represents a significant knowledge gap (Don et al., 2011), which could be addressed by a systematic analysis and review of available global data.

Other factors that have notable impacts on the dynamics of SOC stock and thereby, on its direction and magnitude following afforestation, are climate zone (e.g. tropical moist zone or tropical dry zone or cool temperature zone), forest type (e.g. broadleaf or coniferous tree), forest age and soil physical properties (e.g. soil bulk density and pH) (Berthrong et al., 2009; Laganiere et al., 2010; Shi et al., 2016). However, the changes in SOC following afforestation have been found inconsistent under different categories of each factor. For instance, Post & Kwon (2000) demonstrated that SOC in 0-50 cm soil depth after cropland was converted into forest accumulated at annual rates of 1.7 Mg ha^{-1} in subtropical and 0.6 Mg ha^{-1} in tropical climatic zones. The annual accumulation rate of SOC for the moist forest was also very different compared to that for dry forest (Post & Kwon, 2000; Silver et al., 2000). In a review, Deng et al. (2014) found that broadleaf forest (0.4 Mg ha^{-1} yr^{-1}) had a greater potential capacity to sequester carbon in soil than coniferous forest (0.0 Mg ha^{-1} yr^{-1}). According to Poeplau et al. (2011) and Bárcena et al. (2014), the magnitude of SOC changes following afforestation of different previous land use systems in northern Europe were significantly lower for $\leq$30-year-old forest compared to that >30-year-old forest. Bárcena et al. (2014) further reported that SOC stocks significantly decreased following afforestation of cropland in the first 30 years, but significantly increased thereafter. In Australia, the annual average rates of SOC accumulation at soil depth of 0-30 cm following afforestation of cropland were 0.01 and 0.20 Mg ha^{-1} for forest ages of 7 and 30 years, respectively (Paul et al., 2002).

Soil total nitrogen (TN) and total phosphorus (TP) are necessary macronutrients for plants so are important for the growth of forest as they are both necessary macronutrients for plants (Li et al., 2015; Deng et al., 2017). Additionally, they impact SOC sequestration by influencing the balance between carbon inputs and outputs (Li et al., 2015; Shi et al., 2016). Previous studies demonstrated that limitations in available soil TN and TP stocks can constrain the input rates of organic matter from net primary productivity (Goll et al., 2012; Cleveland et al., 2013). Moreover, the availability of nitrogen and phosphorus has a great impact on microbial processes in soils, and thereby influences the turnover of soil carbon (He et al., 2008; Strickland et al., 2010). Therefore, it is necessary to quantify soil nutrients (i.e. soil TN and TP) following the afforestation of previous land use systems and explore the factors controlling their dynamics.

Understanding the impact of previous land use systems and other controlling factors on the dynamics of SOC, TN, TP and other soil quality indicators is of great importance for forest management and climate change mitigation (Jobbágy and Jackson, 2001; Shi et al., 2016). Although previous synthetic reviews on this topic have been valuable, they were not able to fully address the dynamics of SOC, TN and TP stocks at deeper soil layers (e.g. >30 cm), following afforestation. We addressed this by conducting a global systematic analysis and review, focusing on the impacts of previous land use system on the dynamics of SOC, TN and TP and other selected soil quality indicators (i.e. soil bulk density and pH) at different soil layers between 0 and 100 cm, following afforestation. Likewise, we examined the influences of climatic zone, forest type and forest age on these soil quality indicators, following afforestation. We further explored the relationships between the changes in SOC, TN and TP stocks in both topsoil and subsoil layers. The specific hypotheses we critically evaluated were as follows: a) previous land use systems have significant impacts on SOC, TN and TP stocks, following afforestation; b) changes in SOC, TN and TP stocks are significantly different between climate zones, forest types and forest ages; c) changes in SOC relate significantly to changes in TN and TP stocks, following afforestation.

2. Materials and methods

2.1. Data collection

To collect all possible published global studies that have investigated the impacts of previous land use systems, climate zone, forest type and forest age on SOC, TN, TP stock changes and other selected soil quality indicators (i.e. soil pH and bulk density) changes following afforestation, we conducted a comprehensive search on the Web of Science database (accessed between 1st January 2000 and 1st February 2020). We used the keywords: land use, climate, soil quality indicators, soil organic carbon, afforestation, forest, nitrogen, phosphorus and soil properties. For the best possible coverage, we also checked all references in the papers found in the Web of Science search. In order to reduce publication bias, data were selected according to the following criteria: a) stocks or concentrations of SOC or TN or TP must have been assessed for both of afforestation and control (previous land use) sites; b) the same stratified method for soil sampling must have been applied for both of afforestation and control sites; c) experiments were deployed using paired-sites, chronosequence or retrospective approach; and d) the dominant forest age and/or type must have been given.

The data were extracted directly either from tables or from graphs (i.e. figures or charts) using the GetData Graph Digitizer (version 2.26). We selected studies that measured SOC, TN and TP stocks at various soil depths between 0 and 100 cm. To enhance comparability between the different studies, we normalized soil depth to three soil layers (i.e. 0-20, 20-60 and 60-100 cm). There were many classifications for soil depth distributions published in the literature that we could have used. However, we have selected these three soil layers because they best reflect the soil depths in our data and show the most common soil depth distributions in the literature. The collected data included 70% studies (63 publications) with the depth down to 20cm, 40% (36 publications) with the depth down to 60cm and 23% (22 publications) with the depth down to 100cm, with some of the studies investigating more than one soil depth (Table S1). A similar standardization method was also reported by Hou et al. (2019). Additionally, to decide on which soil depth distribution was suitable for our study, we compared initial SOC in top soils and sub-soils for two soil depth distributions (i.e., one soil distribution is 0-20, 20-60 and 60-100 cm, another one is 0-30 and 30-100 cm) was carried out as shown in Fig. S1. The initial SOC data for the two soil depth distributions, covering different previous land use systems and climate zones, were statistically tested and compared. Similar trends of initial SOC, for the two soil depth distributions, were found. This revealed that the two soil depth distributions were equally good however, we decided to apply the 0-20, 20-60 and 60-100 cm soil depth distribution, which has three layers, to explore the gradual changes in the nutrients from the topsoil to the subsoil layers. We have also assumed that different maximum sampling depths did not affect the SOC, TN and TP stock trends qualitatively, as the systematic analysis based on a relative effect measure. We collected a total of 91 publications on SOC, TN and TP stock changes: 89 of which reported SOC (417 pairwise samples), 70 of which reported TN (341 pairwise samples) and 36 of which reported TP (171 pairwise samples) (Fig. 1 and Table S1). In addition, we found 156 pairwise samples from 34 publications that contained all of the three parameters (i.e. SOC, TN and TP stocks) at the same sites; 250 pairwise samples from 55 publications that contained soil bulk density (BD); 113 pairwise samples from 32 publications that contained soil pH.

2.2. Data classification

To investigate the impacts of previous land use systems on SOC, TN and TP stocks, the data were divided into three groups: afforestation on barren land (i.e. abandoned land, degraded land, sand dunes, heath and bare fields), on cropland (i.e. maize, wheat and rice and others) and on grassland (i.e. pasture, steppe and prairie). The data were also divided into four groups depending on the regional climate zones: moist warm, moist cool, dry warm and dry cool (Fig. 1). These climatic zones were based on the temperature and moisture conditions (cool, warm, dry and moist). The cool zone covers the temperate (oceanic, subcontinental and continental) and boreal (oceanic, subcontinental and continental) regions, whilst the warm zone covers the tropical (lower and highland) and subtropical (summer rainfall, winter rainfall, and low rainfall) regions. The dry zone covers the area with ≤ 500 mm of annual precipitation, while the moist zone covers the area with >500 mm of annual precipitation (Smith et al., 2007; Abdalla et al., 2018). Likewise, to investigate the impacts of forest type, the data were segregated into three groups: broadleaf deciduous forest (i.e. birch, aspen, oak, maple and elm), broadleaf evergreen forest (i.e. eucalyptus and palm) and coniferous forest (i.e. pine, larch and spruce). We considered the default time for SOC stock changes after land use changes as 20 year (IPCC, 2007; Don et al., 2011). Therefore, the forests were divided depending on their age into three groups: <20 years, 20-50 years and >50 years.

2.3. Calculations of SOC, TN and TP values

In most of the studies SOC, TN and TP values were provided as stocks (Mg ha^{-1}), but in some cases they were given as concentrations (g kg^{-1}). In order to convert these concentrations to stocks, the following Equation (1) was used to calculate SOC, TN and TP stock in soil layer (i):

$$X_{\mathrm{istocks}} = \mathrm{X}_i \times \mathrm{D_i} \times \mathrm{BD_i}/10 \qquad (1)$$

Where X_{istocks}, is the stock value of SOC, TN or TP in Mg ha^{-1}. X_i is the concentration of SOC, TN or TP measured in, g kg^{-1}soil; BD_i is soil bulk density (g cm^{-3}) and Di is soil depth in cm. For studies that only reported SOC, TN and TP contents but no BD values, an exponential function between soil bulk density and SOC content was established based on the original samples from 55 published papers (Fig. S2). The missing values of bulk density were interpolated by the predicted values from the following exponential function (Kaur et al., 2002):

$$\mathrm{BD_i} = 1.4162e^{-0.01\mathrm{Xi}} \ (R^2 = 0.39,\ p < 0.001) \qquad (2)$$

The absolute change (ΔX; Mg ha^{-1}) in SOC, TN and TP stocks in the 0-20, 20-60 and 60-100 cm soil layers due to previous land use systems, following afforestation, were calculated by Equation (3), where ΔX is the absolute change in SOC, TN and TP stocks; X_C is the previous land use system and X_F is the forest system:

$$\Delta X = X_F - X_C \quad (3)$$

To quantify the effects of climate zone, forest type and forest age, we compared the absolute change due to previous land use system under different climate zones, forest types and forest ages.

The relative changes in SOC, TN or TP stocks in the 0-20, 20-60 and 60-100 cm soil layers were calculated using Equations (4) and (5). Here, the relative change (Z_1; %) was calculated as the absolute change in SOC or TN or TP stock (ΔX; Mg ha^{-1}) following afforestation divided by the initial SOC or TN or TP stocks (X_C; Mg ha^{-1}); the response ratio (R) was defined as the natural logarithm of the ratio of these parameters under forest divided by their values under the previous land use system (Hedges et al., 1999).

$$Z_1 = \left(\frac{\Delta X}{X_C}\right) \times 100\% \quad (4)$$

$$\ln(\mathrm{R}) = \ln\left(\frac{X_F}{X_C}\right) \quad (5)$$

A positive value of relative change means an increase in SOC or TN or TP stock following afforestation, whilst a negative value means a decrease in the stocks of these parameters.

2.4. Statistical analyses

We used R version 3.6.2 (R Core Team, 2019) to explore, harmonise, analyse and visualise the data. The distributions of SOC, TN and TP measurements were characterised using the "fitdistrplus" package version 1.0-14 (Delignette-Muller and Dutang, 2015). The significance level (alpha) considered for all the tests was 0.05. To investigate differences between the previous treatments and forest systems on SOC (total 417 pairwise samples) or TN (total 341 pairwise samples) or TP (total 171 pairwise samples) or soil BD (total 250 pairwise samples) or pH (total 113 pairwise samples) in the different soil layers (0-20, 20-60 and 60-100 cm), we used the "glmer" method with random effect (different studies) and Gamma (link "log") or gaussian (link "log") distribution (version 1.1-21) (Bates et al., 2015), while p-values were calculated in order to confirm the significance of the relationships using the "lmerTest" package version 3.1-1 (Kuznetsova et al., 2017). Linear models with logarithm transformed response were used to test whether there was a significant difference in percentage changes of SOC, TN and TP between land uses, climate zones, forest types and age in the 0-20, 20-60 and 60-100 cm soil layers. For the relationship between changes of soil pH and bulk density and changes of SOC, TN and TP stock, we created interpolated contour plots using the package "akima" version 0.6-2 (Akima et al., 2016). The changes of the soil pH or bulk density were as x-axis and y-axis, and changes of SOC or TN or TP changes were as the z variable. A contour plot is a graphical technique for representing a three-dimensional surface by plotting constant z slices on a two-dimensional format. That is, given a value for z, lines are drawn for connecting the (x, y) coordinates where that z value occurs. We performed linear regressions of different variables against SOC, TN and TP. For exploring the fits of different models, inspection of residuals patterns for the entire model and posterior predictive simulation were used as diagnostic tools (Gelman & Hill, 2006; Bates et al., 2015; Harrison et al., 2018).

To quantify the importance of different parameters in determining the percentage changes of SOC, TN and TP stocks following afforestation, we used the random forest analysis by the cforest function with 1,000 trees from the "party" package version 1.3-3 (Strobl et al., 2008). Then 100 separate conditional variable importance analyses were performed for each run; the resulting mean decrease in accuracy values were averaged for each variable. Statistical significances for each predictor through a permutation (999) process were estimated with package "rfPermute" version 2.1.7 (Archer, 2018) and these significance values were further corroborated by conducting a secondary analysis using the "Boruta" package version 6.0.0 (Kursa and Rudnicki, 2010).

3. Results

3.1. Initial SOC stock

The initial SOC values in barren land for soil depth down to 100 cm (25.30, 18.82 and 5.62 Mg ha^{-1} at 0-20, 20-60 and 60-100 cm soil depth, respectively) and cropland for soil depth down to 60 cm (25.28 and 23.37 Mg ha^{-1} at 0-20 and 20-60 cm soil depth, respectively) were significantly less ($p<0.05$) than that in grassland (42.92, 36.18 and 26.69 Mg ha^{-1} at 0-20, 20-60 and 60-100 cm soil depth, respectively) (Fig. S1a). There was no significant difference for initial SOC at 0-60 cm soil depth between barren land and cropland, but for 60-100 cm, initial SOC stock was significantly lower in barren land (5.62 Mg ha^{-1}) than cropland (19.09 Mg ha^{-1}) (Fig. S1a). The mean initial SOC value in barren land significantly decreased ($p<0.05$) from 25.3 at 0-20 cm to 5.62 Mg ha^{-1} at 60-100 cm soil depth (Table S2). Those values in cropland and grassland decreased from 25.28 Mg ha^{-1} and 42.92 Mg ha^{-1} at 0-20 cm to 19.09 Mg ha^{-1} and 26.69 Mg ha^{-1} at 60-100 cm soil depth, respectively (Table S2).

The initial SOC was significantly greater ($p<0.05$) in the moist warm climate zone (41.31, 49.46 and 39.66 Mg ha^{-1} at 0-20, 20-60 and 60-100 cm soil depth, respectively) than that in the moist cool zone (30.93, 16.07 and 12.38 Mg ha^{-1} at 0-20, 20-60 and 60-100 cm soil depth, respectively), dry warm (18.73 and 29.14 Mg ha^{-1} at 0-20 and 20-60 cm soil depth, respectively) and dry cool climate zone (33.26, 29.9 and 9.55 Mg ha^{-1} at 0-20, 20-60 and 60-100 cm soil depth, respectively) at soil depth down to 100 cm (Fig. S1b). For moist warm climate zone, there was no significant difference for initial SOC among three soil layers (Table S2). By contrast, for the moist cool climate zone, the initial SOC value significantly decreased ($p<0.001$) from 30.93 Mg ha^{-1} at 0-20 cm to 12.38 Mg ha^{-1} at 60-100 cm soil depth. For the dry cool climate zone, the initial SOC significantly decreased ($p<0.05$) from 33.26 Mg ha^{-1} at 0-20 cm to 9.55 Mg ha^{-1} at 60-100 cm soil depth. However, for the dry warm climate zone, the initial SOC significantly increased ($p<0.05$) from 18.73 at 0-20 cm to 29.14 Mg ha^{-1} at 20-60 cm, with no data at 60-100 cm.

3.2. SOC, TN and TP stock following afforestation

Overall, afforestation significantly ($p<0.05$) increased SOC by 46%, 52% and 20 % in the soil layers 0-20, 20-60 and 60-100 cm, and TN stocks by 28% and 22% in the 0-20 and 20-60 soil layers, respectively, but had no significant effects on TP stock changes for whole soil profile (Table 1). However, changes of SOC, TN and TP stocks for all investigated soil depths down to 100 cm following afforestation were significantly affected by previous land use system, climate zone, forest type and forest age.

The importance of different land use variables (previous land use, climate zone, forest type and forest age) for predicting changes in SOC, TN and TP stocks following afforestation, is illustrated in Fig. 2. All of the four variables were found to have statistically significant contributions ($p<0.05$) to these changes. The previous land use system was ranked first (for changes of TN and TP stocks) or second (for change of SOC stock) as the most important predictor for changes in SOC, TN and TP stocks. By contrast, climate zone, forest type and forest age had different ranks regarding their importance for predicting changes in SOC, TN and TP stocks.

3.2.1. Impacts of previous land use system

Afforestation significantly ($p<0.001$) increased SOC stock at soil depths down to 60 cm on barren land (94% and 106% at 0-20 and 20-60 cm, respectively) and cropland (58% and 76% at 0-20 and 20-60 cm, respectively), while there were no significant changes of SOC stock following afforestation on grassland (Table S3). Similar results were also found for TN stock changes, with an increase by 82% and 25% at 0-20 and 20-60 cm, respectively, for barren land, and 25% and 30% at 0-20 and 20-60 cm, respectively, for cropland (Table S4). Afforestation of barren land significantly ($p<0.001$) increased TP by 44% at 0-20 cm but had no impacts below 20 cm soil depth. However, afforestation significantly ($p<0.05$) decreased TP stock by 5% for cropland, or had no significant impacts on TP for grassland at 0-20 cm soil depth (Table S5).

The changes (%) in SOC stock following afforestation from the previous land use systems of barren land, cropland and grassland to soil depth down to 60 cm were significantly different (p<0.01) from each other (Fig. 3a). The greatest change in SOC stock (%) was found in barren land, followed by cropland and then grassland. However, SOC stock at soil depth of 60-100 cm was unaffected by the previous land use system. Similarly, at the soil depth of 0-20 cm, the greatest differences in the relative TN and TP stock changes were found in barren land compared to cropland and grassland (Fig. 3b and 3d). There were no significant differences in relative changes of TN and TP stocks among the three previous land use systems below 20 cm soil depth.

3.2.2. Impacts of climate zone

For moist cool climate zone, SOC stock significantly (p<0.001) increased in all investigated soil layers (75%, 98% and 35% at 0-20, 20-60 and 60-100 cm soil depth, respectively), whilst SOC significantly increased only at soil depth of 0-20 cm for moist warm (31%), dry warm (44%) and dry cool (24%) (Table S3). TN stock significantly (p<0.05) increased at soil depth down to 60 cm in moist warm (35% and 19% at 0-20 and 20-60 cm, respectively) and moist cool (24% and 31% at 0-20 and 20-60 cm, respectively) climate zones, and only at 0-20 cm soil depth in dry warm (46%) and dry cool (20%) (Table S4). TP stock did not change at any climate zone/ soil depth following afforestation, except for the dry cool climate soil at 60-100 cm depth where TP stock significantly (p<0.05) decreased by 5% following afforestation (Table S5).

The relative changes of SOC, TN and TP stocks (%), following afforestation varied with climate zones. These relative changes were significantly (p<0.05) different at soil depth down to 60 cm for SOC, at 0-20 cm for TN and 20-60 cm for TP (Fig. 3d-3f).

3.2.3. Impacts of forest type

When pooling all the data together, SOC and TN stocks increased significantly (p<0.05) following afforestation with broadleaf deciduous and/or broadleaf evergreen forest types but had no significant change with coniferous forests (Table S3 and S4). TP stock did not change at any forest type/ soil depth following afforestation (Table S5). Afforestation with broadleaf deciduous forests significantly (p<0.001) increased SOC stock at soil depth down to 100 cm (64%, 76% and 35% at 0-20, 20-60 and 60-100 cm soil depth, respectively), and TN stocks at soil depth down to 60 cm (35% and 29% at 0-20 and 20-60 cm, respectively) (Table S3 and S4). Afforestation with broadleaf evergreen forest significantly (p<0.05) increased SOC by 24% and TN by 30% at 0-20 cm, but data were insufficient to determine a change for 20-60 cm and 60-100 cm soil layers.

The relative changes (%) of SOC, TN and TP stocks due to forest type varied among forest types. These relative variations were significantly (p<0.05) different at soil depths down to 60 cm for SOC, but in the topsoil (0-20 cm) only for the TN and TP stocks (Fig. 3g-3i).

3.2.4. Impacts of forest age

The SOC and TN stocks increased significantly only in the 0-20 cm soil layer by 21% and 22%, respectively, for forest age of <20 years (Table S3 and S4). By contrast, for 20-50 and >50-year-old groups, SOC and TN stocks significantly (p<0.05) increased for all investigated soil layers. TP stock significantly (p<0.05) decreased by 23% following afforestation at 0-20 cm for <20-year-old group but did not change for any soil layer for other >20-year-old forest (Table S5). The percent changes in SOC and TN stocks varied according to the age of forest (Fig. 3j-3l). These changes were significantly (p<0.05) different at soil depth down to 60 cm for SOC and below 20 cm for TN values. By contrast, TP changes were not significantly different among different age groups (p>0.05) (Fig. 3j-3l).

3.3. Impacts of afforestation on selected soil properties (BD and pH)

Afforestation significantly decreased soil BD and pH ($p<0.001$) (Table 1). As shown in Fig. 4, these changes in soil BD and pH explained 17.3% of overall variance in the relative SOC stock changes (%) at 0-100 cm soil depth. The relative SOC stock changes were significantly related to BD changes ($t = -4.7$; $p < 0.001$). Similarly, changes in soil BD and pH explained 8.0% of the overall TN relative stock changes at soil depth of 0-100 cm. Relative TN changes were also significantly related to BD changes ($t = -2.9$; $p<0.01$). By contrast, changes in BD and pH were not related to changes in TP stock, at any soil depth between 0 and 100 cm.

3.4. Relationships between SOC and TN or TP stocks

There was a significant positive relationship between Ln(R) of SOC and TN stocks at 0-20 cm (<20-year-old forests: n=30, r^2=0.55, $p<0.001$; >20-year-old forests: n=75, r^2=0.65, $p<0.001$) (Fig. 5a) and 20-100 cm (<20-year-old forests: n=13, r^2=0.41, $p<0.05$; >20-year-old forests: n=39, r^2=0.40, $p<0.001$) (Fig. 5b) soil depths, with similar slope values under <20-year-old and >20-year-old forests. Interestingly, there was a significant positive relationship between Ln(R) of SOC and TP stocks for <20-year-old (n=30, r^2=0.24, $p<0.01$) and >20-year-old forest (n=75, r^2=0.23, $p<0.001$) at soil depth of 0-20 cm (Fig. 5c), with a higher slope value in the >20-year-old forest than that in the <20-year-old forest. By contrast, at soil depth of 20-100 cm, there was no significant ($p>0.05$) relationship between Ln(R) of SOC stock and TP stock under all forest age groups (Fig. 5d).

4. Discussion

4.1. Comparisons with previous syntheses

Afforestation on land historically not having had forest cover is one of the most effective ways to sequester carbon into soil and to improve soil quality (IPCC, 2007; Berthrong et al., 2009; Bárcena et al., 2014). In this critical global systematic analysis and review, we found that previous land use system, climate zone, forest type and forest age, all had significant impacts on SOC, TN, TP stock and other selected soil indicators (i.e. BD and pH) following afforestation. Unlike previous published regional/global reviews (Berthrong et al., 2009; Bárcena et al., 2014; Liu et al., 2018; Shi et al., 2016) which mostly focused on soil depths down to 30 cm, we collected and systematically analysed our data on SOC, TN and TP stocks down to 100 cm depth. Changes in SOC, TN and TP at >30 cm are very important to accurately estimate the ability of soil to sequester carbon. Up to 50% of SOC has been predicted to be stored at these depths, so ignoring it results in a massive underestimate. Although a few review studies that explored SOC stock changes following afforestation in deeper soil layers, of down to 60 cm or even100 cm depth (Li et al., 2012; Shi et al., 2013; Deng et al., 2014; Song et al., 2014; Hou et al., 2019), they did not investigate the impacts of previous land use system, climate zone, forest type and forest age on SOC in the different soil layers.

Obtaining the necessary data for our systematic analysis and review was challenging, producing some sources of error that could affect predictions. This was checked by assessing the uncertainty in our results, due to assumptions made, which was conservatively estimated by calculating the standard deviations for all values and 95% confidence interval for relative changes. One limitation of this study was that we did not directly correct the dataset on SOC, TN and TP stocks based on equivalent soil mass (Ellert & Bettany, 1995; Don et al., 2011), but relied on a pedotransfer function to calculate soil bulk density for each soil layer if it was missing. Another limitation is that we were not able to include some factors (e.g. soil texture), due to lack of data for deeper soil layers. Additionally, the common limitation of unbalanced sampling and geographic distribution of sites might increase uncertainty in our results.

4.2. SOC, TN and TP stock following afforestation

4.2.1. Impacts of previous land use system

Initial SOC stocks under different previous land use systems had a significant influence on the changes of SOC following afforestation, which is consistent with the previous reviews by Bárcena et al.

(2014) and Shi et al. (2016). The calculated relative changes in SOC stock for afforestation on barren land, at down to 60 cm soil depth, were significantly greater in comparison with that for cropland and grassland, especially in the topsoil layer (i.e. 0-20 cm) (Table S3 and Fig. 3a). Shi et al. (2016) and Liu et al. (2018) reported that afforestation on barren land, is an effective way to enhance carbon sequestration of topsoil (i.e. 0-30 cm) compared with the other previous land use types. For afforestation on cropland, in this study, SOC stock was increased significantly for soil depth down to 60 cm but had no significant changes at deeper soil layer (i.e. 60-100 cm). Similar results at a global scale were reported by Guo & Gifford (2002), Laganiere et al. (2010) and Shi et al. (2016) for topsoil of 0-30 cm depth. In contrast to cropland and barren land, afforestation on grassland had no effect on SOC stock changes for the whole soil profile. Laganiere et al. (2010) and Shi et al. (2016) investigated topsoil and found that afforestation on grassland had no effect on SOC stock.

Generally, land with poor initial SOC stock (i.e. barren land with poor vegetation growth and/or cropland with regular soil disturbance during tillage or harvest practices leading to low SOC inputs) have greater potential to become SOC sinks following afforestation, due to the high SOC inputs provided by the forest (Nave et al., 2013; Lal, 2018). Nevertheless, land with greater initial SOC stock (i.e. grassland with aboveground permanent vegetation cover and roots system resulting in large SOC inputs) have less potential to accumulate SOC following afforestation within the same forest age. Additionally, grassland could experience a slight SOC loss at the beginning of afforestation due to the soil disturbance which accelerates SOC decomposition (Bárcena et al., 2014; Shi et al., 2016; Richards et al., 2017). The root system in a forest is generally deeper than that in a grassland, which could increase carbon inputs in the deep soil depths following afforestation from grassland, causing a gain of SOC stocks in the subsoil layers (Laganiere et al., 2010).

Afforestation on barren land was an effective method to increase TN stocks at soil depths down to 60 cm (Table S4). Shi et al. (2016) and Liu et al. (2018) reported that TN stocks at 0-30 cm soil depth were significantly increased, following afforestation on barren land. However, Li et al. (2012) found that

TN stocks did not change in mineral soil layers of 0-100 cm. Our results showed that afforestation on cropland significantly increased TN stocks at 0-60 cm soil depth but had no significant effect at a deeper layer of 60-100 cm (Table S4). Nonetheless, afforestation on grassland did not change TN stock at soil depths down to 100 cm. A similar conclusion, of no effect on TN stock following afforestation on grassland, was also reported by Liu et al. (2018). In contrast, Shi et al. (2016) reported a significant decrease in TN stocks in topsoil. These differences between studies could be explained by the differences in the distribution of dataset sources, forest age groups, climate zones, and forest types and soil properties. We found that afforestation on barren land significantly increased TP stocks only at 0-20 cm soil depth, whilst afforestation on cropland significantly decreased TP stocks at 0-20 cm soil depth (Table S5). Grassland had no significant effects on TP stock changes at soil depths down to 100 cm. Similar conclusions with regard to TP stock changes following afforestation on different previous land use systems were reported by Deng et al. (2017). In order to reach the higher demand for P, forests may invest more carbon and other resource in root exudates and microbial symbioses that degrade clay minerals or organic P compounds, thus leading to an increase in P sources in soil compared with previous land use (e.g. barren land) (Deng et al., 2017). By contrast, a stopping of P fertilizer input with afforestation could lead to less soil TP stock in planted forests than in cropland (MacDonald et al., 2012).

4.2.2. Impacts of climate zone

The significant influence of climate on SOC stock changes following afforestation agreed with previous studies (Guo & Gifford, 2002; Li et al., 2012; Shi et al., 2016). SOC increased after afforestation in the moist cool climate zone at soil depths down to 100 cm, whilst, for moist warm, dry warm and dry cool climate zones, SOC stocks increased significantly only at 0-20 cm soil depth (Table S3). The poorer carbon sequestration potential in moist warm climate zone could be related to the greater decomposition due to the higher temperature and precipitation condition (Lal, 2005), while in the dry cool zone it could be related to slower tree growth under dry and cold conditions, thus lower organic matter inputs (Laganiere et al., 2010).

It should be noted that soil in the moist cool zone had the greatest values of the relative SOC changes following afforestation, especially in topsoil (i.e. 0-20 cm) (Fig. 3d), implying a relatively greater carbon sequestration potential compared to other climate zones. This probably occurred due to the greater forest plant productivity (Deng et al., 2014) driving larger carbon inputs, and cooler, moister conditions in decreasing decomposition in moist cool regions (Baritz et al., 2010). Over time, podzolic soils can form under forests in a moist cool climate, further affecting carbon accumulation due to leaching and decreased soil pH. Additionally, uneven datasets where some categories in certain factors are clearly dominating, could contribute to the observed differences in the relative changes of SOC stock between the climate zones (Yang et al., 2011; Deng et al., 2014). Shi et al. (2016) reported that the increase of SOC stock becomes larger when forests are older than 20 years. Previous studies have shown that SOC stock tends to decrease following afforestation with coniferous forests and tends to increase under broadleaf forest (Guo & Gifford, 2002; Paul et al., 2002; Laganiere et al., 2010). In fact, 80% of the SOC dataset used in our review for the moist cool zone were collected from forests that were older than 20 years and 99% of them were broadleaf forests, which favours an increase of SOC stocks following afforestation.

Our study confirmed that climate significantly influenced TN stock following afforestation. TN stock significantly increased in all climate zones if all data were pooled together (Table S4). In contrast, Li et al. (2012) reported that TN stock over 0-100 cm soil depth significantly increased in the subtropical zone, but did not change in the tropical zones, and decreased in the boreal and temperate zones. This difference between the two studies could be explained by difference in the dataset sources. In our study, afforestation on barren land was considered as a separate group, whilst previous studies focused on afforestation on cropland and grassland/pasture only (Yang et al., 2011; Li et al., 2012). A recent global review showed that all TN stocks increased following afforestation on barren land in all climate zones in the 0-20 cm soil layer, but with different values for each climate zone (Shi et al., 2016). We found that TP stocks did not significantly change and did not differ among the four climate zones, which is consistent with the findings by Deng et al. (2017). By contrast, TP stock change (%) following afforestation was significantly different for the four climate zones below 20 cm soil depth in our study, with the larger values of TP stock change in the moist warm zone. Therefore, TP stock changes at deeper soil depth under different climate zones deserve to be investigated further in future studies.

4.2.3. Impacts of forest type

To the best of our knowledge, only one global review explored the effects of forest type on both SOC and TN stock following afforestation in deeper soil layers (i.e. down to 100 cm) and found that SOC and TN stocks significantly increased for deciduous forest, but did not change for coniferous forest (Deng et al., 2017), which is consistent with our findings. Other studies, focused on the topsoil layers (i.e. 0-20/30 cm), showed that SOC and/or TN stocks following afforestation, tends to decrease or not change for coniferous forest but tends to increase for broadleaf forests, especially broadleaf deciduous forests (Guo & Gifford, 2002; Paul et al., 2002; Berthrong et al., 2009; Laganiere et al., 2010; Shi et al., 2016). In contrast to our result, Deng et al. (2017) showed that TP stocks decreased significantly in the top 20 cm of soil, for both coniferous and broadleaf forests, except for Eucalyptus.

The difference between the influences of forest types on SOC or TN or TP stocks could be related to the difference in their carbon or nutrient inputs (i.e. litter fall, root turnover and root exudates), transfer (i.e. the quality of litter and humification rate) and potential loss (Guo & Gifford, 2002; Paul et al., 2002; Hobbie et al., 2007; Laganiere et al., 2010; Li et al., 2012; Deng et al., 2017). For example, since most of the study sites (including this study) with coniferous forests are more prone to be located in cooler climate zones, the possibility of detecting SOC or nutrient stock changes is less as trees grow slower and thus provide fewer carbon and nutrient inputs (Smith, 2004; Laganiere et al., 2010; Shi et al., 2016). Previous studies showed that substrate quality of conifer needles is poorer than for leaves of broadleaf forest, resulting in slower litter decomposition times that exacerbates fewer carbon and nutrient inputs to the mineral soil (Paul et al., 2002; Deng et al., 2014). Additionally, coniferous forests acidify soil, which reduces decomposition rate, earthworm activity (Johnston, 2019), and carbon inputs (Jo et al., 2019). Furthermore, our analysis indeed found that mean values of soil pH under coniferous forest was 5.53, which was significantly lower than for broadleaf forest (Table S6) and will inhibit earthworm activity. More importantly, compared with coniferous forest, most broadleaf forests have a larger and deeper root system, which generally results in greater soil organic matter inputs (Strong & Roi, 1983; Laganiere et al., 2010). Other mechanisms have been proposed to explain differences in the effects of forest type on SOC and soil nutrient stock changes. For example, forest types can affect SOC and TN dynamics through their influence on the physical or chemical protection of soil organic matter (Hobbie et al., 2007). Forest types also potentially influences SOC, TN and TP inputs and losses by their interaction with herbivores, soil microbial communities and their symbiotic interaction with N-fixing bacteria (Knops et al., 2002; Laganiere et al., 2010; Shi et al., 2016).

4.2.4. Impacts of forest age

Forest age was an important factor in determining SOC stock following afforestation. Afforestation for <20 years had significantly increased SOC stock at 0-20 cm soil depth, but afforestation for >20 years had significantly accumulated SOC stock down to 100 cm soil depth (Table S3). Previous studies reported a faster change in SOC stocks related to forest age in topsoil compared to deeper soil layers (Paul et al., 2002; Shi et al., 2013; L. Deng et al., 2014). The time for significant net accumulation of SOC stocks, above and below 20 cm depth, varies greatly. For example, studies on SOC stock changes following afforestation on grassland and cropland in the tropical zone found that a net accumulation of SOC generally occurred within 20-40 years (Cerri et al., 2007; Solomon et al., 2007; Don et al., 2011; Berthrong et al., 2012). In certain parts of the boreal zone, however, Ritter (2007) reported that it would take more than 100 years to observe a significant increase of SOC stocks following afforestation in certain parts of the boreal zone. This may be due to the cool temperature and poor soil nutrients of former land use system, leading to the slow growth of forest trees, and consequently lower carbon inputs. Additionally, a recent study reported that afforestation on cropland and barren land significantly increased SOC stock for forests younger or older than 20 years, but there was no change of SOC stock on grassland regardless of stand age (Shi et al., 2016). This implies that previous land use system may have an effect on the time for a net accumulation of SOC stocks.

In addition, we found that the SOC stock accumulation following afforestation at down to 60 cm soil depth increased most after 20 years (Fig. 3j), as reported by others (Laganiere et al., 2010; Shi et al., 2016). This could be related to the equilibrium of the system following afforestation, as the canopy spreads and the green area index develops. As the trees grow, the carbon inputs generally increase, along with a new microclimatic environment (Bouwman and Leemans, 1995) and strengthened soil organic matter protection (Del et al., 2003), thus increasing SOC accumulation until system equilibrium (Laganiere et al., 2010).

Forest age was also an important factor in determining TN stock changes following afforestation. We found that afforestation for <20 years produced significantly increased TN stock only down to 20 cm soil depth, whereas TN increased significantly down 100 cm soil depth at >20 years growth (Table S4), probably driven by greater biomass (Johnson, 1992). Previous studies that investigated the effects of forest age on TN stock changes at soil depths down to 100 cm reported that TN stocks significantly increased in 50 years following afforestation. The difference of time for the significant increase of TN stock may be related to the previous land use system. For example, regardless of forest age, afforestation on cropland and barren land may significantly increase TN stock, but on grassland it may decrease (Shi et al., 2016). In this review, the TP stocks was significantly decreased in the 0-20 cm soil layer for <20-year-old forest, which is consistent with the conclusion reported by Shi et al. (2016). There were no significant changes for forest age of >20 years at any soil depth, however, implying that P may be taken up by the growing forests as the nutrient demand of mature forests increases. Unlike C and N, there is no exchange of P with the atmosphere and thus increasing P requires its extraction from the mineralogy of the soil parent material, which is strongly affected by weathering and biology.

4.3. Impacts of afforestation on selected soil properties (i.e. BD and pH).

Land use change generally leads to a change in soil BD (Poeplau et al., 2011). Indeed, this study showed that the change in soil BD following afforestation, at soil depths down to 100 cm, had a significant negative relationship with SOC stock changes (Fig. 4). This is in accordance with the findings reported by Don et al. (2011), who showed that positive SOC stocks changes at 0-30 cm soil depth following afforestation on cropland and grassland, resulted in negative soil BD changes. The reason for this inverse relationship could be the development of root networks (biopores developed) and leaf litter following afforestation. The greater amount of soil organic matter can aggregate soil, leading to a decrease in soil BD as humus has a density of ~1g cm^{-3} compared to minerals like quartz with a density of 2.65 g cm^{-3} (Prévosto et al., 2004; Ritter, 2007). Additionally, we found that changes in soil BD had a significant relationship with TN stock at soil depths down to 100 cm following afforestation, indicating decreased soil BD could promote nutrient supply (i.e. TN stock) (Wu et al., 2018), and potentially increase carbon inputs from enhanced net primary productivity (Goll et al., 2012 ; Cleveland et al., 2013). Moreover, the development of root networks following afforestation could increase the partial pressure of CO_2 due to high root respiration and decomposition of dead roots. The greater levels of CO_2, together with water in the soil and SO_4^{2-}, forms carbonic acid (H_2CO_3) and sulphuric acid (H_2SO_4), which reduce soil pH (Singh et al., 2012). Reducing pH tend to reduce decomposition rate and may leach organic material into the lower layers forming a podzol (Laganiere et al., 2010). Furthermore, our analysis indeed found that afforestation significantly decreased soil pH (Table 1).

4.4. Implications of the interaction between SOC and nutrients dynamics

The long-term soil carbon sequestration process is regulated by the dynamics of N and P cycles in terrestrial ecosystems (Yang et al., 2011; Deng et al., 2017). Indeed, we found significant positive relationships between relative changes of SOC and TN stocks at depths down to 100 cm soil depth under all forest age groups (Fig. 5). The increase of TN stocks following afforestation could offset progressive N limitation (Luo et al., 2006), and maintains SOC accumulation as forests aged (Luo et al., 2006; Yang et al., 2011). A similar conclusion regarding an increase in TN stock accompanied by an increase in SOC stock following afforestation was reported by other studies (Yang et al., 2011; Shi et al., 2013; Liu et al., 2018). Our results also show that there was a significant positive relationship between relative changes of SOC and TP stocks in topsoil under all forest age groups, but no significant relationship in sub-soils. We found no change in TP stock with increasing forest age, which may become a limiting factor for further soil carbon sequestration following afforestation. Therefore, a greater TP concentration may be required compared with TN concentration during long-term forest stand development.

5. Conclusions

This global systematic analysis and review revealed that overall, afforestation significantly increased SOC stock for each soil layer down to 100 cm and TN stock down to 60 cm, but had no significant impacts on TP stock throughout the investigated soil profile. Changes in SOC, TN and TP stock following afforestation for all soil layers between 0 and 100 cm were significantly affected by previous land use system, climate zone, forest type and forest age. Previous land use system was the most influential factor for all changes in SOC, TN and TP stocks following afforestation. Afforestation on barren land and cropland significantly increased SOC and TN stocks for each soil layer down to 60 cm. By contrast, at 0-20 cm, afforestation significantly increased TP stock only for barren land, whilst significantly decreased it for cropland. Afforestation on grassland had no significant effects on SOC, TN and TP stock for any soil layer. Moist cool climate zones had greater potential for SOC, TN and TP stock accumulations below 20 cm soil depth, compared to other climate zones. Broadleaf forests were better than coniferous forests for increasing SOC, TN and TP accumulations throughout the investigated soil profile (0-100 cm). Afforestation for <20 years significantly increased both SOC and TN stocks only at 0-20 cm soil depth, but afforestation for >20 years caused significant accumulation of SOC and TN stocks down to 100 cm soil depth. Changes to SOC and TN stocks were positively correlated at depths down to 100 cm under all forest age groups. By contrast, there was a significant positive relationship between relative changes of SOC and TP stocks in topsoil, but no significant relationship in sub-soils under all forest age groups. TP stock decreased significantly at a soil depth of 0-20 cm following afforestation for <20 years and did not change after 20 years in any soil layer, suggesting that TP may become a limiting factor for further soil carbon sequestration following afforestation. A higher TP than TN concentration would be required during long-term forest stand development. Following afforestation, soil BD decreased alongside significant increases in SOC and TN stocks to 100 cm depth, but had no relationship with the TP. We suggest that future studies should measure soil changes to at least 100 cm depth and forms of P to assess its mobilisation and uptake.

Declaration of competing interest

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

CRediT authorship contribution statement

Yang Guo: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Mohamed Abdalla:** Conceptualization, Methodology, Writing – review & editing. **Mikk Espenberg:** Formal analysis, Methodology, Writing – review & editing. **Astley Hastings:** Conceptualization, Methodology, Writing – review & editing. **Paul Hallett:** Writing – review & editing. **Pete Smith:** Writing – review & editing.

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