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META-ANALYSIS

The effects of plantation practice on soil properties based on the comparison between natural and planted forests: a meta-analysis

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ABSTRACT

Aim The effects of planted forests on soils are of great concern in the context of the increasing demands for timber production and atmospheric CO_2 sequestration. However, the effects of plantations on soil properties have not well been quantified. We determined the effects of plantation practice on soil properties based on a comparison between natural forests and plantations.

Locations All the continents except for Antarctica.

Methods The meta-analysis approach was used to examine the differences in 14 soil variables in the mineral layer, including pH, bulk density, C, N, P, K, Ca, Mg, Na and Al concentrations, C/N ratio, cation exchangeable capacity, base saturation, and moisture between plantations and their adjacent natural forests from 73 published studies.

Results Plantations did not differ from natural forests in soil pH or soil Na and Al concentrations. Soil bulk density below plantations increased by 12.5%, and soil C and N concentrations decreased by 36.0% and 26.5%, respectively, relative to natural forests. The other eight variables were 8.4–30.6% lower in plantations than in natural forests. The general patterns also held true for planted trees from the genus *Pinus* and for study regions in China. The patterns for soil bulk density and C and N concentrations were not different between the two groups in relation to various factors: stand age (< 25 years versus ≥ 25 years), leaf form (broadleaved versus coniferous) and leaf seasonality (deciduous versus evergreen), tree species origin (native versus exotic), land-use history (afforestation versus reforestation) and site preparation for plantations (burnt versus un-burnt treatment), and biogeographic zone (tropical versus temperate).

Main conclusions Our results suggest that the level of soil fertility in plantations is unlikely to restore to the level in natural forests, implying that the replacement of natural forests by plantations may be a practice best avoided to maintain the ecosystem sustainability.

Keywords
Biogeographic factor, carbon sequestration, natural forests, plantation forests, soil fertility, soil properties, stand types.

INTRODUCTION

Planted forests (plantations) have been a significant element of land-use change. The world-wide area of plantations was as large as 1.39×10^8 ha in 2005, and the relative rate of annual expansion is predicted to be approximately 2% (FAO, 2005; van Dijk & Keenan, 2007). The growing area of plantations can result from the demand of the world's increasing population for domestic and industrial timbers (e.g. Berthrong *et al.*, 2009). More importantly, plantations have been promoted as a measure

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to sequestrate increased atmospheric CO_2 to mitigate future climate change (Winjum & Schroeder, 1997; Jackson *et al.*, 2005; van Dijk & Keenan, 2007). Reforestation in primary and secondary forest (natural forest) lands accounts for about half of the total increased area of plantations (FAO, 2005; van Dijk & Keenan, 2007).

It is important to sustainably maintain soil fertility in plantations in the context of the increasing demands for timber production and atmospheric CO_2 sequestration. However, plantations can potentially alter the biogeochemical cycles of ecosystem as a consequence of changes in tree species composition when compared with their adjacent natural forests (e.g. Aborisade & Aweto, 1990; Wall & Hytönen, 2005; Freier *et al.*, 2010) and the intervention of silvicultural activities (e.g. Yang *et al.*, 2005; Zheng *et al.*, 2008). Many soil properties, for instance, soil pH, soil bulk density and soil C and N concentrations, whose changes may have prominent impacts on tree growth, are key indicators of soil fertility. Natural forests are considered to be of importance for maintaining and/or improving soil fertility (e.g. Behera & Sahani, 2003; Ashagrie *et al.*, 2005; Yang *et al.*, 2005; Zheng *et al.*, 2008). Thus, the issue of whether plantations like natural forests can maintain or even improve soil fertility has attracted much attention.

An increasing number of field studies have shown that soil properties are significantly different between plantations and natural forests. For example, soil pH as well as soil C and N concentrations are lower (Solomon *et al.*, 2002; Chen *et al.*, 2005; Nsabimana *et al.*, 2008) and soil bulk density is higher in plantations than in natural forests (e.g. Aborisade & Aweto, 1990; Behera & Sahani, 2003; Lemma *et al.*, 2006). Soil acidification, nutrient depletion and compaction may lead to decreased soil fertility. However, other studies have reported that soil pH, and soil C and N concentrations increase (Wall & Hytönen, 2005) and soil bulk density decreases below plantations when compared with natural forests (Yang & Xie, 2002; Wall & Hytönen, 2005; Pibumrung *et al.*, 2008). These mixed results among field studies prevent us from fully understanding whether plantations can maintain soil fertility.

The inconsistent results might have stemmed from the fact that the experimental results are influenced by a number of factors including stand types and land-use history of plantations and geographic conditions in study regions. Soil pH is higher in broadleaved plantations with *Eucalyptus urophylla* × *Eucalyptus grandis* (Gong & Liao, 2009), but lower in coniferous ones with *Larix olgensis* than in natural forests (Wang *et al.*, 2007). Soil bulk density is greater in plantations reforested in natural forests (Behera & Sahani, 2003), but lower in ones afforested in agricultural lands than in natural forests (Wall & Hytönen, 2005). Soil C and N concentrations decrease in plantations in tropical regions (Aborisade & Aweto, 1990; Solomon *et al.*, 2002; Lemenih *et al.*, 2004), but increase in temperate regions in comparison with natural forests (Yang & Xie, 2002; Wall & Hytönen, 2005; Deng & Shangguan, 2009). Stand age, tree species origin (native or exotic) (Cavelier & Tobler, 1998; Ashagrie *et al.*, 2005; Kasel & Bennett, 2007) and site preparation (e.g. burnt or unburnt treatment) for plantations (Chen *et al.*, 2005; Kasel & Bennett, 2007; Gong & Liao, 2009) may influence the differences in soil properties between plantations and natural forests. However, individual field studies cannot take all these factors into account, which precludes a broader generalization of their results.

Some time ago soil scientists began to pay much attention to the question of how plantation practice affects soil properties (e.g. Stone & Gibson, 1975; Binkley & Giardina, 1998; Johnson & Curtis, 2001). However, due to high variability in biogeographic conditions, complexity of silvicultural activities, inherent soil heterogeneity and so on their studies failed to show a general pattern. Recently, several quantitative reviews have been conducted and found significant impacts of plantations on soil properties (e.g. Jackson *et al.*, 2005; Berthrong *et al.*, 2009; Laganière *et al.*, 2010). They have focused on the comparison between plantations and non-forested lands, but their findings are inconsistent. This inconsistency can be attributed to the fact that the non-forested lands, the reference relative to plantations, mainly consist of agricultural systems (Paul *et al.*, 2002; Jackson *et al.*, 2005; Berthrong *et al.*, 2009; Laganière *et al.*, 2010) which are inherently disturbed by frequent human-induced activities (e.g. removal of crop biomass, fertilization and weed control). Thus, it is necessary to use the naturally occurring forests as a reference to determine the effects of plantations on soil properties.

In this study, published studies with paired-site design were synthesized, using a meta-analysis approach, to quantify the overall direction and magnitude of the differences in soil properties (mineral layer) between plantations and natural forests. Together with soil pH, bulk density and C and N concentrations mentioned above, C/N ratio, P, K, Ca, Mg, Na and Al concentrations, cation exchangeable capacity (CEC), base saturation, and moisture conferring mineral soil properties (Table S1 in Supporting Information) were included in this quantitative synthesis. We were also interested in variables from the soil O horizon; however, the available datasets from the horizon were limited (Table S2).

The meta-analysis has the potential to examine whether the differences between plantations and natural forests are associated with various factors. There is a lot of information on these factors recorded in the field studies, but the most common factors like stand age (< 25 years versus ≥ 25 years) (SA: le vs. mo), tree leaf form (broadleaved versus coniferous) (TLF: br vs. co) and seasonality (deciduous versus evergreen) (TLS: de vs. ev), tree species origin (native versus exotic) (TSO: na vs. ex), land-use history (afforestation versus reforestation) (LUH: af vs. re) and site preparation for plantations (burnt versus unburnt treatment) (SP: bt vs. unbt) and biogeographic zone (e.g. tropical versus temperate) of study regions (BZ: tr vs. te) were considered in this synthesis. More specifically, the meta-analysis was performed to address the following three questions. First, to what extent were soil properties different between plantations and natural forests? Second, which factors contributed to the differences? Third, what were the consequences of plantation practice to future timber production, soil nutrient cycles and environmental change?

MATERIALS AND METHODS

Data sources

To avoid potential bias in publication selection, the following five criteria were set for the inclusion of data related to soil variables for both plantations and natural forests. First, the reference systems relative to plantations were primary (e.g. Smith *et al.*, 2002) and secondary forests (e.g. Yang *et al.*, 2005), which were naturally generated forests and free of obvious disturbances (i.e. natural forests). Second, the trees in plantations were arboreal species (excluding bamboos), shrubs, or even fruit and non-timber trees such as apple, coffee or rubber. Third, experimental studies were conducted by paired-site design in the field (Paul *et al.*, 2002; Laganière *et al.*, 2010). If studies were conducted by chronosequence design for plantations compared with natural forests, the oldest plantations were included. If studies followed a retrospective design for plantations compared with natural forests, the dataset sampled in the last time was used. Fourth, studies were free of experimental treatments (e.g. free-air CO_2 enrichment and warming) which do not belong to the normal range of silvicultural activities. Fifth, data were collected from samples of the soil surface layer. If data from samples of different layers in a soil profile had been compiled into one, the compiled data were used.

Databases of Blackwell, CNKI, Elsevier, ESA, Kluwer, JSTOR, Springer and Web of Science, licensed to Fudan University library, were used for source data from inception to July 2010. In total, 73 studies were available for this meta-analysis. Study regions were located in all continents except Antarctica. All the data used here were directly extracted from figures or tables in published papers. For each variable, the mean, standard error (SE) or deviation (SD) or 95% confidence interval (CI), and sample size (n) in both plantations and natural forests were extracted. Information on factors like stand type and land-use history of plantations, and latitude of study regions was also obtained.

Given that the tree species of the genus *Pinus* are widely used to establish plantations and that China has the largest area of plantations in the world, the planted tree species from the genus *Pinus* and study regions from China were singled out to determinate the differences between plantations and natural forests. In addition, plantations were categorized into two groups in relation to SA (le vs. mo), SLF (br vs. co), SLS (de vs. ev), TSO (na vs. ex), LUH (af vs. re), SP (unbt vs. bt) or BZ (tr vs. te) to examine the effects of these factors on the differences between plantations and natural forests. We arbitrarily set 25 years of plantation age as a threshold value in view of the common practice that mature plantation stands with fast-growing trees are generally considered to be less than 25 years old. Study regions were categorized into tropical and temperate groups according to the threshold latitude of 23.4° (north/south). Study regions were also grouped into different continents to determine the effects of geographic zone on the differences between plantations and natural forests.

Data analysis

The method of meta-analysis used in this study followed previous studies (e.g. Luo *et al.*, 2006; Liao *et al.*, 2008). Plantations were regarded as treatment relative to natural forests. A response ratio (*RR*, the logarithm ratio of the mean value of a concerned soil variable under plantations to that in natural forests) was used here as an index of the magnitude of the difference in soil variable between plantations and natural forests. To summarize the results from independent studies, the weighted response ratio (RR_{++}) was calculated from response ratios (*RR*s) to increase the precision of the combined estimate and the power of the tests. Mean, SE or SD or 95%CI, and n were used to calculate *RR*, RR_{++}, and 95%CI of RR_{++}. Dixon's *Q*-test was performed to exclude outliers of *RR*s at $\alpha = 0.05$. If the 95%CI value of RR_{++} for a soil variable overlapped with zero, the variable was not significantly different between plantations and natural forests. Otherwise, they were statistically different. The percentage change in a variable was estimated by $[\exp(RR_{++}) - 1] \times 100\%$.

In addition to the significance test of differences in soil variables between plantations and natural forests, the frequency distribution of *RR*s was plotted to examine whether the results from the meta-analysis approach were consistent with those from the frequency distribution for soil pH, soil bulk density and soil C and N concentrations. The frequency distribution was assumed to follow a normal distribution, which was ensured by fitting the data to a Gaussian function (i.e. normal distribution):

$$y = a\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \tag{1}$$

where x is the mean of *RR* in individual intervals, y is the frequency (i.e. the number of *RR* values) in an interval, a is a coefficient showing the expected number of *RR* values at $x = \mu$, and μ and σ^2 are mean and variance of frequency distributions of *RR*, respectively (Luo *et al.*, 2006).

For the above four variables, if the 95%CI value of RR_{++} did not overlap between the two groups in relation to SA (le vs. mo), TLF (br vs. co), TLS (de vs. ev), TSO (na vs. ex), LUH (af vs. re), SP (unbt vs. bt) and BZ (tr vs. te), the RR_{++} was considered to be significantly different between the two groups and the factor had a significant impact on the variable. If the 95%CI value of RR_{++} overlapped, Student's *t*-test was used to further examine the difference between the two groups, which was considered to be significant at the level of $P < 0.05$. The percentage change in RR_{++} and its 95%CI for soil pH were calculated based only on mean value of *RR* from each case, because pH is a logarithmic scale and its SE, SD or 95%CI cannot be converted back to calculate RR_{++} (see Berthrong *et al.*, 2009).

In order to better understand impacts of plantations on soil systems, correlation analysis was conducted to examine whether *RR*s of the above four variables were significantly correlated with each other, and with plantation age and latitudes of study regions, respectively. We did not take precipitation and temperature into account for the divisions and the correlation analysis

Table 1 Soil variables with numbers of published papers and cases of negative (decrease) and positive (increase) for plantations relative to natural forests, mean and its range of plantation age and soil depth for this meta-analysis.

	Number of							
		Cases			Plantation age (year)		Soil depth (cm)	
Variables	Papers	Total	Decrease	Increase	Mean	Range	Mean	Range
Soil pH	48	89	40	44	32	7–80	18	0 to 5–30
Soil bulk density	40	65	9	54	27	7–75	14	0 to 5–25
Soil C concentration	57	94	76	17	30	7–80	17	0 to 5–30
Soil N concentration	49	81	63	16	30	7–80	18	0 to 5–30
Soil C/N ratio	26	40	23	17	35	11–70	18	0 to 5–30
Soil P concentration	20	31	22	9	27	7–80	14	0 to 5–20
Soil K concentration	17	27	13	13	30	7–80	16	0 to 5–30
Soil Ca concentration	18	26	16	10	31	9–80	21	0 to 5–30
Soil Mg concentration	16	21	15	6	28	9–80	22	0 to 5–30
Soil Na concentration	9	14	8	4	34	12–80	15	0 to 5–20
Soil Al concentration	6	7	4	3	17	10–25	9	0 to 5–15
Soil CEC	17	31	28	3	27	7–60	15	0 to 5–20
Soil base saturation (%)	6	13	10	3	23	10–33	12	0 to 5–20
Soil moisture (%)	11	21	17	4	34	7–70	16	0 to 5–20

Soil CEC, soil cation exchange capacity.

because latitude (north/south) was highly correlated with mean annual precipitation and temperature based on our literature (both $P < 0.001$). We did not intend to focus on the above four variables, as the volume of the data set constructed from selected studies for the residual variables was not large enough ($n < 50$).

RESULTS

A total of 73 published field studies (Appendix S1) with paired-site designs were synthesized for 14 variables from the soil mineral layer (Table 1). A constructed database consisting of 560 lines of entries was used to compute the response ratios of soil variables (Table S1). Secondary forests were dominant in the reference systems. The database covered 22 countries on five continents (North and South America were pooled), but most studies were conducted in four countries: China, the USA, Brazil, and Australia. The three most common species used for plantations were *Cunninghamia lanceolata*, *Pinus caribaea* and *Pinus radiate*, and consequently most of the plantations were coniferous stands. Overstorey stands of plantations were mostly monocultures. The mean age of plantation stands was 30 years, with a range from 7 to 80 years (Table 1). Mean soil depth for the measured variables was 16 cm with a range from 0 to 30 cm (Table 1).

For soil pH, the 95%CI value of percentage change overlapped with zero, suggesting that soil pH did not differ between plantations and natural forests on a global scale (Fig. 1a). Soil bulk density significantly increased by 12.5%, and soil C and N concentrations decreased by 36.0% and 26.5%, respectively, in plantations relative to natural forests (all $P < 0.001$; Fig. 1a). Soil C/N ratio, soil P, K, Ca and Mg concentrations, soil CEC, base saturation and moisture were 8.4–30.6% lower in plantations than in natural forests. Soil Na and Al concentrations were not different between plantations and natural forests. For soil pH, bulk density and soil C and N concentrations ($n > 50$), the frequency distribution of *RR*s could be characterized by a Gaussian normal distribution (all $R \geq 0.93$ and $P < 0.001$; Table 2). For four of the soil variables, the results from the RR_{++} of the meta-analysis approach were consistent with those from the μ simulated by a Gaussian function model. In addition to the 14 variables in the soil mineral layer, the amount of organic matter in the soil O horizon greatly decreased in plantations compared with natural forests ($RR_{++} \pm$ 95%CI = -0.87 ± 0.06, $n = 11$) (Table S2).

General patterns of the differences in the 14 soil variables between plantations and natural forests did not change in association with the planted tree species from the genus *Pinus* (Fig. 1b) and the study regions in China (Fig. 1c). Differences in percentage changes of soil bulk density and soil C and N concentrations were significant between the two groups in relation to SA (le vs. mo), TLF (br vs. co), TLS (de vs. ev), TSO (na vs. ex) (Fig. 2), LUH (af vs. re) and SP (unbt vs. bt) for plantations, and BZ (tr vs. te) (Fig. 3) (all $P < 0.01$). The general patterns of percentage changes for soil bulk density and soil C and N concentrations were similar between the two groups across these factors (Figs 2 & 3). These patterns held true for the study regions of five continents of Africa, America, Asia, Europe and Oceania (Fig. 4b–d). However, the differences in percentage change of soil pH were not significant between the two groups in relation to these various factors (Figs 2 & 3), or among the five continents (Fig. 4a).

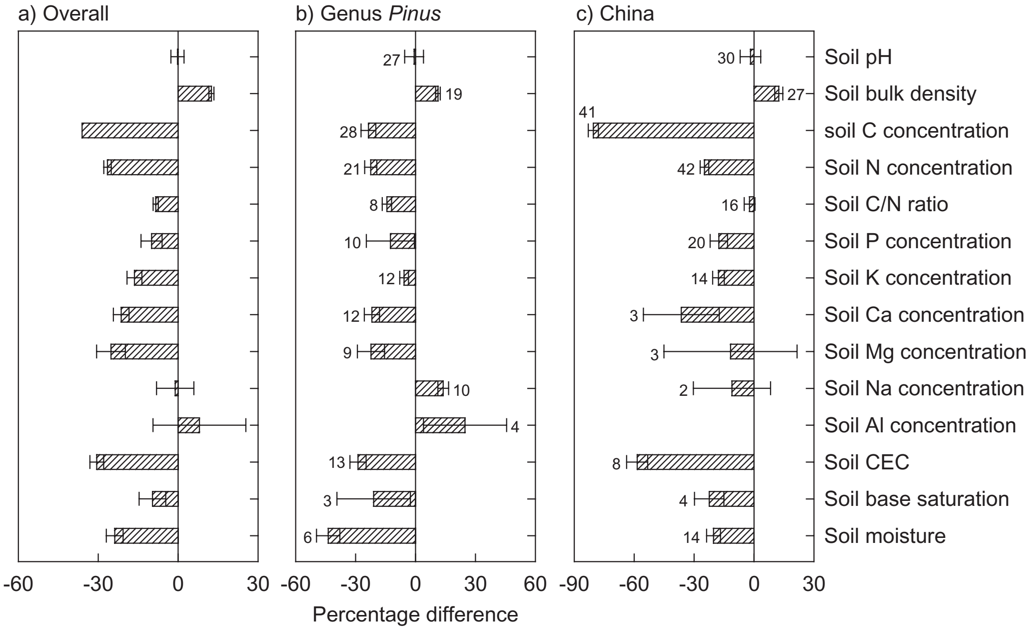

Figure 1 Percentage difference in 14 soil variables between natural forests and plantations on a global scale (a), from the planted tree species of the genus *Pinus* (b) and for study regions of China (c). Bars represent mean ± 95%CI. Values near each bar indicate the numbers of cases synthesized.

Table 2 Statistical values for the meta-analysis approach and the Gaussian function for mineral soil pH, bulk density and C and N concentrations.

	Meta-analysis approach	Gaussian function	
Variables	RR_{++} ± 95%CI	μ ± 95%CI	*R*
Soil pH	−0.00 ± 0.02	−0.08 ± 0.16	0.99***
Soil bulk density	0.12 ± 0.01	0.12 ± 0.04	0.98**
Soil C concentration	−0.31 ± 0.01	−0.26 ± 0.06	0.97***
Soil N concentration	−0.24 ± 0.02	−0.25 ± 0.08	0.93**

RR_{++}, weighted response ratio; μ, mean of frequency distributions of *RR*; *R*, correlation coefficient.
$^{**}P < 0.01$; $^{***}P < 0.001$.

Correlation analysis showed that for the four variables of soil pH, soil bulk density and soil C and N concentrations, *RR* of one variable was significantly correlated with that of another (all $P < 0.05$) except for the correlation between soil pH and soil C concentration (Table 3). Correlation analysis also showed that *RR*s of the four soil variables were not statistically correlated with the stand age of plantations and latitude (degrees north/south) of study regions except for the correlation between *RR*s of soil C concentration and stand age ($P = 0.04$).

DISCUSSION

Impact of plantations on soil pH

Our results showed that soil pH did not differ between plantations and natural forests across various factors. This is in contrast with results from previous reviews by Jackson *et al.* (2005) and Berthrong *et al.* (2009). They showed that mean soil pH significantly decreased by 0.3 units below plantations compared with non-forested lands. They also found that soil Na concentration was 71% higher below plantations than below non-forested lands. The increase in soil Na concentration might be responsible for the reduction in soil pH. However, the soils from regions with the same climate tend to be more acidic below forests than non-forested lands such as grasslands (Chapin *et al.*, 2002; Berthrong *et al.*, 2009). As the strongest predictors of soil pH, soil Na and Al concentrations did not differ between plantations and natural forests in this meta-analysis (Fig. 1a). Therefore, we concluded that the effect of plantations on soil pH was to a certain extent determined by their reference systems.

Impact of plantations on soil bulk density

This meta-analysis showed that in 54 of 65 cases soil bulk density was higher in plantations than in natural forests

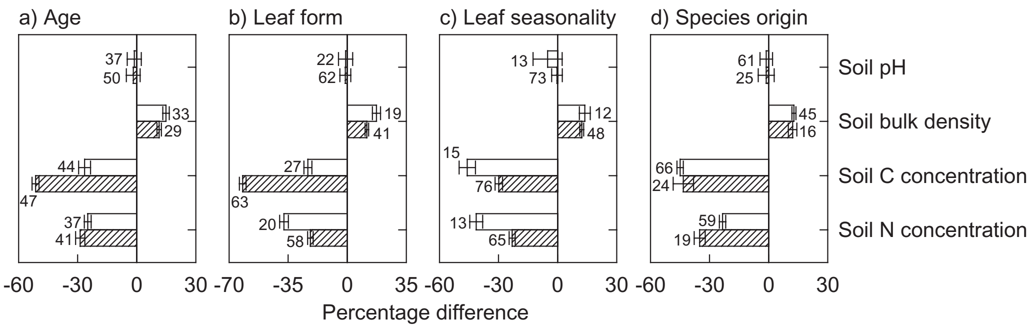

Figure 2 Percentage difference in soil pH, soil bulk density and soil C and N concentrations between natural forests and plantations globally in relation to stand age (a), tree leaf form (b) and seasonality (c), and species origin of plantations (d). Bars represent mean ± 95%CI. Values near each bar indicate the numbers of cases synthesized. Note: open bars (a) < 25 years, (b) broadleaved, (c) deciduous, and (d) native; hatched bars (a) ≥ 25 years, (b) coniferous, (c) evergreen, and (d) exotic.

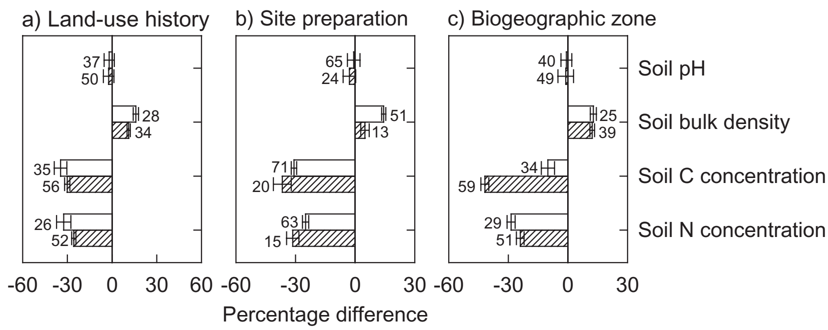

Figure 3 Percentage difference in soil pH, soil bulk density and soil C and N concentrations between natural forests and plantations globally in relation to land-use history (a), site preparation for plantations (b), and study region (c). Bars represent mean ± 95%CI. Values near each bar indicate the numbers of cases synthesized. Note: open bars (a) afforestation, (b) unburnt treatment, and (c) tropical; hatched bars (a) reforestation, (b) burnt treatment, and (c) temperate.

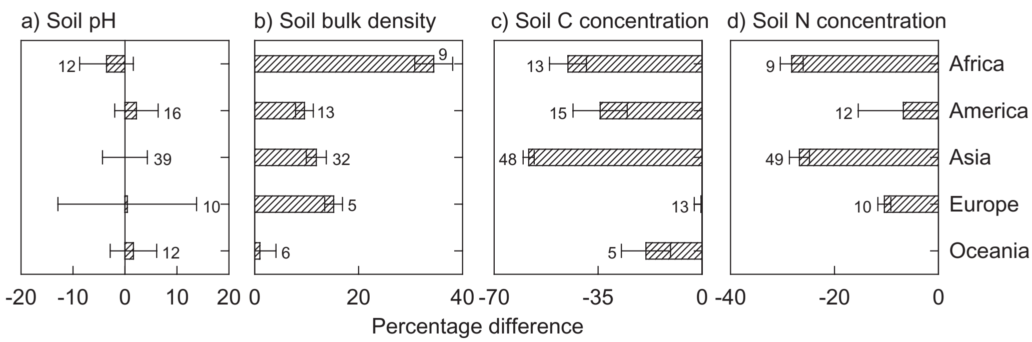

Figure 4 Percentage difference in soil pH (a), soil bulk density (b), soil C (c) and N concentrations (d) between natural forests and plantations for five continents. Bars represent mean ± 95%CI. Values near each bar indicate the numbers of cases synthesized.

(Table 1). Considerable aboveground biomass was removed from lands when plantations were established (e.g. Johnson & Curtis, 2001; Chen *et al.*, 2005; Berthrong *et al.*, 2009; Nave *et al.*, 2010). In addition, site preparation, slash thinning and weed control can lead to little or no understorey herbaceous cover under plantations which are mostly monocultures (Yang *et al.*, 2005; Zheng *et al.*, 2008). These activities may expose the soil to solar radiation, leading to higher temperatures during the cultivation of plantations, and consequently increasing soil evaporation. Besides the environmental changes, other activities such as frequent trampling of heavy harvesters and trucks on the soil surface may make soil compact, increasing soil bulk density in plantations. Increase in soil bulk density, i.e. soil compaction, is a global concern due to adverse effects on soil environments and stand productivity (FAO, 2005). Soil compaction may limit the access of roots to water and nutrients, destroy soil structural

	Soil bulk density		Soil C concentration		Soil N concentration	
Variables	d.f.	*R*	d.f.	*R*	d.f.	*R*
Soil pH	43	–0.44**	64	0.20	60	0.44***
Soil bulk density			50	–0.68***	34	–0.68***
Soil C concentration					70	0.84***

d.f., degree of freedom; *R*, correlation coefficient; $^{**}P < 0.01$; $^{***}P < 0.001$.

Table 3 Correlation analysis of response ratios (*RR*) among soil pH, bulk density, and C and N concentrations. *RR* is the logarithm ratio of the mean value of a concerned soil variable under plantations to that in natural forests.

units, slow gaseous diffusion and reduce rates of root respiration and litter decomposition (Tokunaga, 2006).

Impact of plantations on soil nutrients

The decreased soil C and N concentrations could be attributable to the differences in ecosystem properties between plantations and natural forests. Plantations had significantly lower net primary production (percentage change ± 95%CI = –10.6 ± 3.1, $n = 9$), aboveground biomass (–21.5 ± 4.1, $n = 16$), litterfall (–36.3 ± 1.8, $n = 27$), aboveground litter mass (–29.1 ± 3.5, $n = 29$) and fine root biomass (–75.8 ± 10.5, $n = 19$) than natural forests (Liao *et al*., 2010). These differences may result in lower C input into soils under plantations than under natural forests. Besides these, some forest management measures, for instance, whole-tree harvesting, may also cause a reduction in soil C for plantations (Johnson & Curtis, 2001). The decrease in soil C can lead to a reduction of soil N due to the tight coupling between ecosystem C and N cycles (e.g. Luo *et al*., 2006). Additionally, site preparations involving burning for establishing plantations might also increase soil C and N losses (Fig. 3b).

There might be limitations in examining soil C concentration instead of its pool size. However, 57 of 73 papers constructed for the datasets in this meta-analysis were overlapped with those from the synthesis by Liao *et al*. (2010), in which the soil C pool decreased by 18.7% in plantations relative to natural forests. Consequently, the soil C pool was smaller, even though soil bulk density was higher in plantations than in natural forests. A previous quantitative review showed that the soil C pool decreased by 13% after the conversion of natural forests to plantations ($n = 30$). A recent study using $\delta^{13}C$ analysis and mathematical modelling also demonstrates that there is a significant difference in the soil C pool (soil organic carbon, SOC) between plantations (18.6 ± 2.7 kg SOC m^{-3}, mean ± SE) and natural forests (23.5 ± 3.2 kg SOC m^{-3}) (Freier *et al*., 2010).

The decreases in soil P, K, Ca and Mg nutrients in plantations relative to natural forests might be caused by harvesting biomass, burning slash and logging residues during site preparation, thinning during silvicultural activities, and uptake of cations into aboveground biomass by fine roots in plantations (Paul *et al*., 2002; Jobbágy & Jackson, 2003; Berthrong *et al*., 2009). The reduced soil K, Ca and Mg nutrients can lead to the reduction of soil CEC and cation saturation. In this meta-analysis, soil Na and Al concentrations did not differ between plantations and natural forests. The possible reason is that soil Na and Al elements are not essential to plant growth (Jobbágy & Jackson, 2003; Berthrong *et al*., 2009).

Unlike soil C and N nutrients, soil P, K, Ca, Mg, Na and Al nutrients from parental rock weathering and groundwater, could not be fixed from the atmosphere by plants (Chapin *et al*., 2002; Jobbágy & Jackson, 2003). Biogeographic conditions control weathering processes of soil parental rocks, and to some extent determine the magnitude of the differences in these soil P, K, Ca, Mg, Na and Al concentrations between plantations and natural forests (e.g. Stone & Gibson, 1975; Augusto *et al*., 1998; Binkley & Giardina, 1998; Jobbágy & Jackson, 2003). For example, the difference in buffering capacity of soil P concentration between plantations and natural forests was different among yellow-brown, red and latosolic red soils, and varied with latitude, precipitation and temperature (Hu *et al*., 2005). The effects of plantations on these variables might be minor relative to those of biogeographic factors (Augusto *et al*., 1998; Binkley & Giardina, 1998; Chapin *et al*., 2002). Due to the manifold factors that might have contributed to the differences in these variables, it will probably be rewarding to perform further meta-analysis when new data become available.

Impact of plantations on soil moisture

The decreased soil moisture in plantations relative to natural forests (Fig. 1a) was in good agreement with results from reviews by Jackson *et al*. (2005) and van Dijk & Keenan (2007). Plantations afforested in croplands, grasslands and shrublands decreased stream flow by 180 mm $year^{-1}$ and 38% on average globally, and the climate feedbacks are unlikely to offset the soil water loss (Jackson *et al*., 2005). In our study, the decreased soil moisture might be due to the net deficiency between evapotranspiration and precipitation which are two major processes in ecosystem water cycles. The amount of water lost through evapotranspiration is greater than the amount of water gained through precipitation in plantations (Benyon *et al*., 2006; Stape *et al*., 2008). The decreased soil moisture may limit root growth and the increment of stand biomass in plantations.

Relationships among soil variables and ecological factors

*RR*s of soil bulk density and soil C and N concentrations were correlated with each other (Table 3). Our results were consistent with many previous field studies, in which soil bulk density increased and soil C and N concentrations decreased in plantations relative to natural forests (e.g. Aborisade & Aweto, 1990; Solomon *et al.*, 2002; Nsabimana *et al.*, 2008). This meta-analysis also showed that soil variables were weakly correlated with stand age of plantations and latitude of study regions, indicating that the present soil fertility in plantations might be unlikely to restore to the level in natural forests regardless of temporal and geographic conditions. The decrease in soil C/N ratio (Fig. 1a) might alter soil stoichiometric relationships and disrupt the balance between soil C and N cycles in plantations in comparison with natural forests. We did not find a case from our literature for this meta-analysis, in which plantations were established intentionally on degraded lands. This meta-analysis revealed that the overall direction and magnitude of impacts of plantations on soil variables were similar at either a regional or continental scale (Figs 1c, 3c & 4). These findings might facilitate model simulation and projection of global biogeochemical cycles for plantation feedbacks to future climate change.

Methodological considerations

There are some uncertainties with a meta-analysis approach. Different experimental designs such as paired-site, chronosequence and retrospective designs, measuring a given variable, could cause uncertainties from different individual studies (Laganière *et al.*, 2010). Different sampling methods could lead to uncertainties in individual studies. For instance, soil pH was measured with a different range of soil depth, such as 0 to 10 cm by Solomon *et al.* (2002) and 0 to 20 cm by Chen *et al.* (2005). Study regions were not randomly distributed in forest ecosystems, and datasets constructed for meta-analysis might have come from regions where ecologists have conducted extensive studies, for example in China, while many other plantation regions have not attracted much attention from ecologists. This could cause biases in evaluation of the impacts of plantations. In addition, management options such as fertilization, thinning and pruning for plantations could lead to uncertainties. For example, fertilization with N, P, K and other nutrients may increase soil fertility, but we did not observe such results in our comparisons possibly due to the limited number of cases used. Furthermore, the number of study cases for some variables such as soil Na concentration ($n = 7$, Table 1) was relatively small, and the RR_{++} might be sensitive to additions and deletions of published studies. However, it is difficult to evaluate these uncertainties (Liao *et al.*, 2008; Laganière *et al.*, 2010). Nevertheless, together with the modelling of Gaussian distribution and the correlation analysis, the method of meta-analysis offers a powerful statistical analysis, and these uncertainties might be unlikely to change the general patterns of the differences in soil properties between plantations and natural forests.

Implications for forest management

It has been acknowledged that plantations established in marginal agricultural or bare lands can reduce soil erosion, diversify landscapes and improve revenues over a long history. At the same time, plantations can provide wood for a variety of uses. Our results from this meta-analysis have several ecological implications for forest management. First, degradation of soil fertility might occur in plantations relative to natural forests, which might not meet the increasing demands for timbers from plantations in the long term. As the country with the largest area (6.2×10^7 ha) of plantations in the world, China might now face a great challenge for plantation management. Second, our results might argue against the common practice that the replacement of natural forests by plantations is used as a measure for C sequestration, which is a hot topic for the United Nations' Climate Change Conference. Soil compaction, soil nutrient depletion and soil desiccation induced by plantations might possibly accelerate the ongoing environmental changes. Third, at present, what can be done is to conserve natural forests. For example, the 'Natural Forest Protection Project' that began in 1998 has effectively covered more than half of the total area of natural forests in China (1.20×10^8 ha). At the same time, it is urgent that more efforts are made to develop a management policy for plantation practice that minimizes their negative impacts on soil fertility but maximizes their commodity values.

Conclusions

This meta-analysis has demonstrated that plantation practice had negative impacts on a number of soil properties including soil bulk density and soil C and N concentrations when compared with their adjacent natural forests. This indicates that plantations do not have the same functions of maintaining or improving soil fertility as natural forests. Differences in percentage change of soil properties in plantations relative to natural forests can be in association with categorized groups of various factors such as stand type, land-use history and site preparation of plantations, and biogeographic conditions in the study regions, but the general patterns of the percentage changes hold true for most soil properties.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1 *RR* or RR_{++} and the number of cases for 14 soil variables extracted from each of the 73 papers.

Table S2 *RR* or RR_{++} and the number of cases for organic matter pH value, C and N stocks, P, K, Ca and Mg concentrations in the soil O horizon.

Appendix S1 A list of 73 published papers from which data on soil variables were extracted for this meta-analysis.

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BIOSKETCHES

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