Effects of conversion from a natural evergreen broadleaf forest to a Moso bamboo plantation on the soil nutrient pools, microbial biomass and enzyme activities in a subtropical area

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Abstract

Converting natural forests to plantations would markedly change soil physiochemical and biological properties, as a consequence of changing plant vegetative coverage and management practices. However, the effects of such land-use change on the soil nutrient pools and related enzymes activities still remain unclear. The aim of this study was to explore the effects of conversion from natural evergreen broadleaf forests to Moso bamboo plantations on the pool sizes and forms of soil N, P and K, microbial biomass, and nutrient cycling related enzyme activities. Soil samples from four adjacent evergreen broadleaf forest-Moso bamboo plantation pairs were collected from a subtropical region in Zhejiang Province, China. The soil organic C (SOC), total N (TN), total P (TP) and total K (TK) concentrations and stocks and different N, P and K forms were measured, and the microbial biomass C (MBC), microbial biomass N (MBN), microbial biomass P (MBP) and four soil enzymes (protease, urease, acid phosphatase and catalase) were determined. The results showed that converting broadleaf forests to Moso bamboo plantations decreased the concentration and stock of SOC but increased those of TK in both soil layers (0–20 and 20–40 cm), and such land-use change increased the concentration and stock of TN and TP only in the 0–20 cm soil layer ($P < 0.05$). This land-use conversion increased the concentrations of NH_4^+-N, NO_3^--N, resin-P_i, $NaHCO_3$-P_i, NaOH-P_i, HCl-P_i, available K and slowly available K, but decreased the concentrations of water-soluble organic nitrogen (WSON), $NaHCO_3$-P_o and NaOH-P_o ($P < 0.05$). Further, this land-use change decreased the microbial biomass and activities of protease, urease, acid phosphatase and catalase ($P < 0.05$). In addition, the acid phosphatase activity correlated positively with the concentrations of MBP and $NaHCO_3$-P_o, and the activities of urease and protease correlated positively with the concentrations of MBN and WSON ($P < 0.01$). To conclude, converting natural broadleaf forests to Moso bamboo plantations had positive effects on soil inorganic N, P and K pools, and negative effects on soil organic N and P pools, and on N- and P-cycling related enzyme activities. Therefore, management practices that increase organic nutrient pools and microbial activity are needed to be developed to mitigate the depletion of organic nutrient pools after the land-use conversion.

Keywords: Evergreen broadleaf forest; Land-use conversion; Microbial biomass; Moso bamboo plantation; Soil nutrient form; Soil enzyme.

1. Introduction

Land-use conversion can significantly affect the soil physicochemical and biological properties (Yang et al., 2004; Don et al., 2011; Moghimian et al., 2017). Over the past few decades, in order to gain higher economic benefits and to supply the growing demands of timber, paper and fuel, among other commodities, the conversion from natural forests to plantations is becoming more frequent (Burton et al., 2007; Li et al., 2014; Hu et al., 2018). To increase the growth of plantations after land-use change, intensive management practices, mainly including fertilization, understory vegetation control, and deep ploughing, have been commonly adopted (Li et al., 2013; Zhang et al., 2015a; Dangal et al., 2017; Zhang et al., 2017a). Various studies have revealed that the intensive management practices applied can significantly change the soil pH, nutrient status, and microbial biomass and community composition (Li et al., 2013; Yuan et al., 2015; Xie et al., 2017), and consequently influence soil fertility and plant growth (Pransiska et al., 2016; Tiecher et al., 2017). Therefore, it is great of significance to investigate the effects of land-use change and subsequent management practices on the pool sizes and forms of soil nutrients and associated enzyme activities.

The effects of land-use change from natural forest to plantation on soil nutrient status and associated enzyme activities may include the following: (1) the input of exogenous fertilizer can have a direct effect on the pool sizes and forms of soil nutrients (Chang et al., 2007; Sainju et al., 2012; Yang et al. 2017; Li et al. 2018), and (2) the differences in chemical composition and root exudates of different vegetation types may change the microbial growth environment, which affects microbial biomass and soil enzyme activity (Yang et al., 2010; Li et al., 2011; Wang et al., 2013; Yuan et al., 2015). For example, the input of exogenous organic fertilizer and root exudates can increase the availability of water-soluble nitrogen (N) (Scott and Rothstein, 2011; Sainju et al., 2012; Li et al., 2017a). In addition, an increase in N fertilizer application can reduce soil enzyme activity and microbial biomass (Shen et al., 2010; Zhang et al., 2015b). Previous studies showed that understory vegetation plays important roles in cycling nutrients and decreasing soil erosion (Fukuzawa et al., 2006; Zhang et al., 2010).

The classification of soil nutrients can help to determine soil nutrient status (Ross et al., 1999; Yang et al., 2010). Different forms of N, such as NH_4^+-N, NO_3^--N and water-soluble organic N (WSON), can jointly indicate the N supply capacity of soils (Schimel and Bennett, 2004; Chen and Xu, 2008; Yan et al., 2008; Wu et al., 2010). The different forms of phosphorus (P) in soils are formed through the combination of P with different mineral components and can significantly affect N- and P-cycling (Yang et al., 2010; Wei et al., 2017). In addition, the soil potassium (K) supply is closely associated with the transformation rate of different forms of K in soils (Darunsontaya et al., 2012). The different forms of nutrients respond differently to land-use change. For example, Ouyang et al. (2013) reported that after conversion from wetland to paddy field, the total K concentration increased but the available K concentration decreased in soils. Yang et al. (2004) reported that converting secondary forests to rubber plantations increased the concentration of inorganic N but decreased the concentration of total N. In addition, Yang et al. (2010) found that converting natural forests to larch plantations increased the concentrations of total P (TP) and inorganic P (IP) but decreased the concentrations of microbial biomass P (MBP) and organic P (OP). Therefore, exploring the responses of different forms of soil nutrients to land-use change will enable us to elucidate the mechanisms associated with the land-use conversion effects on the soil nutrient status.

Soil microbes play an important role in the decomposition and mineralization of soil organic matter (Malchair and Carnol, 2009; Guo et al., 2016; Ge et al., 2017; Li et al., 2017b; Luo et al., 2017). Soil enzymes are closely related to the transformation of soil nutrients, and their activities are closely associated with the level of soil organic matter, soil physicochemical properties and soil microbial biomass (Xu et al., 2010; Liu et al., 2015; Chavarría et al., 2016; Ma et al., 2016). For example, Bhattacharyya et al. (2005) found that there was a pronounced linear correlation between soil urease and microbial biomass. Additionally, Yang et al. (2010) found that acid phosphatase activity was positively correlated with the concentrations of $NaHCO_3$-P_i, $NaHCO_3$-P_o, and MBP in a subtropical forest soil. Land-use change can markedly affect the soil enzyme activity as well as the soil microbial biomass and nutrient forms (Dawoe et al., 2014; Guo et al., 2016). However, it remains unclear whether the changes in soil enzyme activity caused by land-use change are closely linked with the changes in soil microbial biomass or nutrient forms.

Natural evergreen broadleaf forests contribute to maintain biodiversity; these forests are considered to be an important vegetation type in the subtropical regions of China (Wang et al., 2007). However, large areas of natural forests have been transformed into plantations over the past two decades (Yan et al., 2015; Chen et al., 2017), most commonly into bamboo plantations (Guan et al., 2015). The area of Moso bamboo (*Phyllostachys edulis*) plantations has increased to 4.2 million ha due to their substantial economic benefit (Yuen et al., 2017). At present, most of the Moso bamboo plantations are intensively managed, with the application of fertilizers, the removal of understory vegetation, and tillage (Li et al., 2013; Yang et al., 2017). It is expected that conversion from natural evergreen broadleaf forests to Moso bamboo plantations, in combination with subsequent management practices, will markedly change the soil physical, chemical and biological characteristics. However, the effects of the aforementioned land-use change on soil nutrient pools and enzyme activities remain unclear. Therefore, the purposes of the present study were (1) to analyze the effects of conversion from evergreen broadleaf forests to Moso bamboo plantations on the pool sizes and different forms of soil nutrients, (2) to investigate the aforementioned land-use conversion effects on the soil microbial biomass and activity of soil enzymes regarding nutrient cycling, and (3) to reveal the relationship between soil enzyme activity and the different forms of soil nutrients or soil microbial biomass.

2. Materials and methods

2.1. Experimental site

The study was carried out in Congkeng (30°14′N, 119°42′E), Hangzhou, Zhejiang, China. The study area belongs to a subtropical monsoon climate zone with four distinct seasons, with an average annual temperature of 15.8 °C and average annual precipitation of 1420 mm. The annual sunshine duration and frost-free period of this site are 1946 hours and 239 days, respectively. The elevation of the study area is approximately 150 m. The soils at this experimental site are classified as Ferralsols (World Reference Base for Soil Resources (WRB) 2006).

We chose two different land-use types, i.e., natural evergreen broadleaf forests and Moso bamboo plantations, to investigate the differences in soil properties. The main tree species in the natural evergreen broadleaf forests were *Cyclobalanopsis glauca*, *Castanopsis eyrie*, and *Castanopsis sclerophylla*, which accounted for approximately 70% of the canopy cover. The understory vegetation in this natural forest was mainly *Litsea cubeba, Lindera glauca*, and *Camellia cuspidata*, of which the surface cover was approximately 85%. Part of the natural evergreen broadleaf forests had been transformed into Moso bamboo plantations. The Moso bamboo plantation in the present study was established in 2004. The bamboo plantation had been managed intensively for 11 years after the land-use conversion. The stocking density in the bamboo plantation was 3,000 stems ha^{-1}, with 10.1 cm mean diameter at breast height. Every year from late June to early July the bamboo plantation was fertilized with urea (200 kg N ha^{-1}), superphosphate (60 kg P ha^{-1}), and potassium chloride (70 kg K ha^{-1}). The fertilizer was usually applied on the soil surface, followed by plowing to a depth of 30–35 cm. The understory vegetation in the bamboo plantation was manually removed each year.

2.2. Experimental design and soil sampling

A paired-plot approach was adopted to investigate the effects of land-use conversion on soil properties. One paired-plot included two adjacent plots, i.e., one in the natural evergreen broadleaf forest and the other in the Moso bamboo plantation. Each paired plot had the same geographic and environmental factors, including soil type, slope (15–20°) and aspect (south). We selected four different locations within ~3 km^2 in the area described above to establish four different paired plots in April 2015; the plot size was 20 m × 20 m (400 m^2). Within one paired-plot, the distance between the two plots (one in the natural evergreen broadleaf forest and the other in the Moso bamboo plantation) was less than 100 m, and there were 4 replications for each land-use type.

In each plot, we collected soil samples from five randomly selected points at the 0–20 and 20–40 cm soil layers. For each soil layer, the five samples were thoroughly mixed to form a composite sample. The soil samples were kept on ice before further processing. A 2-mm sieve was used to homogenize the samples, and visible roots were removed. Samples were divided into two portions: one portion was stored at 4 °C for further analyses, and the other portion was air-dried. We used a bulk density corer with a 200-cm^3 volume to collect samples from the two soil layers to determine the bulk density. The average values for the selective physicochemical properties (see methods described below) in the 0–20 cm soil layer for the aforementioned two forest types were listed below: (1) natural evergreen broadleaf forest: pH of 5.67, bulk density of 0.96 g cm^{-3}, sand of 301 g kg^{-1}, silt of 413 g kg^{-1}, and clay of 286 g kg^{-1}; (2) Moso bamboo plantation: pH of 5.16, bulk density of 1.06 g cm^{-3}, sand of 324 g kg^{-1}, silt of 401 g kg^{-1}, and clay of 275 g kg^{-1}.

2.3. Determination of soil physicochemical properties

The soil pH was measured at a soil-to-water ratio of 1:2.5 (w:v) using a pH meter. The soil moisture content was measured by calculating the mass loss after oven drying at 105 °C for more than 12 hours. The soil bulk density was determined by collecting a fresh 20-g soil subsample from a metal density corer with known volume and oven drying the sample for more than 24 hours at a temperature of 105 °C. The concentrations of soil organic carbon (SOC) and total N (TN) were determined using an elemental analyzer (model CHN-O-RAPID, Heraeus, Germany). The total P (TP) concentration was determined by digesting soil samples with a mixture of concentrated H_2SO_4 and $HClO_4$, and the molybdate-blue colorimetry method (Murphy and Riley 1962) was used to measure the P concentration in the digest. The soil total K (TK) concentration was determined using the NaOH melting method according to Hanway and Heidel (1952). Soil texture was determined using the pipette method after pre-treating the soil samples with solutions of H_2O_2 and $Na_4P_2O_7$ (Gee and Bauder 1986). The stocks of SOC, TN, TP and TK were calculated using the following formula:

$$Y_{\text{stock}}\ (\text{Mg ha}^{-1}) = X \times BD \times th \times 0.1 \qquad (1)$$

Where X is the concentration (g kg^{-1}) of SOC, TN, TP or TK, BD is the bulk density of the soil layer (Mg m^{-3}), and th is the thickness of the soil layer (cm).

2.4. Determination of soil N forms

The concentrations of NO_3^--N and NH_4^+-N in each soil sample were determined according to the method of Li et al. (2014). Briefly, a soil sample was extracted with KCl solution (2 mol L^{-1}), and the concentrations of NO_3^--N and NH_4^+-N in the extract were determined using a Dionex ICS 1500 ion chromatograph (Dionex Corp., Atlanta, USA). The WSON concentration was determined according to Jones and Willett et al. (2006). In short, a fresh subsample equivalent to 20 g of oven-dried soil was suspended in 40 mL of distilled water, shaken for 0.5 hours at 150 rpm at 25 °C and then centrifuged for 20 minutes at 8,000 × g. The supernatant was passed through a 0.45-μm membrane filter (Millipore Corp, USA). The concentration of water-soluble N (WSN) in the filtrate was measured using an automated TOC-TN analyzer (TOC-Vcph, Shimadzu, Kyoto, Japan). The concentrations of NH_3^--N and NH_4^+-N in the filtrate were determined using an ion chromatograph, and the WSON concentration was calculated using the following formula:

$$\text{WSON}=\text{WSN} - (NO_3^{-}\text{-N}) - (NH_4^{+}\text{-N}) \qquad (2)$$

2.5. Determination of P forms

The concentrations of different forms of P were determined by adopting the Hedley procedure (Hedley et al., 1982; Eriksson et al., 2015). (1) Resin-P_i: a fresh soil sample equivalent to 0.5 g of oven-dried soil was suspended in 30 mL of distilled water. Together with a strip of $NaHCO_3$-form anion exchange resin membrane (BDH No. 55164) pretreated by the method of Schoenau and Huang (1991), the suspension was shaken for 16 hours at 150 rpm at 25 °C, and the P absorbed into the resin membrane (resin-P_i) was recovered by shaking the resin membrane in 50 mL of 0.5 mol L^{-1} HCl for 1 h. (2) $NaHCO_3$-P_i and $NaHCO_3$-P_o: two drops of toluene were added to minimize organic P decomposition to the residue from (1) before shaking in 30 mL of 0.5 mol L^{-1} $NaHCO_3$ (pH = 8.5) for 16 hours. (3) NaOH-P_i and NaOH-P_o: 30 mL of 0.1 mol L^{-1} NaOH was added to the residue from (2) and then shaken for 16 hours. (4) HCl-P_i: the residue from (3) was shaken in 30 mL of 1.0 mol L^{-1} HCl for 16 hours. (5) Residual-P: the residue from (4) was digested in concentrated H_2SO_4 and H_2O_2, followed by shaking for 16 hours. After steps (1) to (5), the suspension was centrifuged at 12,000 × *g* for 10 minutes. The supernatants were passed through a 0.45-µm membrane filter (Millipore Corp., USA), and the inorganic P concentration in the filtrates were measured using the molybdate-blue method (Murphy and Riley, 1962). In (2) and (3), the TP concentration in the extracts was measured by digesting the extracts in concentrated H_2SO_4 and H_2O_2, and the organic P concentration in the extracts was calculated as the difference between the TP concentration and the inorganic P concentration.

2.6. Analysis of K forms

The different forms of soil K determined included available K, slowly available K and mineral K. The available K concentration was determined by the method of Zhang et al. (2013). Briefly, 10 g of oven-dried soil sample was suspended in 50 mL of 1.0 mol L^{-1} NH_4OAc, shaken for 0.5 hours at 150 rpm at 25°C, and the suspension was centrifuged at 5,000 × g for 10 minutes and then passed through a 0.45-μm membrane filter (Millipore Corp, USA). The concentration of K in the filtrate was measured using a flame photometer (Tiecher et al. 2017). The slowly available K concentration was determined by suspending 10 g of oven-dried soil in 50 mL of 1.0 mol L^{-1} HNO_3, heated to boiling in an oil bath for 10 minutes, transferred to a 100-mL volumetric flask, and the K concentration was measured using a flame photometer. The soil total K (TK) concentration for each soil sample was determined using the NaOH melting method (Hanway and Heidel, 1952). Slowly available K was calculated as the difference between the concentration of K extracted by the hot HNO_3 solution and the concentration of the K extracted by the NH_4OAc solution. Mineral K was calculated as the difference between the concentration of total K and the concentration of the K extracted by the hot HNO_3 solution.

2.7. Analysis of soil microbial biomass and soil enzymes

The concentrations of microbial biomass C (MBC) and microbial biomass N (MBN) were determined using the chloroform fumigation-K_2SO_4 extraction method as described in Vance et al. (1987). In brief, fumigated and non-fumigated soil samples were suspended in 40 mL of 0.5 mol L^{-1} K_2SO_4, shaken at 150 rpm for 30 minutes at 25 °C, centrifuged for 5 minutes at 3500 × g, and the supernatants were passed through a 0.45-μm membrane filter (Millipore Corp, USA). The concentrations of C and N in the extracts were measured in an automated TOC-TN analyzer (TOC-Vcph, Shimadzu, Kyoto, Japan). The soil MBC concentration was calculated as the difference in the concentration of C between the fumigated and non-fumigated samples (Wu et al., 1990; Burton et al., 2010). Similarly, the soil MBN concentration was calculated as the difference in the concentration of N between the fumigated and non-fumigated samples (Li et al., 2014). The concentration of MBP was determined following the method of Brookes et al. (1982). Briefly, the MBP was calculated as the difference between the concentrations of inorganic P extracted with 0.5 mol L^{-1} $NaHCO_3$ (pH = 8.5) from fumigated and non-fumigated soil.

The soil protease (EC 3.4.2.21–24) activity was measured following the method of Ladd and Butler (1972). 1 g of fresh sample was mixed with 2.5 mL of Tris buffer (0.1 mol L^{-1}, pH = 8.1) and 2.5 mL of 2% sodium caseinate, and incubated at 50 °C for 2 hours. At the end of the incubation, 1 mL of 17.5% trichloroacetic acid (TCA) was added, then centrifuged for 10 minutes at 5,000 × *g*. 2 mL of the supernatant was mixed with 3.0 mL Na_2CO_3 (1.4 mol L^{-1}) and 1 mL threefold diluted Folin-Ciocalteu reagent. After 10 minutes, the absorbance was determined at 700 nm. The protease activity is expressed as the amount of tyrosine released per hour per gram of soil (μmol g^{-1} h^{-1}).

The soil urease (EC 3.5.1.5) activity was determined following the method described in Kandeler and Gerber (1988). Briefly, a fresh soil sample equivalent to 5 g of oven-dried soil was suspended in 2.5 mL of 80 mmol L^{-1} urea and 20 mL of Tris buffer (0.075 mol L^{-1}, pH = 10), and incubated at 37 °C for 2 hours. After incubation, 50 mL of a mixture of 1 mol L^{-1} KCl and 10 mmol L^{-1} HCl was added, and the suspension was shaken at 125 rpm for 30 minutes. The suspension passed through a filter, and the concentration of ammonia in the filtrate was determined using the colorimetric method described in Marschner et al. (2003). The urease activity is expressed as the amount of NH_3-N produced per unit mass of soil per hour (μmol g^{-1} h^{-1}).

The soil acid phosphatase (EC 3.1.3.2) activity was determined following the method of Tabatabai and Bremner (1969). A fresh soil sample equivalent to 1 g of oven-dried soil was suspended in 0.2 mL of toluene, 4 mL of acetate buffer solution (pH = 6.5) and 1 mL of 50 mmol L^{-1} *p*-nitrophenol phosphate solution. The suspension was shaken at 150 rpm at 37°C for 1 hour, and then 1 mL of $CaCl_2$ solution (0.5 mol L^{-1}) and 4 mL of NaOH solution (0.5 mol L^{-1}) were added. After shaking for several seconds, the suspension was passed through filter paper, and the absorbance of the filtrate was determined at 400 nm. The acid phosphatase activity is expressed as the amount of *p*-nitrophenyl produced per unit mass of soil per hour (μmol g^{-1} h^{-1}).

The soil catalase (EC 1.11.1.6) activity was measured following the method of Johnson and Temple (1964). A fresh soil sample equivalent to 2 g of oven-dried soil was suspended in 40 mL of distilled water and 5 mL of 0.3% H_2O_2, and shaken at 150 rpm for 20 minutes at 25°C. Then, 5 mL of 3 mol L^{-1} sulfuric acid was added, and the mixture was titrated using 0.1 mol L^{-1} $KMnO_4$ solution. The baseline was determined by titrating a mixture of 5 mL of 0.3% H_2O_2 and 5 mL of 3 mol L^{-1} sulfuric acid with 0.1 mol L^{-1} $KMnO_4$. The catalase activity is expressed as the amount of consumption of $KMnO_4$ per hour per gram of soil (μmol g^{-1} h^{-1}).

2.8. Statistical analyses

The data presented in this paper are the mean values of four replicates. One-way analysis of variance (ANOVA) and the least significant difference (LSD) test was adopted to determine the land-use conversion effects on the soil physiochemical properties, microbial biomass and enzyme activities. Prior to performing the ANOVA, the normality and homogeneity of variance were evaluated, and data were log-transformed when needed. The relationships between the soil enzyme activity and different soil N and P forms were tested using linear regression analyses. Unless otherwise indicated, differences were taken as statistically significant at $P = 0.05$. Data analyses and visualization were completed using Microsoft Excel 2013 and Origin 9.0, respectively, and the statistical analyses were conducted using SPSS version 18.0 (SPSS, Chicago, IL, USA).

3. Results

3.1. Soil total C, N, P and K concentrations and stocks

Regardless of soil layer, the SOC concentration in the Moso bamboo plantation was lower than that in the evergreen broadleaf forest (Fig. 1a), while the total K concentration in the bamboo plantation was higher than that in the broadleaf forest (Fig. 1g). The total N and P concentrations in the bamboo plantation were higher than those in the broadleaf forest in the 0–20 cm soil layer, while no differences were observed in the 20–40 cm layer (Fig. 1c, e). The effects of land-use conversion on the total C, N, P and K stocks were similar to the effects on the total C, N, P and K concentrations (Fig. 1).

3.2. Soil N forms

Regardless of soil layer, the NO_3^--N and NH_4^+-N concentrations in the Moso bamboo plantation were higher than those in the evergreen broadleaf forest (Fig. 2a and b), while the WSON concentration in the bamboo plantation was lower than that in the broadleaf forest (Fig. 2c).

3.3. Soil P forms

Regardless of soil layer, the resin-P_i and $NaHCO_3$-P_i concentrations in the Moso bamboo plantation were higher than those in the evergreen broadleaf forest, while the $NaHCO_3$-P_o concentration in the bamboo plantation was lower than that in the broadleaf forest (Table 1). The NaOH-P_i, HCl-P_i and residual-P concentrations in the bamboo plantation were higher than those in the broadleaf forest in the 0–20 cm soil layer, while no differences were detected in the 20–40 cm layer (Table 1). The NaOH-P_o concentration in the bamboo plantation was lower than that in the broadleaf forest in the 0–20 cm soil layer, while no significant difference was found in the 20–40 cm layer (Table 1).

3.4. Soil K forms

Regardless of soil layer, the total K, available K and slowly available K concentrations in the Moso bamboo plantation were higher than those in the evergreen broadleaf forest (Fig. 3a–c). The mineral K concentration in the bamboo plantation was higher than that in the broadleaf forest in the 0–20 cm soil layer, while no difference was found in the 20–40 cm layer (Fig. 3d).

3.5. Soil microbial biomass and enzyme activities

Regardless of soil layer, the MBC, MBN and MBP concentrations in the Moso bamboo plantation were higher than those in the evergreen broadleaf forest (Fig. 4). Regardless of soil layer, the activities of protease, urease, and acid phosphatase in the bamboo plantation were lower than those in the broadleaf forest (Fig. 5 a–c). The catalase activity in the bamboo plantation was lower than that in the broadleaf forest in the 0–20 cm soil layer, while no difference was found in the 20–40 cm layer (Fig. 5d). Acid phosphatase activity correlated positively with MBP and $NaHCO_3$-P_o (Fig. 6), and urease and protease activities correlated positively with the concentrations of MBN and WSON (Fig. 7) ($P < 0.01$).

4. Discussion

4.1. Land-use conversion effects on soil nutrient pools

Our results revealed that the land-use conversion from evergreen broadleaf forests to

Moso bamboo plantations significantly decreased the concentration and stock of SOC (Fig. 1). This result coincides with that of Guillaume et al. (2015), who reported that conversion from lowland rainforests to intensively managed rubber plantations significantly decreased the SOC stock. The decrease in concentration and stock of SOC due to the land-use change in our study has two possible explanations. Practices of fertilization and tillage may accelerate the mineralization of SOC and the leaching of soluble soil organic matter (Mancinelli et al., 2010; Sheng et al., 2015; Liu et al., 2018), and the removal of understory vegetation in the plantations may decrease C input into the soil (Wang et al., 2011; Li et al., 2013; Zhang et al., 2014).

In addition, this land-use conversion significantly increased the concentrations and stocks of N, P and K (Fig. 1), which is in agreement with Yang et al. (2010) and Zhang et al. (2017b), who reported that conversion from natural forests to larch and pine plantations, respectively, increased the concentrations and stocks of N in the surface soil. Plausibly, the main sources for the increased concentrations and stocks of N, P and K were the synthetic fertilizers applied in the Moso bamboo plantation, as the natural evergreen broadleaf forest did not receive any fertilization.

4.2. Land-use conversion effects on different soil N forms

In this study, we found that the conversion from broadleaf forest to bamboo plantation increased the concentrations of NO_3^--N and NH_4^+-N (Fig. 2), in agreement with Yang et al. (2004) who reported that the concentration of NO_3^--N increased after the conversion from secondary forest to a larch plantation. In addition, we also found that the aforementioned land-use change significantly decreased the WSON concentration (Fig. 2), which accords with the result of Li et al. (2014), who reported that the conversion of natural shrub forests to intensively managed Chinese chestnut plantations significantly reduced the WSON concentration in the soil.

The changes in soil N forms caused by land-use change can be attributed to a number of possible mechanisms. Intensive managements that include fertilization, tillage and understory vegetation removal, could lead to a decrease in water and soil conservation ability, and consequently cause the loss of WSON (Yüksek et al., 2009; Sheng et al., 2015). Fertilization can accelerate the mineralization of organic N and enhance the uptake of soluble organic N by plants, consequently reducing the WSON concentration in soils (Schimel and Bennett, 2004; Tao et al., 2018). The increase in NO_3^--N and NH_4^+-N concentrations in soils after land-use change are evidently related to the increase in N input from fertilization (Asadiyan et al., 2013).

4.3. Land-use conversion effects on different soil P forms

Results of the present study revealed that converting broadleaf forests to Moso bamboo plantations increased the resin-P_i and $NaHCO_3$-P_i concentrations but decreased the $NaHCO_3$-P_o concentration (Table 1). Similarly, Yang et al. (2010) found that converting natural secondary forests to larch plantations increased the TP and iron-bound P (Fe-P) concentrations in soils but decreased the MBP and $NaHCO_3$-P_o concentrations.

The changes in soil P forms caused by land-use change have two possible explanations. Fertilization significantly increased the inorganic P concentration but reduced the organic P concentration in intensively managed rubber and oil palm plantations (Maranguit et al. 2017). In addition, Yang et al. (2012) showed that fertilization caused a significant increase in the inorganic P concentration and a significant decrease in the organic P concentration in soils. Thus, the increase in the concentration of inorganic P fractions is at least partially related to the application of phosphate fertilizer in the Moso bamboo plantation. In addition, the intensive management measures, e.g. deep tillage and fertilization, applied in the Moso bamboo plantation may decrease the organic P concentration since they can promote the mineralization of P-containing organic matter (Yang et al., 2012; Obour et al., 2017).

4.4. Land-use conversion effects on different soil K forms

Studying the effects of land-use change on different forms of K can help us to understand the response of K nutrient status to land-use conversion (Wang et al., 2016; Islam et al., 2017). The available K concentration increased after the conversion of natural evergreen broadleaf forests to *Phyllostachys praecox* stands and in the conversion from virgin natural forests to alder and sequoia plantations (Zhang et al. 2013; Moghimian et al. 2017). Likewise, our results indicated that conversion from broadleaf forests to Moso bamboo plantations significantly increased the concentrations of total K, available K, slowly available K, and mineral K (Fig. 3).

The KCl fertilizer applied in the Moso bamboo plantation was the possible source of the increased K in soils. The fertilizer can quickly increase the available K, and a part of the available K will be transformed to slowly available K and mineral K forms (Rupa et al., 2003; Islam et al., 2017).

4.5. Land-use conversion effects on soil microbial biomass and enzyme activity

The soil microbial biomass is a sensitive index of the soil nutrient pool, since soil nutrients provide the basis for the survival of soil microbes (Guo et al., 2016; Vitali et al., 2016). In agreement with Fang et al. (2017), who reported that converting natural old-growth broadleaf Korean pine mixed forest to a spruce plantation caused a reduction in the soil MBC concentration, we noticed that the soil MBC concentration was lower in the Moso bamboo plantation than in the broadleaf forest (Fig. 4). In line with our previous study where the MBN concentration decreased significantly 10 years after the conversion from shrub forests to Chinese chestnut plantations (Li et al., 2014), the land-use change in this study decreased the concentrations of MBN and MBP (Fig. 4). The decreased concentrations of MBC, MBN and MBP in the bamboo plantation might have been partially due to the lower pH, which is known to inhibit microbial growth (Luo et al., 2013; Guo et al., 2016; Moghimian et al., 2017). Another possible explanation is the markedly decreased SOC concentration, which might have had a negative impact on the growth of soil microorganisms (Vitali et al., 2016; Moghimian et al., 2017).

The soil enzyme activity is one of the most sensitive indicators of soil nutrient status and fertility, and it is greatly affected by land-use conversion and alterations in management practices (Moghimian et al., 2017). Converting tropical forests to rubber plantations decreased the activity of acid phosphatase, catalase activity decreased after the conversion from a broadleaf forest to a *Michelia macclurei* Dandy plantation, and acid phosphatase activity decreased after converting a broadleaf forest to a *Pinus massoniana* Lamb plantation (Yang et al. 2012; Wang et al. 2013). In this study, the activities of protease, urease, acid phosphatase and catalase, involved in N and P cycling, were significantly lower in soils after the land-use change of broadleaf forests to bamboo plantations (Fig. 5). Low soil pH is likely to have a negative effect on the activity of some soil enzymes (Wallenius et al., 2011; Zhang et al., 2015b), which may partially explain the lower activities in bamboo plantation. Also, the lower activities might have resulted from lower microbial biomass. Since soil enzymes originate mainly from soil microorganisms, changes in microbial growth, activity and function resulting from land-use change could affect enzyme activities (Yang et al., 2012; Kader et al., 2017). Zhang et al. (2015b) found a significant relationship between the decrease in acid phosphatase activity and the application of calcium superphosphate fertilizer. Furthermore, urease activity decreased significantly with an increase in nitrogen fertilizer application (Shen et al. 2010). Thus, fertilization in the bamboo plantation might have decreased the soil enzyme activity.

Soil enzyme activity is closely associated with the level of soil nutrients (Chen et al., 2003; Islam et al., 2011; Zhang et al., 2015b). Xing et al. (2010) reported that the decomposition of soil organic N into NH_4^+-N could be enhanced by increased activities of urease and protease in the subtropics of China. Chen (2003) found that soil acid phosphatase activity in a subtropical fir (*Cunninghamia lanceolata*) plantation in China was closely related with most of the inorganic P fractions except Ca-P. In this study, we found that acid phosphatase activity correlated positively with MBP and $NaHCO_3$-P_o (Fig. 6), and urease and protease activities correlated positively with the concentrations of MBN and WSON (Fig. 7). Therefore, the effects of land-use conversion on the soil enzyme activities may be attributed to its effect on the soil nutrient pools.

5. Conclusions

Converting natural evergreen broadleaf forests to intensively managed Moso bamboo plantation significantly decreased the soil pH and the concentration and stock of SOC, but significantly increased the concentrations and stocks of TN, TP and TK. Further, this land-use conversion increased the concentrations of NH_4^+-N, NO_3^--N, resin-P_i, $NaHCO_3$-P_i, NaOH-P_i, HCl-P_i, residual-P, available K, slowly available K and mineral K but significantly decreased the concentrations of WSON, $NaHCO_3$-P_o, and NaOH-P_o, as well as the soil microbial biomass and enzyme activity. These results clearly demonstrate that the aforementioned land-use conversion had positive effects on the soil inorganic N, P and K pools, while the effects on the soil organic N, P and K pools were negative. Therefore, to manage the Moso bamboo plantations sustainably, it is advisable to increase the organic nutrient pools by applying organic fertilizers and re-establishing understory vegetation. As the duration under intensive management will markedly affect the soil nutrient status, both the short- and long-term effects of intensive management on soil N, P and K forms and enzyme activity need to be explored in further studies.

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Figure captions

Fig. 1 Effects of conversion from evergreen broadleaf forests to Moso bamboo plantations on the total stocks (a, c, e and g) and concentrations (b, d, f and h) of C, N, P and K in soils. Error bars are the standard deviations of the mean (*n* = 4); different lowercase letters within each panel indicate significant differences between different land-use types in each soil layer at *P* = 0.05 level based on the least significant difference (LSD) test.

Fig. 2 Effects of conversion from evergreen broadleaf forests to Moso bamboo plantations on the (a) NH_4^+-N concentration, (b) NO_3^--N concentration, and (c) water soluble organic N (WSON) concentration in soils. Error bars are standard deviations of the mean (*n* = 4); different lowercase letters within each panel indicate significant differences between different land-use types in each soil layer at *P* = 0.05 level based on the least significant difference (LSD) test.

Fig. 3 Effects of conversion from evergreen broadleaf forests to Moso bamboo plantations on the (a) total K concentration, (b) available K concentration, (c) slowly available K concentration, and (d) mineral K concentration in soils. Error bars are the standard deviations of the mean (*n* = 4); different lowercase letters within each panel indicate significant differences between different land-use types in each soil layer at *P* = 0.05 level based on the least significant difference (LSD) test.

Fig. 4 Effects of conversion from evergreen broadleaf forests to Moso bamboo plantations on the (a) microbial biomass C, (b) microbial biomass N, and (c) microbial biomass P. Error bars are the standard deviations of the mean ($n = 4$); different lowercase letters within each panel indicate significant differences between different land-use types in each soil layer at $P = 0.05$ level based on the least significant difference (LSD) test.

Fig. 5 Effects of conversion from evergreen broadleaf forests to Moso bamboo plantations on the soil (a) protease activity, (b) urease activity, (c) acid phosphatase activity, and (d) catalase activity. Error bars are the standard deviations of the mean ($n = 4$); different lowercase letters within each panel indicate significant differences between different land-use types in each soil layer at $P = 0.05$ level based on the least significant difference (LSD) test.

Fig. 6 Relationship between acid phosphatase activity and (a) microbial biomass P, (b) $NaHCO_3$-P_O, and (c) $NaHCO_3$-P_i in the evergreen broadleaf forest and Moso bamboo plantation.

Fig. 7 Relationships (a-d) between urease activity and the concentrations of NH_4^+-N, NO_3^--N, WSON and MBN, and (e-h) between protease activity and the concentrations of NH_4^+-N, NO_3^--N, WSON and MBN in the evergreen broadleaf forest and Moso bamboo plantation. WSON: water soluble organic N; MBN: microbial biomass N.

Table 1 Effect of conversion from evergreen broadleaf forests to Moso bamboo plantations on different P forms in the soil

Forest type	Resin-P_i (mg kg^{-1})	$NaHCO_3$-P_i (mg kg^{-1})	$NaHCO_3$-P_o (mg kg^{-1})	NaOH-P_i (mg kg^{-1})	NaOH-P_o (mg kg^{-1})	HCl-P_i (mg kg^{-1})	Residual-P (mg kg^{-1})
0-20 cm							
Broadleaf forest	2.17 (0.21) b	4.50 (0.26) b	32.1 (2.7) a	47.5 (4.2) b	67.1 (3.9) a	5.89 (0.53) b	241.7 (14.3) b
Bamboo plantation	3.51 (0.18) a	7.23 (0.48) a	24.0 (1.7) b	56.7 (2.6) a	54.7 (2.9) b	9.25 (0.52) a	312.6 (30.4) a
20-40 cm							
Broadleaf forest	1.12 (0.10) b	4.20 (0.31) b	27.0 (2.1) a	48.3 (3.0) a	63.2 (3.2) a	6.24 (0.52) a	226.0 (24.0) a
Bamboo plantation	1.86 (0.13) a	6.79 (0.37) a	21.3 (2.1) b	52.4 (4.6) a	58.3 (4.3) a	7.12 (0.47) a	249.3 (24.9) a

Means with different letters within a column indicate significant differences between the land uses for each parameter within each soil layer at $P = 0.05$ level according to the least significant difference (D) test.

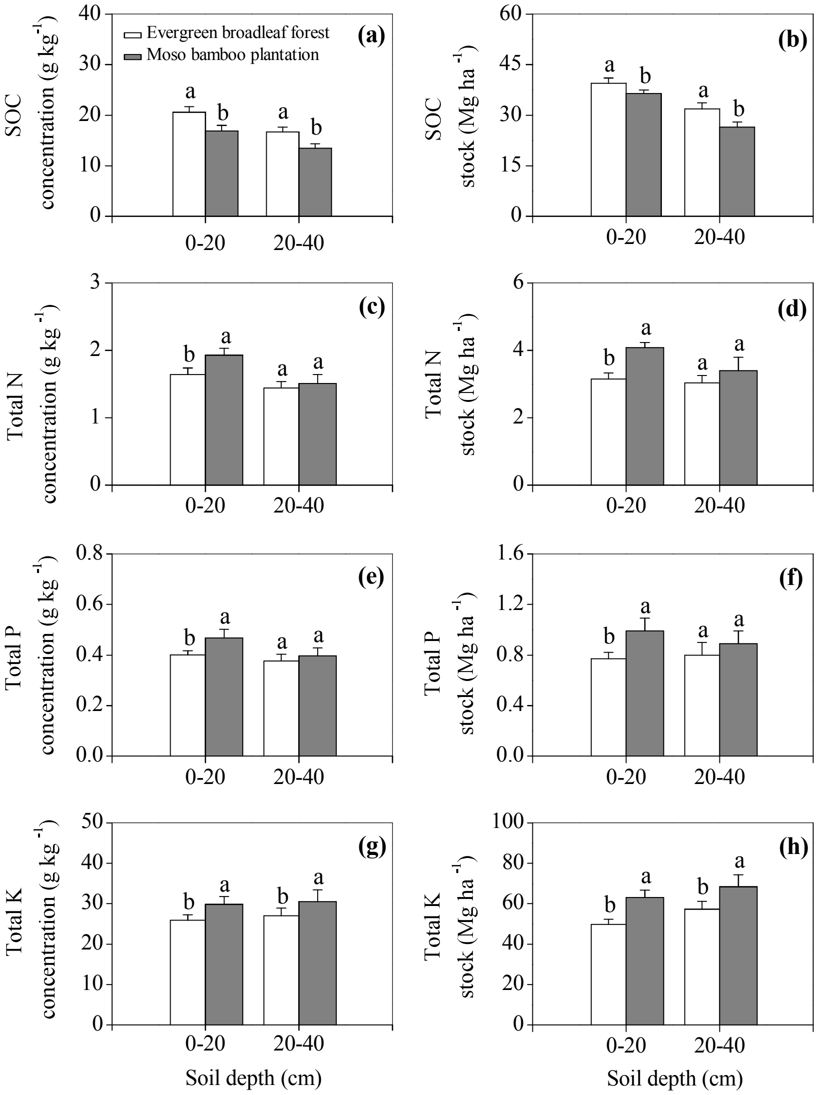

(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Evergreen broadleaf forest
Moso bamboo plantation
SOC concentration (g kg^{-1})
SOC stock (Mg ha^{-1})
Total N concentration (g kg^{-1})
Total N stock (Mg ha^{-1})
Total P concentration (g kg^{-1})
Total P stock (Mg ha^{-1})
Total K concentration (g kg^{-1})
Total K stock (Mg ha^{-1})
0-20
20-40
Soil depth (cm)
a
b

Fig. 1

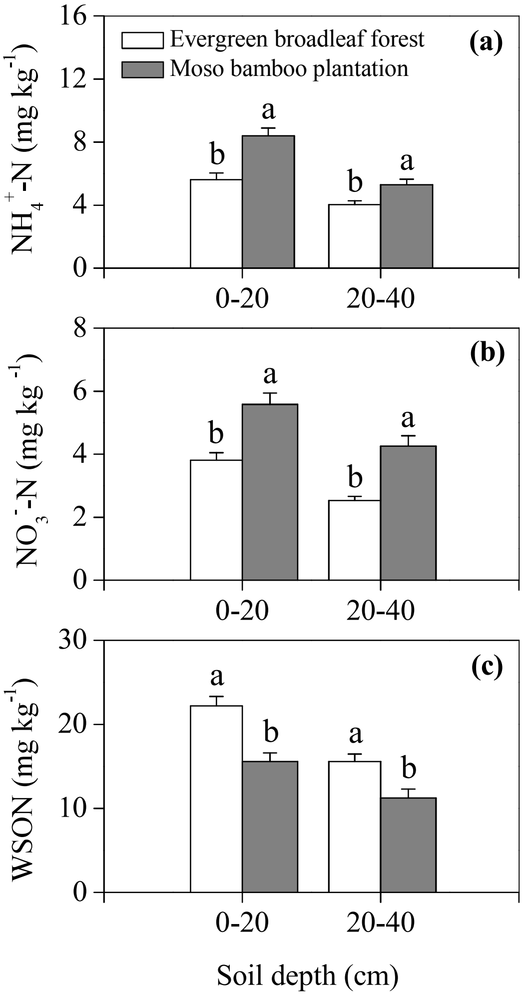

(a)
Evergreen broadleaf forest
Moso bamboo plantation
NH_4^+-N (mg kg^{-1})
0
4
8
12
16
b
a
b
a
0-20
20-40
(b)
NO_3^--N (mg kg^{-1})
0
2
4
6
8
b
a
b
a
0-20
20-40
(c)
WSON (mg kg^{-1})
0
10
20
30
a
b
a
b
0-20
20-40
Soil depth (cm)

Fig. 2

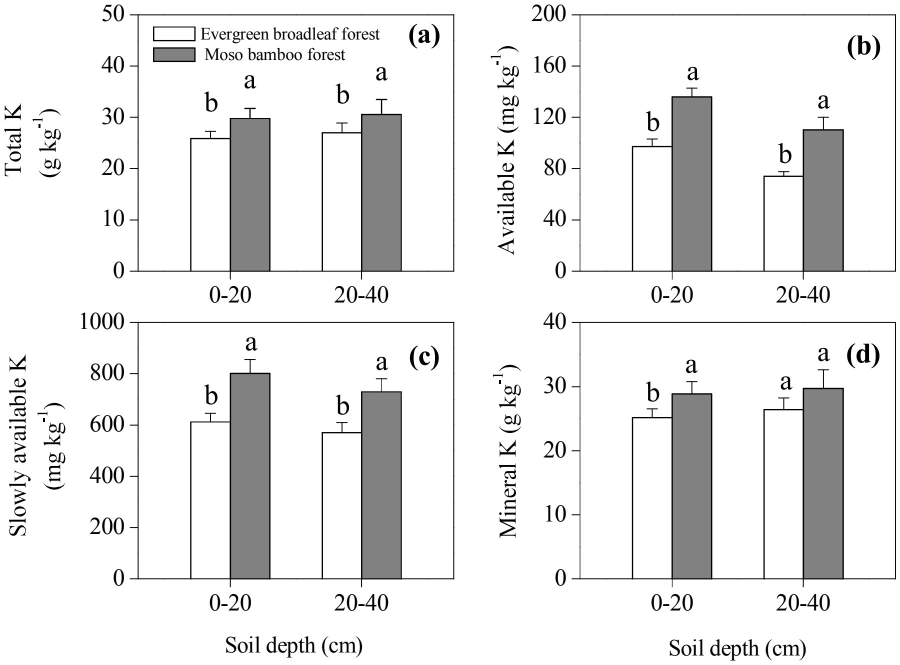

Evergreen broadleaf forest
Moso bamboo forest
(a)
Total K (g kg^{-1})
0
10
20
30
40
50
b
a
b
a
0-20
20-40
(b)
Available K (mg kg^{-1})
0
40
80
120
160
200
b
a
b
a
0-20
20-40
(c)
Slowly available K (mg kg^{-1})
0
200
400
600
800
1000
b
a
b
a
0-20
20-40
Soil depth (cm)
(d)
Mineral K (g kg^{-1})
0
10
20
30
40
b
a
a
a
0-20
20-40
Soil depth (cm)

Fig. 3

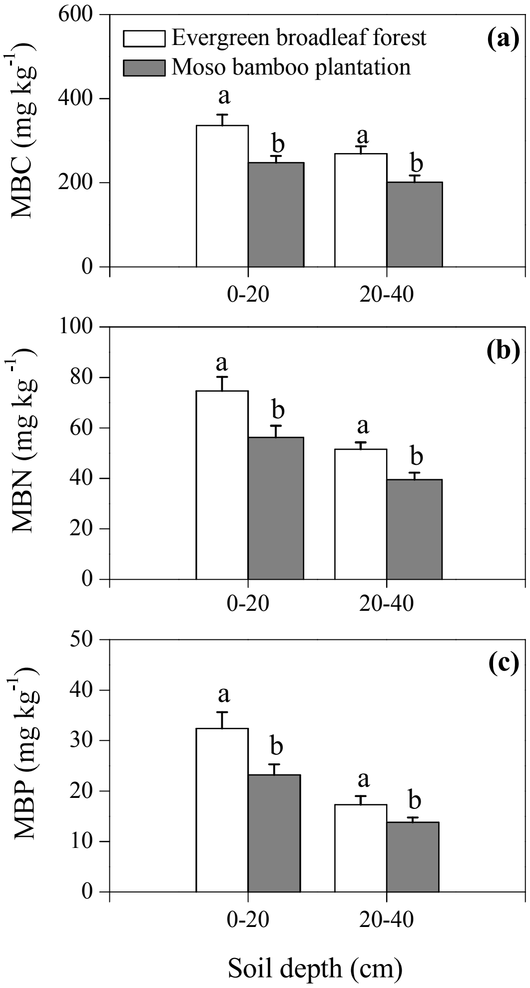

600
400
200
0
MBC (mg kg^{-1})
Evergreen broadleaf forest
Moso bamboo plantation
(a)
a
b
a
b
0-20
20-40
100
80
60
40
20
0
MBN (mg kg^{-1})
(b)
a
b
a
b
0-20
20-40
50
40
30
20
10
0
MBP (mg kg^{-1})
(c)
a
b
a
b
0-20
20-40
Soil depth (cm)

Fig. 4

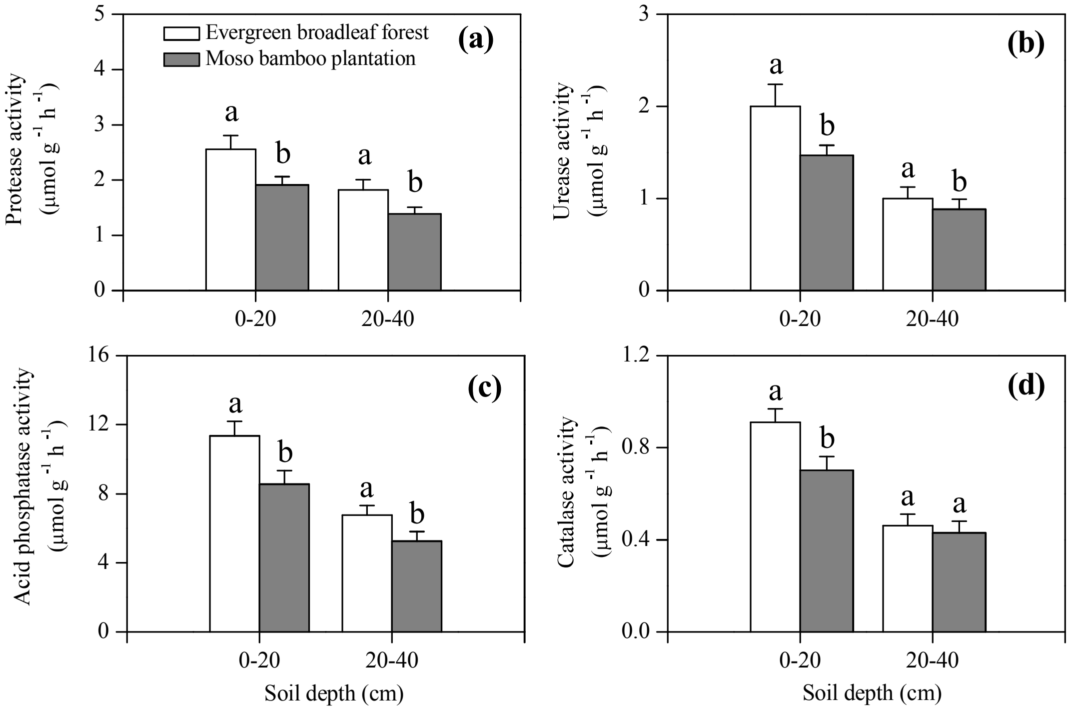

Evergreen broadleaf forest
Moso bamboo plantation
(a)
Protease activity (μmol g -1 h -1)
(b)
Urease activity (μmol g -1 h -1)
(c)
Acid phosphatase activity (μmol g -1 h -1)
(d)
Catalase activity (μmol g -1 h -1)
0-20
20-40
Soil depth (cm)
a
b

Fig. 5

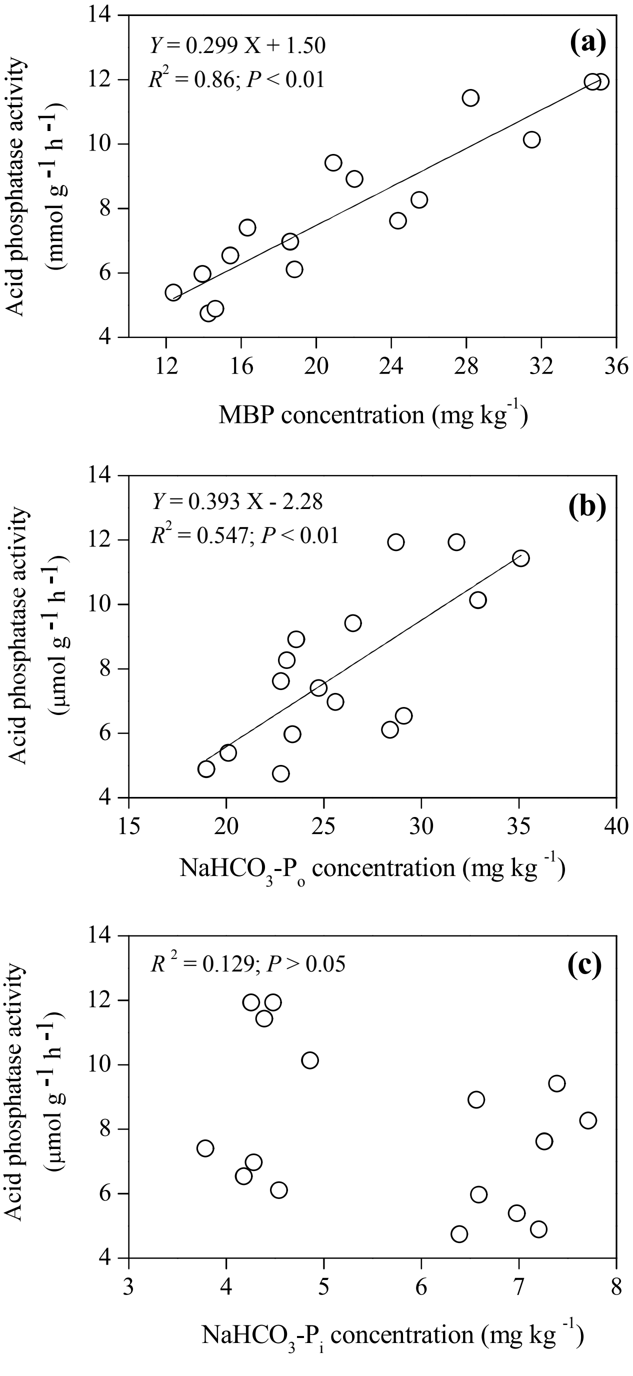
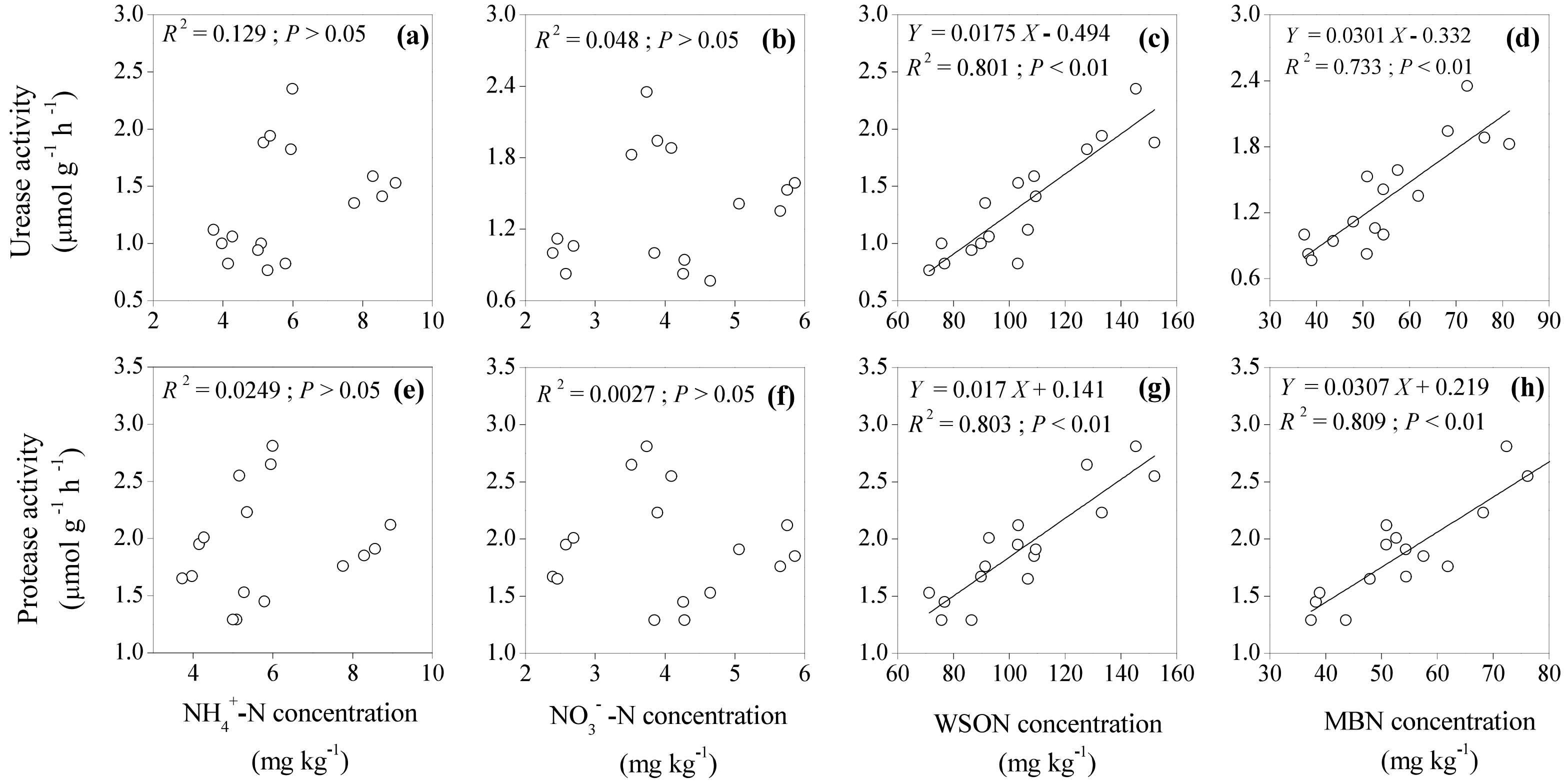

(a)
Y = 0.299 X + 1.50
R2 = 0.86; P < 0.01
Acid phosphatase activity (mmol g -1 h -1)
14
12
10
8
6
4
12
16
20
24
28
32
36
MBP concentration (mg kg-1)
(b)
Y = 0.393 X - 2.28
R2 = 0.547; P < 0.01
Acid phosphatase activity (µmol g -1 h -1)
14
12
10
8
6
4
15
20
25
30
35
40
NaHCO3-Po concentration (mg kg -1)
(c)
R 2 = 0.129; P > 0.05
Acid phosphatase activity (µmol g -1 h -1)
14
12
10
8
6
4
3
4
5
6
7
8
NaHCO3-Pi concentration (mg kg -1)

Fig. 6



Urease activity (μmol g-1 h-1)
Protease activity (μmol g-1 h-1)
R 2 = 0.129 ; P > 0.05 (a)
R 2 = 0.048 ; P > 0.05 (b)
Y = 0.0175 X - 0.494
R 2 = 0.801 ; P < 0.01 (c)
Y = 0.0301 X - 0.332
R 2 = 0.733 ; P < 0.01 (d)
R 2 = 0.0249 ; P > 0.05 (e)
R 2 = 0.0027 ; P > 0.05 (f)
Y = 0.017 X + 0.141
R 2 = 0.803 ; P < 0.01 (g)
Y = 0.0307 X + 0.219
R 2 = 0.809 ; P < 0.01 (h)
NH4+-N concentration (mg kg-1)
NO3- -N concentration (mg kg-1)
WSON concentration (mg kg-1)
MBN concentration (mg kg-1)

Fig. 7