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Effects of precipitation on soil acid phosphatase activity in three successional forests in southern China

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Abstract. Phosphorus (P) is often a limiting nutrient for plant growth in tropical and subtropical forests. Global climate change has led to alterations in precipitation in the recent years, which inevitably influences P cycling. Soil acid phosphatase plays a vital role in controlling P mineralization, and its activity reflects the capacity of organic P mineralization potential in soils. In order to study the effects of precipitation on soil acid phosphatase activity, an experiment with precipitation treatments (no precipitation, natural precipitation and doubled precipitation) in three successional forests in southern China was carried out. The three forests include *Masson* pine forest (MPF), coniferous and broad-leaved mixed forest (MF) and monsoon evergreen broad-leaved forest (MEBF). Results showed that driven by seasonality of precipitation, changes in soil acid phosphatase activities coincided with the seasonal climate pattern, with significantly higher values in the wet season than in the dry season. Soil acid phosphatase activities were closely linked to forest successional stages, with enhanced values in the later stages of forest succession. In the dry season, soil acid phosphatase activities in the three forests showed a rising trend with increasing precipitation treatments. In the wet season, soil acid phosphatase activity was depressed by no precipitation treatment in the three forests. However, doubled precipitation treatment exerted a significantly negative effect on it only in MEBF. These results indicate that the potential transformation rate of organic P might be more dependent on water in the dry season than in the wet season. A decrease in organic P turnover would occur in the three forests if there was a drought in a whole year in the future. More rainfall in the wet season would also be adverse to organic P turnover in MEBF due to its high soil moisture.

1 Introduction

Phosphorus (P) limitation to forest primary productivity and other ecosystem processes is widespread in tropical forests (Attiwill and Adams, 1993). Most soil P is bound in detritus as organic P and remains inaccessible to plants. Apart from the weathering of parent material in soils, P input depends on the mineralization of soil organic matter. Phosphatases, originating from fungi, bacteria and root exudates, catalyze the hydrolysis of ester bonds between phosphate and carbon compounds in organic substrates to enhance P availability to ecosystems (Turner and Haygarth, 2005). The production of phosphatase would be increased when the requirement for P by forest ecosystems is increased (Clarholm, 1993; Olander and Vitousek, 2000). These enzymes therefore play an important role in maintaining and controlling the rate of P cycling in forest ecosystems. Of the phosphatases, acid phosphatase is predominant in forest soils due to their pH optima (Juma and Tabatabai, 1988). Its activity can provide useful information on organic P mineralization potential and biological activity of soils (Speir and Ross, 1978; Dick and Tabatabai, 1993; Krämer and Green, 2000). Acid phosphatase activity has been used as an indicator in several studies to evaluate P limitation in forest ecosystems (Schneider et al., 2001; Gress et al., 2007).

Changes to global precipitation (Houghton et al., 2001) have potential to greatly influence P cycling dynamics, since soil moisture is a key factor of controlling P availability in soils through several processes, including affecting mineralization processes, influencing P demand for plant growth and impacting microbial activity (Leiros et al., 1999; Raghothama, 1999; Grierson and Adams, 2000; Sardans et al., 2007). In some increased drought areas, such as the Mediterranean, dry conditions lead to a great degree of P limitation to plant growth because of a decrease in P supply through impairing soil phosphatase activity (Garcia et

al., 2002; Sardans and Penuelas, 2005). During the latter part of the 20th century, there has been a decreasing trend in precipitation over northern China, while a significant increase in precipitation was also detected over the middle and lower reaches of the Yangtze River and west China (Zhai et al., 1999). Our study also showed that the monthly precipitation in northern Guangdong province had changed a lot in the past decades (Luo et al., 2008). Changes in precipitation are, therefore, likely to affect the rate of P turnover and soil P availability. Soil acid phosphatase associating with P cycling in forest ecosystems is an exceptional entry point for accessing the effects of variations in precipitation on P supply in tropical and subtropical forests of China, which often suffer from P deficiency. Some studies have reported changes in soil acid phosphatase activity in response to a more pronounced drought (Sardans and Penuelas, 2005). However, to the best of our knowledge, such investigations of acid phosphatase activity have not been conducted in any of the tropical and subtropical forests in China.

The Dinghushan Biosphere Reserve (DBR) possesses some typical forests in southern China, consisting of a pioneer community (*Masson* pine forest, MPF), a transition community (coniferous and broad-leaved mixed forest, MF) and a climax community (monsoon evergreen broad-leaved forest, MEBF). These forests provide an excellent opportunity to study P cycling along with a natural forest successional gradient. Previous studies have suggested that soil available P is relatively low in this region (Huang et al., 2009) and P is possibly one of the factors limiting the plant productivity in MEBF of the DBR (Mo et al., 2000). In this case, we try to examine different responses of soil acid phosphatase activity to precipitation in the three forests with different P requirements. A field experiment of precipitation treatments, including no precipitation (NP), natural precipitation (control) and doubled precipitation (DP) in the three forests, was conducted to test the hypotheses: (1) driven by seasonality of precipitation, soil acid phosphatase activity would be higher in the wet season than in the dry season; (2) soil acid phosphatase activity would be greater in the later stages of forest succession and exhibit different responses to precipitation treatments depending on forest types; (3) precipitation treatments would exert different effects on soil acid phosphatase activity between the dry and wet seasons.

2 Materials and methods

2.1 Site description

This study was carried out in the DBR (23°09′21″ N–23°11′30″ N, 112°30′39″ E–112°33′41″ E), located in the central part of Guangdong province, South China. DBR is the first natural reserve in China with an area of 1133 ha. The reserve is characterized by a typical subtropical monsoon humid climate with an annual average relative humidity

of 80 %. The mean annual temperature is 21 °C, with a minimum monthly average temperature at 12.6 °C in January and a maximum one at 28 °C in July. The annual average precipitation of 1927 mm has a distinct seasonal pattern, with about 80 % of it falling from April to September (wet-warm season) and 20 % occurring from October to March (dry-cool season). The bedrock is sandstone and shale. Soils are classified in the ultisol group and udult subgroup according to USDA soil classification system (Buol et al., 2003).

In the DBR, key vegetation types consist of MPF, MF and MEBF, and they represent a sequence of natural successional stages, from pioneer community (MPF), transition community (MF) to regional climax vegetation (MEBF). MPF, belonging to the first stage of the successional processes, occurs in the periphery of the reserve at an elevation of about 200 m. It was planted in the 1950s. The dominant species in MPF is *Pinus massoniana* Lamb. (Brown et al., 1995). The texture of top soil in MPF is medium gravel-medium loam, and the capacity of field moisture and wilting coefficient in the soil expressed as gravimetric water content are 26.0 % and 10.9 %, respectively (Zhang and Zhuo, 1985). The MF is distributed between the core area and periphery of the reserve at an elevation of about 200–300 m. It originated from MPF planted in the 1930s. Due to a gradual invasion of some pioneer broadleaf species through natural succession, the plant composition in MF had greatly changed. Dominant species in the canopy layer of MF are *P. massoniana*, *Schima superba* Gardn. et Champ, *Castanopsis chinensis* Hance, and *Craibiodendron scleranthum* var. *kwangtungense* (S. Y. Hu) Judd. If sufficient time was allowed, MF is believed to develop into MEBF (Wang and Ma, 1982). The texture of top soil in MF belongs to medium gravel-heavy loam with field capacity and wilting point at 25.3 % and 8.2 % gravimetric water content, respectively (Zhang and Zhuo, 1985). MEBF is distributed in the core area of the reserve at an elevation varying from 200 to 300 m. It has been undisturbed for more than 400 yr (G. Y. Zhou et al., 2006). Major species in MEBF include *C. chinensis*, *Machilus chinensis* (Champ. ex Benth.) Hemsl., *S. superba*, *Cryptocarya chinensis* (Hance) Hemsl., *Syzygium rehderianum* Merr. et Perry in the canopy and subcanopy layers. The texture of top soil in MEBF is light gravel-heavy loam. The water retention ability of top soil is the highest with the capacity of field moisture and wilting coefficient at 34.6 % and 11.4 % gravimetric water content, respectively (Zhang and Zhuo, 1985).

2.2 Experiment design

The precipitation experiment was started within the three forests in December 2006. Three precipitation treatments consisted of no precipitation (NP), natural precipitation (control) and doubled precipitation (DP). Each treatment was replicated three times. In each forest, we selected the plots with similar slope aspect, slope degree, slope position and community structure in order to minimize the heterogeneity

among them. Each plot had a dimension of 3×3 m, and the distance between plots was more than 1 m. Precipitation was intercepted in the NP plots using polyvinyl chloride (PVC) sheer roof and was redistributed to the DP plots (Borken et al., 2006; X. H. Zhou et al., 2006). The control plot receiving natural precipitation was built beside these treatment plots. Around each NP plot, the thick PVC plates were inserted into grounds at 15 cm deep to prevent surface runoff and lateral movement of water from the surrounding soil. The litter falling on precipitation interception roofs of NP plots was removed manually and periodically sprinkled on soils below the plates (Chen et al., 2010). Soil moisture of the top 5 cm soil layer, determined as volumetric soil water content (%, $cm^3 \, cm^{-3}$), was measured on five random locations twice a month throughout the experiment within a plot using a MP-Kit (ICT, Australia, see http://www.ictinternational.com.au/soils.htm), which consists of three amplitude domain reflectometry (ADR) moisture probes (MP406) and a data logger (MPM160 meter) (Tang et al., 2006).

2.3 Soil sampling

We conducted soil sampling in February (the dry season) and June (the wet season) 2009. For each plot, we collected soil samples from 0–20 cm mineral soils after removal of the litter layer. Six soil cores (2.5 cm in diameter) were randomly taken and evenly combined to one sample in each plot. Soil samples were put in sealed plastic bags and immediately taken to the laboratory. Each sample was passed through a 2 mm sieve after removing roots, stones and other impurities. We divided each sample into two aliquots. One aliquot was air dried for analysis of related soil chemical properties. The other one was kept without drying at 4 °C until analysis of acid phosphatase activity was conducted. The measurement procedures of soil acid phosphatase activity were completed within 28 days.

2.4 Soil chemical properties and acid phosphatase activity measurements

Gravimetric soil moisture was determined from mass loss after drying for 24 h at 105 °C. Soil pH was measured in a deionized water suspension using glass electrodes at a ratio of 25 ml water to 10 g soil (Liu et al., 1996). Total carbon (C) was determined by dichromate oxidation before titration with a Fe^{2+} solution (Liu et al., 1996). Total N was measured by semimicro-Kjeldahl digestion followed by steam distillation and final titration of ammonium (Liu et al., 1996). Total P was determined colorimetrically after digestion (Liu et al., 1996). Available P was extracted with a solution containing $0.03 \, M \, NH_4F$ and $0.025 \, M \, HCl$ (Liu et al., 1996).

Soil acid phosphatase activity was measured using para-nitrophenyl phosphate (p-NPP) as an orthophosphate monoester analogue substrate. We used the method of Schneider et al. (2000) based on the original one of Tabatabai and Bremner (1969). We took 1 g of fresh soil ($<$2 mm) in a 100 ml Erlenmeyer flask, added 4 ml of modified universal buffer (pH 6.5) and 1 ml of 100 mM p-NPP substrate dissolved in the buffer, and swirled the flask slightly for a few seconds to mix the contents. The flask was then sealed and incubated at 30 °C for 30 min. After incubation, we immediately placed the flask on ice and then added 1 ml of $2 \, M \, CaCl_2$ and 4 ml of $0.2 \, M \, NaOH$ to terminate the reaction and extract the para-nitrophenol (p-NP) formed. The sample was diluted with 90 ml of deionized water and then filtered through Whatman-42 filter paper. Absorbance of released p-NP was determined spectrophotometrically at 400 nm. Four replicates including one blank were used for each soil sample. For the blank, p-NPP was added after (instead of before) the incubation. The acid phosphatase activity was expressed as μmol p-NP per gram dry soil and incubation time (μmol p-NP $g^{-1} \, h^{-1}$).
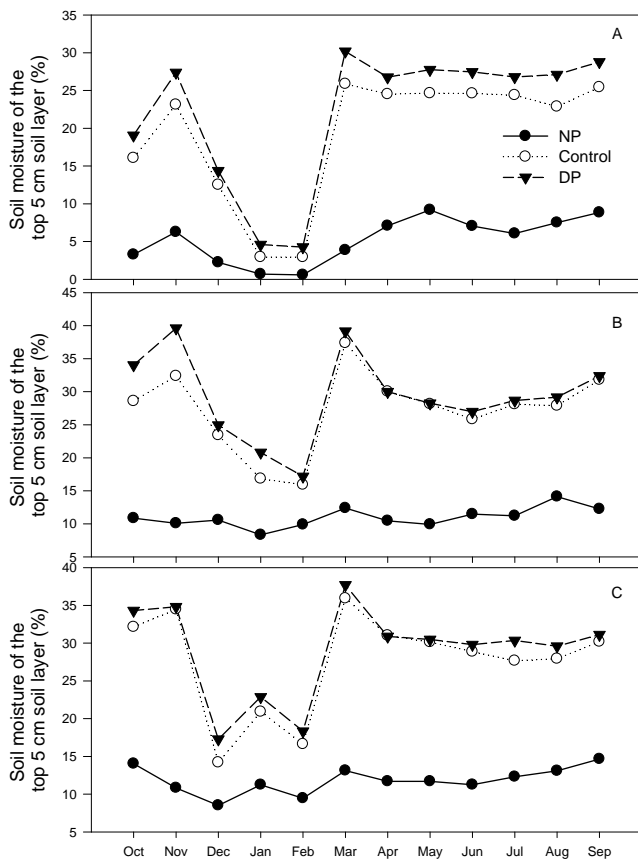
2.5 Statistical analysis

Data analyses were carried out with SPSS 11.5 for windows. We applied the t-test for independent samples to analyze differences between the dry and wet seasons for soil moisture, soil chemical properties and soil acid phosphatase activity in the three forests. A two factorial ANOVA was used to study the effects of season, forest type and their interaction on the variables. We used ANOVA followed by Tukey multiple comparison test to study: (1) the differences among the controls of three forests for soil moisture, soil chemical properties and soil acid phosphatase activity; (2) the effects of precipitation intensity on soil moisture, soil chemical properties and soil acid phosphatase activity among the treatments separately for each season and forest. In addition, Pearson correlation coefficients were calculated to show the relationships between soil chemical properties and acid phosphatase activity. For all statistical tests, we chose the probability level to reject the null hypothesis to be inferior or equal to 0.05 unless otherwise stated.

3 Results

3.1 Soil moisture

The mean soil moisture in the dry season (from October to March of the next year) was relatively lower than in the wet season (from April to September) (Fig. 1), but the difference in soil moisture between the two seasons was significant only in MPF ($P < 0.01$). In controls, the values of annual mean soil moisture were 19.2 % for MPF, 27.2 % for MF and 27.5 % for MEBF, respectively. MF and MEBF showed significantly greater annual mean soil moisture than MPF ($P < 0.01$), but there was no significant difference between MF and MEBF. In all the three forests, NP treatments significantly decreased soil moisture ($P < 0.01$), while DP treatments had no significant effects on it except for MPF in

Fig. 1. Seasonal dynamics of soil moisture of the top 5 cm soil layer under different precipitation treatments from October 2008 to September 2009 in *Masson* pine forest (**A**), coniferous and broad-leaved mixed forest (**B**) and monsoon evergreen broad-leaved forest (**C**) of Dinghushan Biosphere Reserve. NP, no precipitation; Control, natural precipitation; DP, double precipitation.

the wet season, which showed significantly greater soil moisture in DP treatment than in control ($P < 0.01$).

3.2 Soil chemical properties

The wet season exhibited significantly higher soil pH but lower available P ($P < 0.01$) than the dry season, while there were no significant differences in total C, total N and total P between the two seasons (Tables 1 and 2). Soil chemical properties significantly differed between forest types (Table 1).

For the dry season, significantly higher soil pH but lower total C were detected in the control of MPF than in those of MEBF ($P < 0.01$ for soil pH) and MF ($P < 0.01$ for both). Total P and available P were significantly higher in MEBF than those in MF ($P < 0.01$ for both). There were no significant differences in total N among the three forests. Precipitation treatments did not significantly affect related soil chemical properties except for available P in MEBF, which was

Table 1. Effects of season, forest type and their interactions on soil chemical properties. Numbers are F-values. Stars indicate the level of significance at $P < 0.05$ (no star, not significant at $P > 0.05$).

	pH	Total C	Total N	Total P	Available P
Season	14.61*	0.01	3.19	3.31	30.44*
Forest type	65.28*	26.29*	50.28*	109.54*	23.74*
Season* Forest type	0.48	1.88	1.36	2.25	15.88*

significantly reduced by DP treatment in comparison with NP treatment (Table 2).

For the wet season, MPF exhibited significantly higher soil pH and lower total P ($P < 0.01$) than MEBF in the controls. Total C and total N in the controls of MEBF and MF were significantly higher than those of MPF ($P < 0.01$ for all), while the concentrations of available P in both MEBF and MF were significantly lower than that in MPF ($P < 0.01$ for both). The differences of the soil chemical properties between MEBF and MF did not arrive at a significant level. Soil pH exhibited an increasing trend with increasing precipitation treatments in three forests, but it was only significantly lowered by NP treatment when compared with DP treatment and control ($P < 0.01$ for both) in MEBF. The other chemical properties were not greatly affected by precipitation treatments.

3.3 Soil acid phosphatase activity

In all cases, the wet season showed significantly higher soil acid phosphatase activities than the dry season ($P < 0.01$). On average, the value of soil acid phosphatase activity in the wet season was 1.33 times greater than in the dry season. In the two seasons, the controls of MEBF and MF exhibited significantly higher soil acid phosphatase activities than that of MPF ($P < 0.01$ for both), and the difference between MEBF and MF was not significant. The mean values of soil acid phosphatase activity in the two seasons were 4.89 μmol p-NP g^{-1} h^{-1} for MPF, 12.41 μmol p-NP g^{-1} h^{-1} for MF and 12.29 μmol p-NP g^{-1} h^{-1} for MEBF, respectively.

The responses of soil acid phosphatase activity to precipitation varied with seasons and forests (Fig. 2). In the dry season, increasing precipitation treatments exerted positive impacts on soil acid phosphatase activities in the three forests (Fig. 2a). For MPF, DP treatment significantly increased soil acid phosphatase activity when compared with NP treatment and control ($P < 0.01$ for both), and the difference between NP treatment and control was not significant. For MF, soil acid phosphatase activity in NP treatment was around 21 % and 23 % lower than control and DP treatment, respectively. As for MEBF, although the differences in soil acid phosphatase activity among treatments

Table 2. Soil chemical properties and their responses to precipitation treatments in 0–20 cm mineral soils of three forests in the dry and wet seasons at Dinghushan Biosphere Reserve. Mean values within a column in each forest for each season followed by different lowercase letters have significant treatment differences at $P < 0.05$. MPF, *Masson* pine forest; MF, coniferous and broad-leaved mixed forest; MEBF, monsoon evergreen broad-leaved forest. NP, no precipitation; Control, natural precipitation; DP, double precipitation.

Time	Forest	Treatment	pH	Total C	Total N	Total P	Available P
				mg g^{-1}			mg kg^{-1}
Dry season	MPF	NP	4.06	15.49	1.16	0.16	1.61
		Control	4.09	13.80	1.25	0.14	1.05
		DP	4.13	12.17	0.88	0.15	1.21
	MF	NP	3.82	24.10	1.51	0.16	0.72
		Control	3.81	29.69	1.81	0.16	0.65
		DP	3.93	23.95	1.52	0.16	0.74
	MEBF	NP	3.67	27.32	1.76	0.22	2.62a
		Control	3.81	23.90	1.49	0.21	1.47ab
		DP	3.77	27.38	1.67	0.21	1.44b
Wet season	MPF	NP	4.14	21.32	1.10	0.16	1.45
		Control	4.15	15.24	1.05	0.15	1.39
		DP	4.23	15.11	1.07	0.15	1.27
	MF	NP	3.95	22.84	1.64	0.17	0.22
		Control	3.99	27.04	1.88	0.20	0.30
		DP	4.01	26.14	1.74	0.17	0.22
	MEBF	NP	3.67b	24.51	1.94	0.21	0.74
		Control	3.90a	23.75	1.83	0.23	0.43
		DP	3.92a	22.76	1.77	0.22	0.21

were not significant, it showed a positive response to increasing precipitation. The values were in this order: 8.70 µmol p-NP g^{-1} h^{-1} for NP treatment <9.77 µmol p-NP g^{-1} h^{-1} for control <10.54 µmol p-NP g^{-1} h^{-1} for DP treatment. In the wet season, soil acid phosphatase activities were all significantly lowered by NP treatments in the three forests ($P < 0.01$ for all) (Fig. 2b). However, they were not stimulated by DP treatments in both MPF and MF, and it was even significantly depressed by DP treatment in MEBF. Among the three forests, the responses of soil acid phosphatase activity to precipitation treatments were the most pronounced in MEBF. The differences among the three treatments in MEBF all came up to significant levels.

3.4 Relationships between soil chemical properties and soil acid phosphatase activity
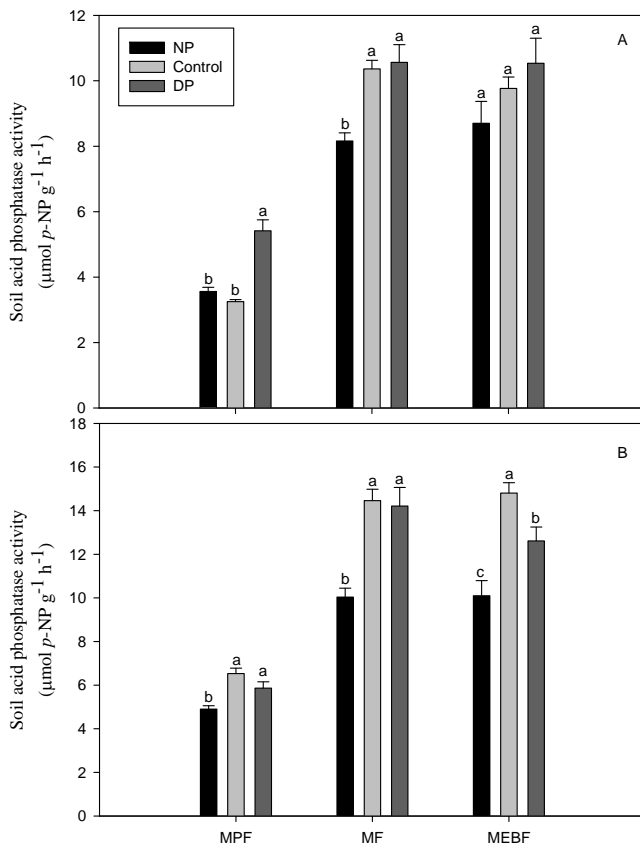
Soil acid phosphatase activity had a significantly negative correlation with soil pH and available P. The relationships of soil acid phosphatase activity to total C, total N and total P were all significantly positive (Table 3).

4 Discussion

The acid phosphatase activity in soils of the three forests was assayed under the optimum acidity condition with pH equal to 6.5 (Tabatabai and Bremner, 1969; Tabatabai, 1994; Schneider et al., 2000). Although enzyme activity determined at the optimum pH is usually higher than that under soil pH (Turner et al., 2002), the optimum condition can provide a consistent background for comparison. In our study, it is important to detect P demand and potential mineralization of soil organic P in response to precipitation across the three forests. The same acidity condition can minimize the influence of soil pH on acid phosphatase activities across the three forests, and thus, the measured results better reflect the differences in P demand.

4.1 Soil acid phosphatase activity in the dry and wet seasons

Phosphatases are inducible enzymes regulated by end-product inhibition. Plant roots and microbes will increase the excretion of phosphatases into soils when available P does not meet their demands (Goldstein et al., 1988). This mechanism was clearly evident from the significantly negative correlation between acid phosphatase activity and available P in

Fig. 2. Soil acid phosphatase activity in the dry (**A**) and wet (**B**) seasons under different precipitation treatments in 0–20 cm mineral soils of three forests at Dinghushan Biosphere Reserve. Error bars represent standard errors. Different lowercase letters denote significant differences between treatments at $P < 0.05$ in the same forest. MPF, *Masson* pine forest; MF, coniferous and broad-leaved mixed forest; MEBF, monsoon evergreen broad-leaved forest. NP, no precipitation; Control, natural precipitation; DP, double precipitation.

Table 3. Pearson correlation coefficients between soil acid phosphatase activity and soil chemical properties at Dinghushan Biosphere Reserve.

	pH	Total C	Total N	Total P	Available P
Soil acid phosphatase activity	−0.463	0.650	0.743	0.623	−0.460
Significant level	< 0.00	< 0.00	< 0.00	< 0.00	< 0.00

Table 4. Mean soil microbial biomass C of the top 20 cm soil layer under different precipitation treatments in 2008 in three forests of Dinghushan Biosphere Reserve. Mean values within a column in each season followed by different lowercase letters have significant treatment differences at $P < 0.05$. MPF, *Masson* pine forest; MF, coniferous and broad-leaved mixed forest; MEBF, monsoon evergreen broad-leaved forest. NP, no precipitation; Control, natural precipitation; DP, double precipitation.

Time	Treatment	MPF	MF	MEBF
		mg kg^{-1}		
Dry season*	NP	156c	175b	311b
	Control	279b	384a	451a
	DP	368a	411a	456a
Wet season*	NP	287b	347c	483b
	Control	442a	527b	711a
	DP	542a	697a	705a

* Significant difference between the dry and wet seasons at $P < 0.05$. Data in the table cited from Q. Deng et al. (unpublished data, 2011).

our results (Table 3). It is expected that soil acid phosphatase activity would be clearly greater in the wet season than in the dry season in our experiment, a seasonal pattern observed previously by Grierson and Adams (2000). Actually, in the wet season, plants grow fast, and microbial biomass is always high (Table 4). This increasing enzyme activity would respond to meet the increasing P demand by plant and microbe growth in the wet season. Since heavy rain in the wet season often leads to nutrient loss, low available P detected in the wet season (Tables 1 and 2) further intensifies the competition for P in ecosystems in the growing season. On the contrary, dry season is the least biologically active period. Soil available P was relatively high (Tables 1 and 2) to meet the biological demands because of the accumulation of nutrients released from litter decomposition and low soil nutrient diffusion (Xia et al., 1997).

4.2 Effects of forest succession on soil acid phosphatase activity in the controls

Results showed that MF and MEBF exhibited higher soil acid phosphatase activities than MPF. Although available P could exert a negative feedback on phosphatase activity, the pattern in acid phosphatase activity across the three forests was not explained by the variability in available P in the three forests. An alternative explanation could be that soil nutrient status and vegetation conditions in the three forests influence soil acid phosphatase activity (Harrison, 1983; Ushio et al., 2010).

Our results also showed that soil chemical properties had close relationships with soil acid phosphatase activity (Table 3). This was also partly confirmed by other studies (Schneider et al., 2000; Turner and Haygarth, 2005; C. R. Chen et al., 2003, 2008), indicating that the better soil nutrient condition, the higher soil acid phosphatase activity would be. In the DBR, soil nutrient condition in MF was comparable with that in MEBF despite their different successional stages, but they were both superior to

that in MPF (Table 2). Soil microbial biomass was elevated in the later stages of forest succession (Table 4). This necessarily resulted in high soil acid phosphatase activities in MF and MEBF as this enzyme partly originates from microbes. Moreover, with progressive forest succession (MPF→MF→MEBF), plant community developed from almost monospecific with only occasional broad-leaved tree species to rich and diversiform species. The biomass, litterfall production (Table 5) and litter decomposition rate (Mo et al., 2006), which were very important in balancing loss and removal of P from mineral soils by plant uptake and microbial activity (C. R. Chen et al., 2000, 2003), exhibited an increasing tendency with progressive successional stages. Thus, acid phosphatase activity was enhanced with forest succession.

As soil acid phosphatase activity is a prevailing indicator of the degree in P limitation (Turner et al., 2002), our result might reflect an enhanced biological P limitation in the later successional forests. This was partly supported by Mo et al. (2000), suggesting that P was possibly one of the factors limiting the plant productivity in the mature forest of the DBR.

4.3 Effects of precipitation treatments on soil acid phosphatase activity

In the dry season, increasing precipitation treatments had positive effects on soil acid phosphatase activity in the three forests, although the extent of effects differed between forest types. Zhou and Yan (2001) studying in this area stated that owing to moderate solar radiation input in dry season, plant growth potential still kept high and demanded for moderate water, but less rainfall in the season could not meet the need. Increased precipitation input has a direct benefit to plant growth, and correspondingly, P demand will be enhanced. We observed that precipitation treatments did not affect soil total C, total N and total P (Table 2). The results indicate that changes in soil acid phosphatase activity might be more dependent on soil moisture rather than a consequence of changes in the substrate.

However, the amount of water requirement varied with forest types. In MPF, our results showed that soil acid phosphatase activity was only greatly enhanced by DP treatment, demonstrating that water was a key limiting factor in controlling the P cycling due to its own quite low soil moisture (Fig. 1). As a transition community, MF had higher acid phosphatase activities in control and DP treatment than in NP treatment. This indicates that soil water is not a limited factor to P mineralization, and that increased water in MF is not as important as that in MPF. As a regional climax community, MEBF had a wholesome self-regulating mechanism and a high capability of resisting outside interference. Thus, in the dry season, precipitation treatments did not markedly influence soil acid phosphatase activity. In this case, the significantly low available P in DP treatment (Table 2), possibly

Table 5. Relevant factors related to soil acid phosphatase activity in three forests of Dinghushan Biosphere Reserve. MPF, *Masson* pine forest; MF, coniferous and broad-leaved mixed forest; MEBF, monsoon evergreen broad-leaved forest.

Forest	MPF	MF	MEBF
Biomass (Mg C ha^{-1})	40.6	116.2	147.8
Litterfall production (g m^{-2} yr^{-1})	356	861	849
Fine root biomass (Mg C ha^{-1})*	1.9	2.8	4.9
Soil available N (mg kg^{-1})	6.24	6.22	14.77

* Fine root biomass refers to root biomass in 0–20 cm depth of soils. Data in table cited from Fang et al. (2004), Peng and Zhang (1994), Tang et al. (2006), Wen et al. (1998), and Zhou et al. (2007).

induced by P loss from leaching, was not accompanied by sufficiently high acid phosphatase activity. This would further intensify competition for P in the mature forest.

In the wet season, soil acid phosphatase activities in three forests exhibited different patterns in responses to precipitation treatments. That NP treatment had a clearly negative effect on soil acid phosphatase activity was consistent with the results reported in other literatures, representing that phosphatase activity was well correlated with soil water availability (Krämer and Green, 2000; Sardans and Penuelas, 2005, Sardans et al., 2008). Q. Deng et al. (unpublished data, 2011) found that soil microbial biomass was significantly depressed by NP treatments in the three forests (Table 4). This could be responsible for the decrease in acid phosphatase activity. In MEBF, the increasing acidity of soil accompanied by the prolonged drought condition (Table 2) might be another mechanism involved in the reduction of soil acid phosphatase activity. There is a considerable risk for aluminum toxicity in a relatively low soil pH, which would inhibit plant root growth and nutrient absorption (Liu, 2000). Thus, these factors would decrease acid phosphatase activity as it is closely related to microbe and root growth (Tarafdar and Claassen, 1988). The decrease in soil acid phosphatase activity produced by drought would result in a reduction of P availability to plants, and further aggravate the stress of competition for P in this region in the long time.

Nevertheless, in the wet season, no positive effects and even some negative effects of DP treatments on soil acid phosphatase activity were detected in the three forests. Water brought by natural rainfall is sufficient for plant growths because of large rainfall occurring in the wet season (Zhou and Yan, 2001). More water has no competitive advantage under enhanced P demands in the growing season. As soil moisture was already high in MEBF (Fig. 2), more water input would impede the diffusion of oxygen in the soils (Davidson et al., 1998). In an anoxic condition, plant root growth and microbial activity would be restrained (Q. S. Chen et al., 2003), which could be responsible for the significantly lower acid phosphatase activity in DP treatment in MEBF.

The implication of the decreased acid phosphatase activity would be a decline in the potential mineralization of organic P in MEBF. Moreover, from our observation, the N input with the rainfall was about 35 kg N ha^{-1} yr^{-1} during the past twenty years (Huang et al., 2011b). Doubled rainfall brought about more available N input into MEBF, which already had great soil available N (Table 5). In this case, more available P would be required to match the increase in N (Huang et al., 2011a). Thus, higher N availability and lower acid phosphatase activity induced by DP treatment would be involved in more intensified P deficiency in the mature forest.

5   Conclusions

Driven by the seasonality of precipitation, soil acid phosphatase activities presented an obvious seasonal pattern, with high values in the wet season and low ones in the dry season, which corresponded to the most biological activity and lower soil available P in the growing season. Forest succession and soil acid phosphatase activity were positively related, with the smallest values in MPF, followed by MF and MEBF. This suggests that the requirements for P by ecosystems might be enhanced in the later stages of forest succession. Our results also show that a reasonable distribution of water plays a critical role in controlling the rate of P cycling in subtropical forest soils. In the dry season, there was a trend toward increasing soil acid phosphatase activity with elevating precipitation treatments in the three forests, while the extent of increase differed between forest types. In the wet season, drought caused decreases in soil acid phosphatase activities within the three forests. However, DP treatments exerted little effects on soil acid phosphatase activity except for that in MEBF, showing clearly negative effects on it. The negative effects of precipitation on soil acid phosphatase activity suggest that drought throughout the year would be adverse to organic P turnover in the three forests, while more rainfall in the wet season would depress organic P turnover in the mature forest.

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