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Changes in soil quality due to converting *Pinus* to *Eucalyptus* plantations and subsequent successive *Eucalyptus* planting in southern China

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Abstract

Plants play a key role in maintaining soil quality, but long-term changes in soil quality due to plant species change and successive planting are rarely reported. Using the space-for-time substitution method, adjacent plantations of *Pinus* and 1st, 2nd, 3rd and 4th generations of *Eucalyptus* in Guangxi, China were used to study changes in soil quality caused by converting *Pinus* to *Eucalyptus* and successive *Eucalyptus* planting. Soil chemical and biological properties were measured and a soil quality index (SQI) was calculated. Soil organic carbon, total nitrogen, alkaline hydrolytic nitrogen, microbial biomass carbon, microbial biomass nitrogen, cellobiosidase, phenol oxidase, peroxidase and acid phosphatase activities significantly decreased in the 1st and 2nd generations of *Eucalyptus* plantations after conversion from *Pinus* to *Eucalyptus*, but gradually recovered in the 3rd and 4th generations. Soil total and available potassium were significantly lower, but total phosphorus was significantly higher in *Eucalyptus* plantations compared to the *Pinus* plantation. As an integrated indicator, SQI was highest in the *Pinus* plantation (0.92), but decreased to 0.24 and 0.13 in the 1st and 2nd generations of *Eucalyptus* plantations, respectively. However, it recovered to 0.36 and 0.38 in the 3rd and 4th generations, respectively. Changing tree species, reclamation and fertilization may have contributed to the "U" shaped change observed in soil quality during conversion of *Pinus* to *Eucalyptus* and successive *Eucalyptus* planting. Litter retention, keeping understory coverage, and reducing soil disturbance during logging and subsequent establishment of the next rotation should be considered to help improving soil quality during plantation management.

1 Introduction

Vegetation plays a key role in soil development due to its influence on nutrient cycling, hydrological processes and soil erosion (de la Paix et al., 2013; Zhao et al., 2013). Soil degradation caused by deforestation is a serious problem and afforestation is of-

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ten recommended as an effective way to protect soil surface and improve soil quality (Miao et al., 2012; Zhao et al., 2013), as well as produce timber. *Eucalyptus* is an important tree species for afforestation in tropical or subtropical regions and has been introduced to many countries around the world. In southern China, millions of hectares of degraded land, cropland and natural secondary forest have been converted into *Eucalyptus* plantations and successive planting has been undertaken (Wen et al., 2009). However, due to nutrient limitations in many areas (LeBauer and Treseder, 2008) and a high demand for nutrients by *Eucalyptus* (Laclau et al., 2010), this kind of land use change may exhaust soil nutrients and decrease soil quality. Inappropriate plantation management also accelerates the decline in soil quality (Yu et al., 2009). There is an urgent need to assess the effects that *Eucalyptus* planting has on soil quality since it plays a key role in sustaining forest productivity.

Soil quality includes soil physical, chemical and biological properties, as well as soil processes and their interactions (Andrews and Carroll, 2001). Many studies have focused on soil physicochemical properties (Garay et al., 2004), microbial communities (Wu et al., 2012) or enzyme activities (Wang et al., 2008), which only reflect some aspects of soil quality. The soil quality index (SQI) provides a tool for quantifying the combined biological, chemical and physical response of soil to land use and soil/crop management practices (Andrews and Carroll, 2001; Andrews et al., 2002). It provides an intelligible and more holistic measurement of soil quality and, in recent years, the SQI has been used to assess the impacts of land use change, forest and cropland management and ecological restoration (Navas et al., 2011). Methods used to calculate SQI include expert opinion and principal component analysis (PCA) (Andrews et al., 2002), with the latter more widely used in recent studies (Navas et al., 2011).

The ecological consequences of *Eucalyptus* planting are important and have been studied in depth. Some studies have reported that soil organic carbon, nitrogen, microbial biomass and the metabolic quotient were significantly lower in *Eucalyptus* plantations compared to natural and regenerated forests or pastures (Behera and Sahani, 2003; Chen et al., 2013; Sicardi et al., 2004; Araújo et al., 2010). However, other stud-

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ies have found that the conversion of native savanna or sugarcane fields to *Eucalyptus* plantations did not change soil total organic carbon, microbial biomass carbon or nitrogen levels (Binkley et al., 2004). Fialho and Zinn (2012) compiled paired-plot studies on how SOC stocks under native vegetation change after planting fast-growth *Eucalyptus* species in Brazil and found that *Eucalyptus* plantations on average had no net effect on soil organic carbon stocks. The results of these different studies were not consistent and the effect of successive *Eucalyptus* planting has rarely been reported.

In order to access the effects of converting *Pinus* to *Eucalyptus* and subsequent successive *Eucalyptus* planting on soil quality, we selected adjacent plantations of local *Pinus massoniana* Lamb. (*Pinus*) and 1st, 2nd, 3rd and 4th generations of *Eucalyptus urophylla* × *grandis* (*Eucalyptus*) in Guangxi, China. The changes in soil quality were investigated by measuring the soil chemical and biological properties and by calculating a SQI using the PCA method for each plantation. Considering soil nutrients exhaustion was the main problem in *Eucalyptus* plantation, the soil physical attributes were not considered in this study. We hypothesized that (1) converting *Pinus* to *Eucalyptus* plantations would significantly decrease soil quality, and (2) soil quality would continue to decrease with successive *Eucalyptus* planting.

2 Materials and methods

2.1 Study area

This study was conducted at Fusui, Guangxi, China (22°14′–22°21′ N, 107°47′–107°56′ E). The altitudes of our study sites were between 140 and 250 m a.s.l., the slope aspects were southeast and the slope angles were less than 15°. The region has a typical subtropical monsoon climate with mean annual temperatures of 21.2–22.3 °C. The rainfall is 1100–1300 mm per year, concentrated during June–August. Soils in the region are mainly lateritic red earth with soil depth of 80 cm or more and are derived from arenaceous shale with a pH ranging from 4 to 5.

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This area was dominated by *Pinus* until the end of the 1970s and had a rotation of about 30 years. No management practices were carried out in the *Pinus* plantations, except lacerating the tree bark for oil. However, over time, fast-growing *Eucalyptus* began to replace *Pinus* and it has become the dominant tree species in this area. Clear-cutting and fire clearance were carried out during the conversion of *Pinus* to *Eucalyptus* plantations and full reclamation (plowed to 50 cm depth) was conducted prior to *Eucalyptus* planting (1st generation) with seedlings. The tree density in the *Eucalyptus* plantations was 1250–1667 trees ha^{-1} and there was a 5 year rotation period. The 2nd generation *Eucalyptus* was regenerated by sprouts without plowing. After strip reclamation (plowed to 50 cm depth), the 3rd generation *Eucalyptus* was planted with seedlings. The 4th generation was regenerated by sprouts without plowing. The surface soil was bare for about 2 months before *Eucalyptus* seedling planting. During the crop transition periods, soil erosion happened easily due to the lack of vegetation protection.

Before planting, base fertilizer (500 g $seedling^{-1}$, N : P : K = 10 : 15 : 5) was put into a 20 cm deep soil hole and covered with soil. At 6, 12 and 24 months after planting, 250, 500 and 500 g, respectively, of fertilizer (N : P : K = 15 : 10 : 8) per tree was separately applied in soil holes that were 30 cm away from each tree. The application of herbicide (glyphosate) was performed once a year during the first 3 years after *Eucalyptus* planting and consequently the coverage of understory plants was less than 50 %. However, the understory coverage increased gradually in the 4th and 5th year after *Eucalyptus* planting. The leaf, branch and bark litter were kept in the plantation during the plant growth period, but at harvest time, most branch litter was removed and burned before the next rotation.

2.2 Experimental design and sampling

The adjacent plantations of local *Pinus* and 1st, 2nd, 3rd and 4th generations of *Eucalyptus* at the Dongmen Forestry Farm were selected to represent *Pinus* planting and 1st, 2nd, 3rd and 4th generations of successive *Eucalyptus* planting. Three 20 m × 20 m plots were marked out in each plantation site. During sampling time, the tree, shrub and

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grass coverage in the *Pinus* plantation was about 60 %, 25 % and 70 %, respectively. The tree, shrub and grass coverage in the *Eucalyptus* plantations was similar, about 40 %, 10 % and 45 %, respectively. The litter layer was about 3 cm depth in the *Pinus* plantation and 1 cm depth in the *Eucalyptus* plantations.

In October 2010, soil from the top 0–10 cm layer was collected from the study sites. At the time of soil sampling, the ages of *Pinus* and *Eucalyptus* were 20 years and 3 years, respectively. Ten soil cores were randomly collected in each plot using a 3.6 cm diameter soil auger and mixed together as a composite sample. Three composite samples were collected at each site. The soil samples were immediately transported to the laboratory. Stones and roots were removed from the soil samples by hand and then the soil samples were sieved through 2 mm sieves. Some soil was stored at 4 °C for soil microbial biomass and enzyme activity analyses, while the remaining soil was air dried for chemical analyses.

2.3 Soil chemical and biological analyses

Soil water content was determined gravimetrically after oven-drying at 105 °C for 24 h in order to correct sample weights in biochemical property measurements. Soil pH was measured in deionized water (1 : 2.5 w/v) using a Delta 320 pH-meter (Mettler–Toledo Instruments (Shanghai) Co., Ltd.). Soil organic carbon (SOC) was measured using the Walkley and Black wet oxidation procedure method as outlined in Bao (2000). Soil total nitrogen (TN) was determined by combustion in a Vario EL III Elemental Analyzer (Elementar Analysensysteme GmbH, Germany). Soil alkaline hydrolytic nitrogen (AN) was measured according to Bao (2000). 1 g air-dried soil was incubated in 5 mL sodium hydroxide solution (1.2 M) in the outside ring of an airtight Conway diffusion cell and 3 mL boric acid (0.3 M) was put in the inner well at 40 °C for 24 h. With Methyl red-bromocresol green as indicator, 0.01 M hydrochloric acid was used to titrate ammonia absorbed in the boric acid. For total phosphorus (TP) and total potassium (TK), air-dried soil samples were digested using 18.4 M sulfuric acid (1 : 10 w/v) and 12.7 M perchloric acid at 275 °C for 6 h, TP and TK were measured using a Prodigy High Dis-

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persion ICP-OES (Teledyne Technologies Incorporated, USA). Available phosphorus (AP) was measured after extraction with 0.05 N sulfuric and 0.025 N hydrochloric acids (1 : 5 w/v) with shaking for 5 min and available potassium (AK) was measured after extraction with 1 N ammonium acetate solution (1 : 10 w/v) with shaking for 30 min (Bao, 2000). AP and AK were measured using the Prodigy High Dispersion ICP-OES.

Soil microbial biomass carbon and nitrogen (MBC and MBN) were estimated using the chloroform fumigation extraction method (Vance et al., 1987). Soil β-glucosidase (BG), phenol oxidase (PO), peroxidase (POD) and acid phosphatase (ACP) activities were measured according to Waldrop et al. (2000). Soil protease (PRO) activity was estimated according to Ladd and Butler (1972). Soil urease (URE) activity was assessed according to Kandeler and Gerber (1988). Soil cellobiosidase (CBH) activity was measured using the fluorimetric method according to Saiya-Cork et al. (2002).

2.4 SQI

SQI was calculated according to Andrews and Carroll (2001). Three steps were involved in the elaboration of this quality index: definition of a minimum data set (MDS), assignment of a score to each indicator by linear scoring functions and data integration into an index.

Three steps were used to identify the MDS in our study. (1) Data screening. One-way analysis of variance (ANOVA) was performed for soil chemical and biological properties. Only variables with significant differences between treatments ($p < 0.05$) were chosen for the next step. (2) Selection of representative variables. PCA was performed on the variables chosen from step (1). Only principal components (PCs) that explained at least 5 % of the variation in the data up to 85 % of the cumulative variation were examined. Within each PC, only weighted factors with absolute values within 10 % of the highest weight were retained for the MDS. (3) Redundancy reduction. Multivariate correlation coefficients were used to determine the strength of the relationships among variables. Well-correlated variables (Correlation coefficient > 0.70) were considered redundant and candidates for elimination from the data set. To choose variables within

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well-correlated groups, we summed the absolute values of the correlation coefficients for these variables and assumed that the variable with the highest correlation sum best represented the group. The choice among well-correlated variables was also based on the published references and expert opinion about the soils and sites (Xu, 2000; Wang et al., 2008; Yu et al., 2009). Any uncorrelated, highly weighted variables were considered important and retained in the MDS.

Linear scoring was used in our study. Indicators were ranked in ascending or descending order depending on whether a higher value was considered "good" or "bad" in terms of soil function. In our study, all variables were "more is better". The linear scoring function used for converting measured values to scored values is as follows (Zheng et al., 2005):

$$S_{ij} = \frac{V_{ij} - V_{i\min}}{V_{i\max} - V_{i\min}}$$

Where S_{ij} is the score of soil variable i of sample j, V_{ij} is the observed variable value of sample j, $V_{i\max}$ is the highest value of variable i, and $V_{i\min}$ is the lowest value of variable i.

The scores of the indicators were integrated into a SQI according to Andrews et al. (2002) as follows:

$$\mathrm{SQI} = \sum_{i=1}^{n} \frac{S_i}{n}$$

Where S_i is the score assigned to indicator i, and n is the number of indicators included in the MDS.

2.5 Statistical analyses

We acknowledge that the three 20 m × 20 m plots established per site do not constitute true replicates, because they are located within the same site of the 5 plantations

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(*Pinus*, 1st, 2nd, 3rd and 4th generations *Eucalyptus* plantations) and no plots were established in other stands with similar plantation characteristics. Nevertheless, these plantation stands occur in similar topographic conditions and soil parent material, and they were similar in planting history of *Pinus* plantation before the 1970s. That allowed us to consider the five sites as different treatments. Therefore, one-way variance analyses were used to test the significant differences in soil chemical and biological properties and SQIs among these treatments. Normality of the data was tested using the Kolmogorov–Smirnov test and the soil indicators obeyed standard normal distribution. Tukey's test was used for multiple comparison analysis. All statistical analyses were performed using SPSS 10.0 (SPSS Inc., Chicago, IL, USA) and SigmaPlot for Windows version 11.0 (Systa Software Inc.).

3 Results

3.1 Soil chemical properties

The SOC, TN and AN ranges at our study sites were 10.8–26.9 g kg^{-1}, 0.9–1.6 g kg^{-1} and 41.4–60.3 mg kg^{-1}, respectively. They were highest in the *Pinus* plantation, significantly decreased in the 1st and 2nd generations *Eucalyptus* plantations and then gradually recovered in the 3rd and 4th generations (Fig. 1b, c, and f). SOC and TN in the 4th generation *Eucalyptus* were significantly lower than in the *Pinus* plantation, but significantly higher than in the 2nd generation ($p < 0.05$). Soil AN in the 4th generation was significantly higher than in the 2nd generation, but not different from that in the *Pinus* plantation ($p < 0.05$).

Soil TP was significantly lower in the *Pinus* plantation (0.41 g kg^{-1}) than in the *Eucalyptus* plantations (0.90–1.07 g kg^{-1}) ($p < 0.05$). In the *Eucalyptus* plantations, soil TP decreased in the 2nd generation and then recovered in the 3rd and 4th generations (Fig. 1d). Soil AP was 2.98 mg kg^{-1} in the *Pinus* plantation, but increased to 5.03 and 5.14 mg kg^{-1} in the 1st and 2nd generation *Eucalyptus* plantations, respectively, and

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then decreased to 2.56 and 2.93 mg kg^{-1} in the 3rd and 4th generations, respectively (Fig. 1g).

Soil TK and AK ranged from 1.8–6.3 g kg^{-1} and 24–92 mg kg^{-1}, respectively. TK was significantly lower in the *Eucalyptus* plantations than in the *Pinus* plantation, without significant differences among *Eucalyptus* generations (Fig. 1e). AK was significantly higher in the *Pinus* plantation and showed a decreasing trend with successive *Eucalyptus* planting ($p < 0.05$) (Fig. 1h).

3.2 Soil microbial biomass carbon and nitrogen

Soil MBC and MBN in our study sites ranged from 278 to 673 mg kg^{-1} and from 7 to 35 mg kg^{-1}, respectively. They were the highest in the *Pinus* plantation. Soil MBC decreased significantly in the 1st and 2nd generation *Eucalyptus* plantations and then gradually recovered in the 3rd and 4th generations. Soil MBN decreased significantly in the 2nd generation. The difference between changes in soil MBC and MBN was that MBN in the 3rd and 4th generations of *Eucalyptus* plantations recovered to the same level as in the *Pinus* plantation (Fig. 2b), but MBC in the 3rd and 4th generations of *Eucalyptus* plantations was significantly lower than in the *Pinus* plantation (Fig. 2a). The MBC/MBN ratio was significantly higher in the 2nd generation *Eucalyptus* plantation than in other plantations (Fig. 2c).

3.3 Soil enzyme activities

Soil BG activity was highest in the *Pinus* plantation and decreased with successive *Eucalyptus* planting (Fig. 3a). Soil CBH, PO, POD, PRO and ACP activities were the highest in the *Pinus* plantation. Soil CBH and POD activities decreased in the 1st and 2nd generations of *Eucalyptus* plantations, but gradually recovered in the 3rd and 4th generations (Fig. 3b and d). Soil PO, PRO and ACP activities decreased in the 1st generation *Eucalyptus* plantation, but gradually recovered in the 2nd, 3rd and 4th generations (Fig. 3c, e and g). Soil URE activity was significantly higher in the *Pinus* planta-

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tion than in the *Eucalyptus* plantations ($p < 0.05$), with no significant differences among *Eucalyptus* plantations (Fig. 3f).

3.4 Soil quality index

Soil pH is neither a "more is better" nor "less is better" indicator and the difference of soil pH among plantations is not significant. Except for soil pH, all soil properties were analyzed using the PCA method to identify PCs and MDS. Three PCs were selected in our study and they included eight variables (Table 1). PC1 contained SOC, TN, TK, PO, POD and ACP, which represent soil nutrient contents and enzyme activities; PC2 contained AK and PC3 contained CBH. These eight variables were used in the SQI calculation.

The SQI was calculated from the soil quality indicator scores (Table 2). The highest SQI was found in the *Pinus* plantation (SQI = 0.92). In the *Eucalyptus* plantations, the SQI significantly decreased to 0.13 in the 2nd generation plantation ($p < 0.05$), which was 86 % lower than in the *Pinus* plantation. However, in the 4th generation plantation, it had significantly recovered to 0.38 ($p < 0.05$), which was 59 % lower than in the *Pinus* plantation (Fig. 4).

4 Discussion

4.1 Decrease in soil quality in the 1st and 2nd generation *Eucalyptus* plantations after converting pinus to *Eucalyptus* plantation

Our study found that SOC, TN, AN, TK, AK, MBC, MBN and enzyme activities significantly decreased in the 1st and 2nd generation *Eucalyptus* plantations after converting *Pinus* to *Eucalyptus* (Figs. 1, 2 and 3). This is consistent with many studies, which reported that SOC, TN, MBC, carbon metabolic activity and metabolic quotient were significantly lower in *Eucalyptus* plantations than in natural and regenerated forest or pastures (Behera and Sahani, 2003; Sicardi et al., 2004; Chen et al., 2013). However,

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in our study, soil TP was significantly higher in *Eucalyptus* plantations, which might be caused by fertilization in *Eucalyptus* plantations and the low mobility of phosphorus. The decreased soil quality in the 1st and 2nd generations of *Eucalyptus* plantations after converting *Pinus* to *Eucalyptus* plantation may have been caused by tree species change, full reclamation, herbicide application, clear-cutting and short rotation.

Eucalyptus has a fast growth rate and a strong nutrient absorption capacity, which means that it removes and converts more nutrients from the soil into plant biomass (Laclau et al., 2005), resulting in lower nutrient contents in the soil (Fig. 1). Tesfaye et al. (2014) evaluated seven tree species for fuelwood and soil restoration and found that *Eucalyptus* presented the highest growth rates and biomass, but depleted soil nitrogen. The depletion of soil nitrogen in *Eucalyptus* plantations was also found by Wen et al. (2009). Soil nutrient levels affect soil microorganisms (Chen et al., 2013). The lower soil nutrient contents in the 2nd generation *Eucalyptus* plantation may lead to lower soil microbial biomass and enzyme activities and a higher MBC/MBN ratio (Figs. 2 and 3).

Full reclamation normally breaks the soil structure, exposes more aggregates and accelerates organic matter decomposition (Zinn et al., 2002), which would lead to lower soil organic matter levels in the *Eucalyptus* plantations. Understory vegetation may provide a better microcosm for microorganisms and alleviate storm erosion and nutrient leaching (Yu et al., 2000a), but they were destroyed in our study sites by herbicide applications during the first 3 years of *Eucalyptus* planting. Compared to the higher plant coverage and deeper litter layer in the *Pinus* plantation, the lower plant coverage and shallower litter layer in *Eucalyptus* plantations could not offer an appropriate protection for the broken soil structure and increased nutrient availability caused by reclamation, thus resulting in significant soil erosion and nutrient leaching.

At harvest, clear-cutting totally destroyed plant coverage and the subsequent fire clearance burned all the residues and the litter layer, which resulted in bare ground prior to *Eucalyptus* planting. Soil erosion and nutrient leaching can occur during heavy rainfall if there is no protection from plant and litter layers (Yu et al., 2000a). Fire also

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removes significant amounts of organic matter (Certini, 2005) and nutrients are lost through volatilization (Fisher and Binkley, 2000). Soil microbial biomass decreases during fire because of increased decay and death of heat-sensitive microbes or through alterations to soil physico-chemical properties (De Marco et al., 2005). These factors might be the reasons for decreased soil organic carbon, nutrient contents, microbial biomass and enzyme activities after conversion (Figs. 1, 2 and 3) in our study.

Eucalyptus cultivation rotations are very short (only 5 years) compared to *Pinus* (30 years), which means that there is frequent biomass loss in *Eucalyptus* plantations. Furthermore, short rotations have an impact on the nutrient absorption patterns and the soil nutrient returns. During the early stages of plant life, nutrient absorption is high and litter production is small, but during the later growth stages, the reverse happens (Xu, 2000). The short rotation caused *Eucalyptus* in the plantations at the early stages of life, which means a large nutrient absorption from the soil and a very small litter return.

4.2 Recovery in soil quality in the 3rd and 4th generation *Eucalyptus* plantations

Our results showed that after the sudden decline following converting *Pinus* to *Eucalyptus*, SOC, TN, MBC, CBH, PO, POD, ACP activities recovered in the 3rd and 4th generations, albeit lower than that in the native *Pinus* plantation (Figs. 1, 2 and 3). This is inconsistent with Yu et al. (2000b), who recorded that soil physical and chemical properties decreased during successive *Eucalyptus* planting. However, Lima et al. (2006) recorded an increasing soil organic matter trend as the plantation aged after *Eucalyptus* afforestation of degraded pastures. The inconsistency between these studies might be caused by different climate, soil properties, *Eucalyptus* species and management practices amongst the study sites. The soil quality recovery in the 3rd and 4th generation *Eucalyptus* plantations may be attributed to reduced soil disturbance and fertilizer application.

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Soil disturbance caused by strip reclamation in the 3rd generation *Eucalyptus* plantation was much smaller than full reclamation during the conversion from *Pinus* to *Eucalyptus*, which may have led to a reduction in soil organic matter decomposition, soil erosion and nutrient leaching. The decreased soil erosion, nutrient leaching and organic matter decomposition would help improving soil organic matter accumulation and nutrient levels.

Fertilization could increase plant growth and litter input (Madeira et al., 1995), which would improve soil quality. If the soil nutrient inputs through fertilization and litter fall equal the output caused by erosion, plant absorption and leaching, then soil quality would reach a steady status (Xu, 2000). Our results showed a recovery trend of soil quality in the 3rd and 4th generation *Eucalyptus* plantations (Fig. 4), however, we could not predict soil quality changes during more generations of *Eucalyptus* planting due to the lack of data. To better understand the impacts of successive *Eucalyptus* planting on soil quality, evaluation of more generations of *Eucalyptus* plantations is needed in future research.

5 Conclusions

Our study found that soil quality decreased significantly in the 1st and 2nd generation *Eucalyptus* plantations after converting *Pinus* to *Eucalyptus* plantations, but recovered in the 3rd and 4th generations, though it was still significantly lower than in the *Pinus* plantation. Changes in tree species, reclamation, herbicide application and long-term fertilization may contribute to the "U" shaped trend in soil quality changes during successive *Eucalyptus* planting. Our results emphasize the importance of long-term soil quality monitoring. Improving management practices, such as litter retention, keeping appropriate understory plant coverage and reducing soil disturbance during logging and subsequent establishment of the next plantation rotation should be considered to help improve soil quality during plantation management.

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Author contribution. H. Zheng and Z. Y. Ouyang designed the experiment and K. Zhang, F. L. Chen and Y. Wang carried them out. Y. F. Wu, J. Lan, M. Fu and X. W. Xiang helped collecting soil samples and gave suggestion about the experiment. K. Zhang and H. Zheng prepared the manuscript.

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References

Andrews, S. S., Karlen, D. L., and Mitchell, J. P.: A comparison of soil quality indexing methods for vegetable production systems in Northern California, Agr. Ecosyst. Environ., 90, 25–45, 2002.

Andrews, S. S. and Carroll, C. R.: Designing a soil quality assessment tool for sustainable agroecosystem management, Ecol. Appl., 11, 1573–1585, 2001.

Araújo, A. S. F., Silva, E. F. L., Nunes, L. A. P. L., and Carneiro, R. F. V.: The effect of converting tropical native savanna to *Eucalyptus* grandis forest on soil microbial biomass, Land Degrad. Dev., 21, 540–545, 2010.

Bao, S. D.: Soil Agro-Chemical Analysis, China Agriculture Press, Beijing, 2000. (in Chinese)

Behera, N. and Sahani, U.: Soil microbial biomass and activity in response to *Eucalyptus* plantation and natural regeneration on tropical soil, Forest Ecol. Manag., 174, 1–11, 2003.

Binkley, D., Kaye, J., Barry, M., and Ryan, M. G.: First-rotation changes in soil carbon and nitrogen in a *Eucalyptus* plantation in Hawaii, Soil Sci. Soc. Am. J., 68, 1713–1719, 2004.

Certini, G.: Effects of fire on properties of forest soils: a review, Oecologia, 143, 1–10, 2005.

Chen, F. L., Zheng, H., Zhang, K., Ouyang, Z. Y., Lan, J., Li, H. L., and Shi, Q.: Changes in soil microbial community structure and metabolic activity following conversion from native *Pinus massoniana* plantations to exotic *Eucalyptus* plantations, Forest Ecol. Manag., 291, 65–72, 2013.

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de la Paix, M. J., Lanhai, L., Xi, C., Ahmed, S., and Varenyam, A.: Soil degradation and altered flood risk as a consequence of deforestation, Land Degrad. Dev., 24, 478–485, 2013.
De Marco, A., Gentile, A. E., Arena, C., and De Santo, A. V.: Organic matter, nutrient content and biological activity in burned and unburned soils of a Mediterranean maquis area of southern Italy, Int. J. Wildland Fire, 14, 365–377, 2005.
Fialho, R. C. and Zinn, Y. L.: Changes in soil organic carbon under *Eucalyptus* plantations in Brazil: a comparative analysis, Land Degrad. Dev., doi:10.1002/ldr.2158, 2012.
Fisher, R. F. and Binkley, D.: Ecology and Management of Forest Soils, 3rd Edn., John Wiley & Sons Inc, New York, 2000.
Garay, I., Pellens, R., Kindel, A., Barros, E., and Franco, A. A.: Evaluation of soil conditions in fast-growing plantations of *Eucalyptus grandis* and *Acacia mangium* in Brazil: a contribution to the study of sustainable land use, Appl. Soil Ecol., 27, 177–187, 2004.
Kandeler, E. and Gerber, H.: Short-term assay of soil urease activity using colorimetric determination of ammonium, Biol. Fert. Soils, 6, 68–72, 1988.
Laclau, J. P., Ranger, J., Deleporte, P., Nouvellon, Y., Saint-Andre, L., Marlet, S., and Bouillet, J. P.: Nutrient cycling in a clonal stand of *Eucalyptus* and an adjacent savanna ecosystem in Congo 3. Input-output budgets and consequences for the sustainability of the plantations, Forest Ecol. Manag., 210, 375–391, 2005.
Laclau, J. P., Ranger, J., Goncalves, J. L. D., Maquere, V., Krusche, A. V., M'Bou, A. T., Nouvellon, Y., Saint-Andre, L., Bouillet, J. P., Piccolo, M. D., and Deleporte, P.: Biogeochemical cycles of nutrients in tropical *Eucalyptus* plantations: main features shown by intensive monitoring in Congo and Brazil, Forest Ecol. Manag., 259, 1771–1785, 2010.
Ladd, J. N. and Butler, J. H. A.: Short-term assays of soil proteolytic enzyme activities using proteins and dipeptide derivatives as substrates, Soil Biol. Biochem., 4, 19–30, 1972.
LeBauer, D. S. and Treseder, K. K.: Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed, Ecology, 89, 371–379, 2008.
Lima, A. M. N., Silva, I. R., Neves, J. C. L., Novais, R. F., Barros, N. F., Mendonca, E. S., Smyth, T. J., Moreira, M. S., and Leite, F. P.: Soil organic carbon dynamics following afforestation of degraded pastures with *Eucalyptus* in southeastern Brazil, Forest Ecol. Manag., 235, 219–231, 2006.
Madeira, M., Araújo, M. C., and Pereira, J. S.: Effects of water and nutrient supply on amount and on nutrient concentration of litterfall and forest floor litter in *Eucalyptus* globulus plantations, Plant Soil, 168, 287–295, 1995.

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6, 2779–2802, 2014

Miao, C., Yang, L., Chen, X., and Gao, Y.: The vegetation cover dynamics (1982–2006) in different erosion regions of the Yellow River basin, China, Land Degrad. Dev., 23, 62–71, 2012.
Navas, M., Benito, M., Rodríguez, I., and Masaguer, A.: Effect of five forage legume covers on soil quality at the Eastern plains of Venezuela, Appl. Soil Ecol., 49, 242–249, 2011.
Saiya-Cork, K. R., Sinsabaugh, R. L., and Zak, D. R.: The effects of long term nitrogen deposition on extracellular enzyme activity in an *Acer saccharum* forest soil, Soil Biol. Biochem., 34, 1309–1315, 2002.
Sicardi, M., Garcıìa-Préchacb, F., and Frionic, L.: Soil microbial indicators sensitive to land use conversion from pastures to commercial *Eucalyptus grandis* (Hill ex Maiden) plantations in Uruguay, Appl. Soil Ecol., 27, 125–133, 2004.
Tesfaye, M. A., Bravo-Oviedo, A., Bravo, F., Kidane, B., Bekele, K., and Sertse, D.: Selection of tree species and soil management for simultaneous fuelwood production and soil rehabilitation in the Ethiopian central highlands, Land Degrad. Dev., doi:10.1002/ldr.2268, 2014.
Vance, E. D., Brookes, P. C., and Jenkinson, D. S.: An extraction method for measuring soil microbial biomass C, Soil Biol. Biochem., 19, 703–707, 1987.
Waldrop, M. P., Balser, T. C., and Firestone, M. K.: Linking microbial community composition to function in a tropical soil, Soil Biol. Biochem., 32, 1837–1846, 2000.
Wang, Q. K., Wang, S. L., and Liu, Y.: Responses to N and P fertilization in a young *Eucalyptus dunnii* plantation: microbial properties, enzyme activities and dissolved organic matter, Appl. Soil Ecol., 40, 484–490, 2008.
Wen, Y. G., Zheng, X., Li, M. C., Xu, H. G., Liang, H. W., Huang, C. B., Zhu, H. G., and He, B.: Effects of eucalypt plantation replacing Masson pine forest on soil physiochemical properties in Guangxi, southern China, J. Beijing Forest. Univ., 31, 145–148, 2009. (in Chinese)
Wu, J. P., Liu, Z. F., Sun, Y. X., Zhou, L. X., Lin, Y. B., and Fu, S. L.: Introduced *Eucalyptus urophylla* plantations change the composition of the soil microbial community in subtropical China, Land Degrad. Dev., 24, 400–406, 2012.
Xu, D. P.: An approach to nutrient balance in tropical and south subtropical short rotation plantations, in: Studies on Long-Term Productivity Management of Eucalyptus Plantation, edited by: Yu, X. B., China Forestry Publishing House, Beijing, 27–35, 2000. (in Chinese)
Yu, F. K., Huang, X. H., Wang, K. Q., and Duang, C. Q.: An overview of ecological degradation and restoration of *Eucalyptus* plantations, Chin. J. Eco-Agric., 17, 393–398, 2009. (in Chinese)

SED
6, 2779–2802, 2014

Yu, X. B., Chen, Q. B., Wang, S. M., and Mo, X. Y.: Research on land degradation in forest plantation and preventive strategies, in: Studies on Long-Term Productivity Management of Eucalyptus Plantation, edited by: Yu, X. B., China Forestry Publishing House, Beijing, 1–7, 2000a. (in Chinese)

Yu, X. B., Yang, G. Q., and Li, S. K.: Study on the changes of soil properties in Eucalyptus plantation under continuous-planting practices, in: Studies on Long-Term Productivity Management of Eucalyptus Plantation, edited by: Yu, X. B., China Forestry Publishing House, Beijing, 94–103, 2000b. (in Chinese)

Zhao, G., Mu, X., Wen, Z., Wang, F., and Gao, P.: Soil erosion, conservation, and eco-environment changes in the Loess Plateau of China, Land Degrad. Dev., 24, 499–510, 2013.

Zheng, H., Ouyang, Z. Y., Wang, X. K., Miao, H., Zhao, T. Q., and Peng, T. B.: How different reforestation approaches affect red soil properties in Southern China, Land Degrad. Dev., 16, 387–396, 2005.

Zinn, Y. L., Resck, D. V. S., and Silva, J. E. da: soil organic carbon as affected by afforestation with *Eucalyptus* and *Pinus* in the Cerrado region of Brazil, Forest Ecol. Manag., 166, 285–294, 2002.

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Table 1. Principal component analysis of the chosen soil quality indicators.

	PC1	PC2	PC3
Eigenvalue	10.921	3.019	1.131
Percent	68.255	18.868	7.067
Cumulative percent	68.255	87.122	94.190
Eigenvectors			
SOC	0.295*	−0.008	0.082
TN	0.276*	−0.208	−0.041
TP	−0.257	−0.278	0.144
TK	0.281*	0.196	0.039
AN	0.188	−0.426	−0.161
AP	−0.183	0.398	0.104
AK	0.156	0.488*	0.051
MBC	0.258	−0.278	−0.014
MBN	0.185	−0.265	0.523
BG	0.259	0.286	0.088
CBH	0.194	0.045	0.678*
PO	0.293*	0.000	−0.034
POD	0.295*	−0.006	−0.046
PRO	0.256	−0.056	−0.296
URE	0.260	0.144	−0.311
ACP	0.296*	0.088	−0.041

PC, principal component. * are considered highly weighted and correspond to the indicators included in the MDS. SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; TK, total potassium; AN, alkaline hydrolytic nitrogen; AP, available phosphorus; AK, available potassium; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; BG, β-glucosidase; CBH, cellobiosidase; PO, phenoloxidase; POD, peroxidase; PRO, protease; URE, urease and ACP, acid phosphatase.

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Table 2. Soil quality indicator scores (mean ± standard error) for soil samples taken from the *Pinus* and *Eucalyptus* plantations.

	MP	G1	G2	G3	G4
SOC	0.962 ± 0.022^{a}	0.206 ± 0.048^{bc}	0.064 ± 0.038^{c}	0.328 ± 0.011^{b}	0.419 ± 0.103^{b}
TN	0.918 ± 0.053^{a}	0.104 ± 0.022^{d}	0.022 ± 0.011^{d}	0.494 ± 0.022^{c}	0.649 ± 0.037^{b}
TK	0.929 ± 0.056^{a}	0.003 ± 0.002^{b}	0.020 ± 0.004^{b}	0.018 ± 0.002^{b}	0.052 ± 0.006^{b}
AK	0.996 ± 0.002^{a}	0.450 ± 0.010^{c}	0.614 ± 0.017^{b}	0.121 ± 0.013^{d}	0.032 ± 0.020^{e}
CBH	0.972 ± 0.014^{a}	0.816 ± 0.025^{ab}	0.252 ± 0.142^{c}	0.491 ± 0.016^{c}	0.528 ± 0.044^{bc}
PO	0.861 ± 0.080^{a}	0.032 ± 0.017^{d}	0.062 ± 0.009^{cd}	0.235 ± 0.021^{bc}	0.369 ± 0.026^{b}
POD	0.831 ± 0.085^{a}	0.039 ± 0.015^{c}	0.022 ± 0.020^{c}	0.260 ± 0.004^{b}	0.317 ± 0.033^{b}
ACP	0.938 ± 0.035^{a}	0.038 ± 0.022^{c}	0.084 ± 0.018^{c}	0.227 ± 0.031^{b}	0.239 ± 0.024^{b}

MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the 1st, 2nd, 3rd and 4th generation *Eucalyptus* plantations, respectively. SOC, soil organic carbon; TN, total nitrogen; TK, total potassium; AK, available potassium; CBH, cellobiosidase; PO, phenoloxidase; POD, peroxidase and ACP, acid phosphatase. Scores superscripted with different letters (a–d) in each row are significantly different at $p < 0.05$.

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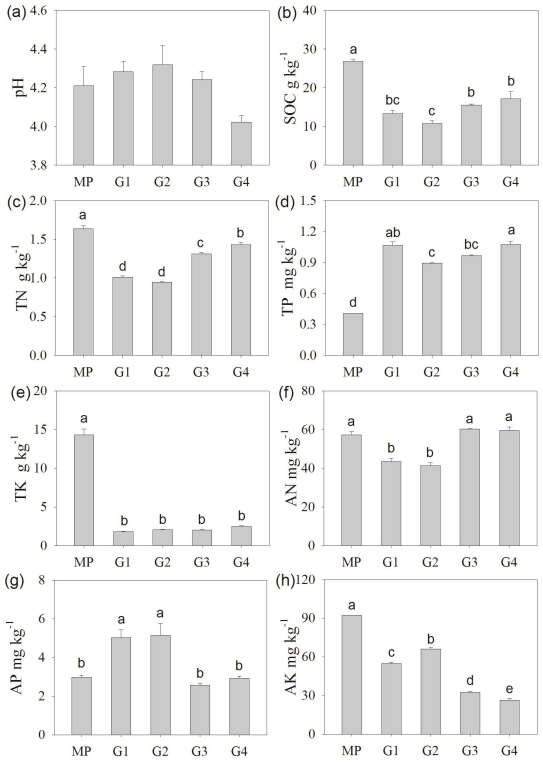

Figure 1. Changes in soil chemical properties during conversion of *Pinus* to *Eucalyptus* and successive *Eucalyptus* planting. MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the 1st, 2nd, 3rd and 4th generation *Eucalyptus* plantations, respectively. SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; TK, total potassium; AN, alkaline hydrolytic nitrogen; AP, available phosphorus and AK, available potassium. Soil chemical properties with the same letter are not significantly different at $p < 0.05$.

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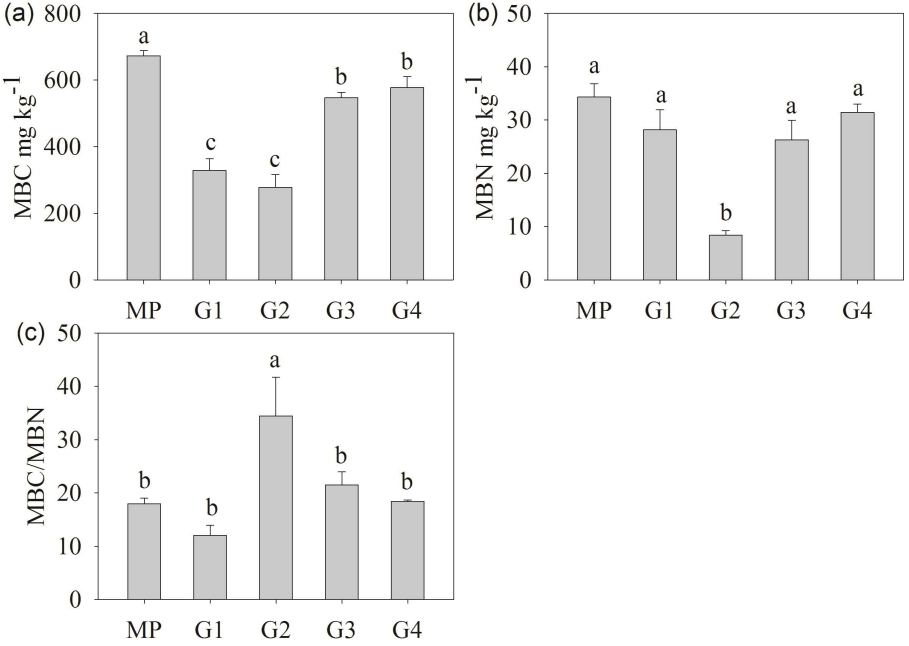

Figure 2. Changes in soil microbial biomass carbon and nitrogen during conversion of *Pinus* to *Eucalyptus* and successive *Eucalyptus* planting. MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the 1st, 2nd, 3rd and 4th generation *Eucalyptus* plantations, respectively. MBC, microbial biomass carbon and MBN, microbial biomass nitrogen. Microbial indicators with the same letter are not significantly different at $p < 0.05$.

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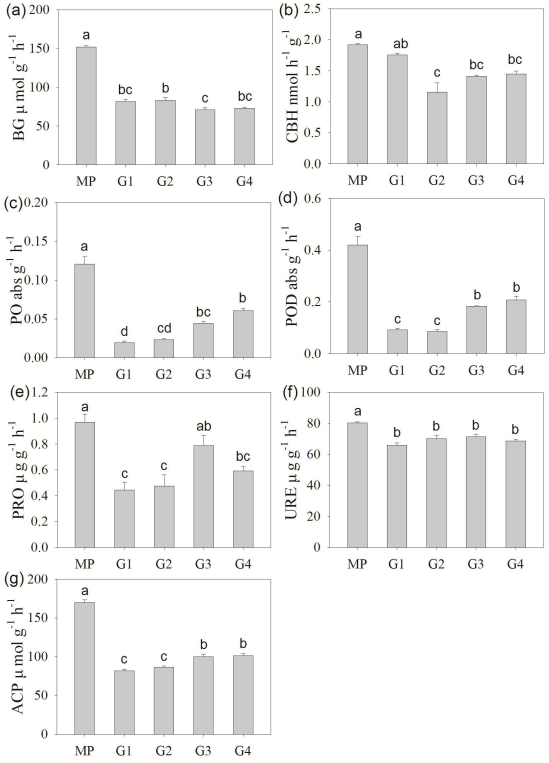

Figure 3. Changes in soil enzyme activities during conversion of *Pinus* to *Eucalyptus* and successive *Eucalyptus* planting. MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the 1st, 2nd, 3rd and 4th generation *Eucalyptus* plantations, respectively. BG, β-glucosidase; CBH, cellobiosidase; PO, phenoloxidase; POD, peroxidase; PRO, protease; URE, urease and ACP, acid phosphatase. Enzyme activities with the same letter are not significantly different at $p < 0.05$.

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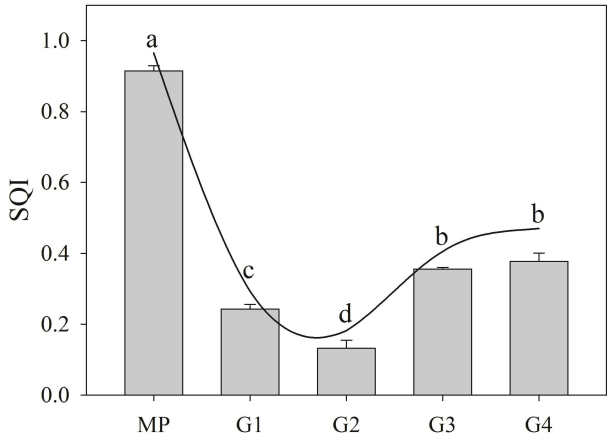

Figure 4. Changes in soil quality index during conversion of *Pinus* to *Eucalyptus* and successive *Eucalyptus* planting. MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the 1st, 2nd, 3rd and 4th generation *Eucalyptus* plantations, respectively. SQI, soil quality index. SQIs with the same letter are not significantly different at $p < 0.05$.

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