Agriculture and Natural Resources 51 (2017) 91-95

Contents lists available at ScienceDirect



Agriculture and Natural Resources

journal homepage: http://www.journals.elsevier.com/agriculture-andnatural-resources/

Original Article

Effects of phosphorus addition on nitrogen cycle and fluxes of N₂O and CH₄ in tropical tree plantation soils in Thailand



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ARTICLE INFO

Article history: Received 3 August 2015 Accepted 15 March 2016 Available online 10 June 2017

Keywords: Soil respiration Nitrous oxide Methane Tropics Phosphorus Tree plantation

ABSTRACT

An incubation experiment was conducted to test the effects of phosphorus (P) addition on nitrous oxide (N₂O) emissions and methane (CH₄) uptakes, using tropical tree plantation soils in Thailand. Soil samples were taken from five forest stands—*Acacia auriculiformis, Acacia mangium, Eucalyptus camaldulensis, Hopea odorata*, and *Xylia xylocarpa*—and incubated at 80% water holding capacity. P addition stimulated N₂O emissions only in *Xylia xylocarpa* soils. Since P addition tended to increase net ammonification rates in *Xylia xylocarpa* soils, the stimulated N₂O emissions were suggested to be due to the stimulated nitrogen (N) cycle by P addition and the higher N supply for nitrification and denitrification. In other soils, P addition had no effects on N₂O emissions or soil N properties, except that P addition tended to increase the soil microbial biomass N in *Acacia auriculiformis* soils. No effects of P addition were observed on CH₄ uptakes in any soil. It is suggested that P addition on N₂O and CH₄ fluxes at the study site were not significant, at least under laboratory conditions.

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Introduction

Since the primary source of phosphorus (P) for terrestrial ecosystems is rock weathering, P has been considered to be the ultimate limiting soil nutrient in terrestrial ecosystems, and ecosystems with old soils can become depleted in P (Walker and Syers, 1976). Thus, highly-weathered lowland tropical forest soils have been considered to have low concentrations of biologically available P (Vitousek and Farrington, 1997; Elser et al., 2007; Vitousek et al., 2010), and it is widely believed that P limits the ecosystem process in tropical forests. Several studies have reported that P availability also limits soil microbial activities in tropical soils (Cleveland et al., 2002; Ilstedt et al., 2003, 2006; Cleveland and Townsend, 2006; Mori et al., 2010; Liu et al., 2012). Thus, changes in P availability may change soil microbial activities, metabolisms

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and community composition, which could be associated with altered nitrous oxide (N_2O) (Mori et al., 2013a, 2013b, 2014) and methane (CH₄) (Mori et al., 2013c) exchange between terrestrial ecosystems and the atmosphere (Mori et al., 2013d).

Soil of tropical forests is an important source of N₂O, which is a by-product or intermediate product of microbial nitrification and denitrification, respectively (Wrage et al., 2001). Tropical forest soils have also the potential to function as substantial sinks of CH₄ (Potter et al., 1996). CH₄ fluxes are the net result of the simultaneous microbial oxidation of CH₄ by methanotrophs in predominantly aerobic soil zones and microbial production of CH₄ by methanogenesis in predominantly anaerobic soil zones (Le Mer and Roger, 2001).

Recently several studies have reported that P addition reduced N₂O emissions through stimulated plant N uptake (Mori et al., 2013d; Baral et al., 2014; Zhang et al., 2014). Mori et al. (2014) experimentally confirmed this suggestion by showing that P addition reduced N₂O emissions from an *Acacia mangium* plantation, but did not if plant roots were excluded by the trenching method. The authors' understanding is still lacking on the effects of P

http://dx.doi.org/10.1016/j.anres.2016.03.002

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addition on microbial activity, without plant interaction, and accompanying N₂O emissions. Hall and Matson (1999) suggested that a P shortage in tropical soils limits microbial N immobilization, resulting in an increase in N resources for nitrification or denitrification or both. Their report implied that P addition alleviates a P shortage and increases microbial N immobilization, resulting in a reduction in N resources for nitrification or denitrification or both and a reduction in N₂O emissions. However, previous papers have reported completely opposite results, with higher N₂O emission rates in P-added soils than in the non-added control (Mori et al., 2010, 2013a). Alleviation of P-limitation on nitrifying or denitrifying bacteria or both, stimulated whole N cycling in the soil, and improved reductive conditions with stimulated denitrifying activity being the suggested mechanism. However only one soil was used (soil taken from an Acacia mangium plantation in South Sumatra, Indonesia), and there are still very few reports testing the effects of P addition on N₂O emissions.

It has been shown that P addition increased (Aerts and Toet, 1997), decreased (Conrad et al., 2000), or had no effects (Lund et al., 2009; Keller et al., 2005) on CH4 fluxes. It was also reported that P application lowered CH₄ fluxes indirectly by stimulating root water uptake (Zhang et al., 2011). Mori et al. (2013b) reported that P addition had no effects on CH₄ fluxes in an *Acacia mangium* plantation, but significantly increased CH₄ uptake when there were no plant interactions. Thus, there are several reports examining the effects of P addition on CH₄ fluxes, but few studies have reported the effects in tropical forest soils, especially tropical tree plantation soils.

The current study conducted another incubation experiment using soils taken from five different tropical, monoculture, tree plantations. The effects of P addition on N_2O and CH_4 fluxes were examined.

Materials and methods

Soil sampling

Soil samples were collected at plantation sites inside the Sakaerat Environment Research Station (SERS) in Nakhon Ratchasima, Thailand (14°30'N, 101°55'E). The climate of the region is classified as tropical savannah (Yamashita et al., 2010). The mean annual temperature was 25.5 °C and annual precipitation was 1407 mm for 2000–2008 (Yamashita et al., 2011). The main soil type is Acrisols (Yamashita et al., 2011). Five forest plantation stands were chosen—*Acacia auriculiformis* (Leguminosae), *Acacia mangium* (Leguminosae), *Eucalyptus camaldulensis* (Myrtaceae), *Hopea odorata* (Dipterocarpaceae), and *Xylia xylocarpa* (Leguminosae). At the beginning of the experiment, each stand was aged 9 yr. Soil samples (0–5 cm depth) were collected from six randomly selected points in each forest stand using 100 mL soil cores. Litter layers were removed before soil sampling. After collection, each soil sample was sieved through a 2 mm sieve. The general physicochemical characteristics of the 0–5 cm soil samples are shown in Table 1. The particle size distribution was determined using the pipette method (Gee and Bauder, 1986). The pH (H₂O) was determined for 1:2.5 water suspensions using a glass electrode (Horiba; Kyoto, Japan). The total C and total N contents were determined using an NC analyzer (JM 1000CN; J-Science Lab Co. Ltd.; Kyoto Japan). The available P contents were determined using the Bray-1 method (Kuo, 1996).

Incubation

Fresh soil samples of 30 g were placed in 223 mL wide-mouth jars for gas sampling, and 5 g samples were placed in 50 mL bottles for chemical analyses (each forest stand had six replications). For each analysis, two subsamples were prepared—one for P addition and the other for the non-P-added control. P was added as KH₂PO₄ solution (100 µg P/g soil, dissolved in distilled water). Non-P-added controls were prepared without P addition in the same manner. After the soil water condition was adjusted to 80% water holding capacity, the samples were incubated at 25 °C in the dark for 48 h. The wide-mouth jars were closed with butyl rubber stoppers equipped with sampling ports, and gas samples were taken at 0 h and 48 h after the closure of the stoppers. Gas concentrations were analyzed using a gas chromatograph (GC-14B; Shimadzu; Kyoto, Japan) equipped with an electron capture detector for N₂O and a flame ionization detector for CH₄. The gas fluxes were calculated from the differences between the gas concentrations at 0 h and 48 h.

Inorganic N and dissolved N were extracted by shaking 5 g of fresh soil with 25 mL of 0.5 M K₂SO₄ for 30 min. The NH₄ and NO₃ contents were determined using a flow-injection analyzer (AQLA-700-NO; Aqualab; Tokyo, Japan). The dissolved N concentration was analyzed using a total organic carbon analyzer with a total organic nitrogen measurement unit (TOC-V_E/TNM-1; Shimadzu; Kyoto, Japan). The soil microbial biomass N was determined using a chloroform fumigation extraction method (Jenkinson et al., 2004). Fresh soil samples of 5 g were exposed to CHCl3 vapor for 24 h in a vacuum desiccator at 25 °C. After the residual CHCl3 had been removed, the fumigated soils were shaken with 50 mL of 0.5 M K₂SO₄ extractant for 30 min and the dissolved N was extracted. The soil microbial biomass element contents were calculated from the differences of the dissolved N contents between the fumigated and unfumigated samples using a conversion factor of 0.45 (Jenkinson et al., 2004). The soil pH (H₂O) was measured at the end of the incubation period.

Statistical analysis

Statistical analyses were performed using the Excel software (version 2013; Microsoft Corp; Redmond, WA, USA). The level of

Table 1

Physicochemica	l properties of soils at	different plantation sites	(data from Mori et al.,	2016)
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Site ^a	pH (H ₂ O)	Total C ^b (mg C/g soil)	Total N ^b (mg N/g soil)	Available P ^c (µg P/g soil)	Clay ^d (%)	Silt ^d (%)	Sand ^d (%)
AA	4.9	21.6	2.1	12.1	7.3	21.3	71.5
AM	5.1	12.0	1.4	7.0	3.8	16.0	80.2
EC	5.3	13.5	1.4	12.2	6.4	15.6	78.0
HO	5.0	10.7	1.5	9.9	5.1	17.3	77.5
XX	5.2	11.7	1.4	10.9	3.1	16.5	80.4

^a AA, Acacia auriculiformis; AM, Acacia mangium; EC, Eucalyptus camaldulensis; and HO, Hopea odorata; XX, Xylia xylocarpa.

^b Average of three replications.

^c Average of six replications.

^d Average of two replications.

significance was examined using a paired *t*-test assuming normality. The correlation coefficient was obtained by single simple regression analysis. One of the six *Acacia auriculiformis* samples and three of the six *Eucalyptus camaldulensis* samples showed unnaturally high N₂O emissions and so these were excluded from further analyses.

Results and discussion

P addition significantly (p < 0.05) increased N₂O emissions from *Xylia xylocarpa* soils, from 1.0 ± 0.16 ng N/g soil to 1.4 ± 0.22 ng N/g soil (Fig. 1A). In other soils, no differences were observed between the P-added soils and non-added controls. P addition had no effects on the CH₄ uptake in all soil samples (Fig. 1B). Both the NH⁴ and NO³ contents did not change by P addition, except for *Xylia xylocarpa* with a tendency for higher NH⁴ contents in P-added soils (p < 0.1, Table 2). In *Xylia xylocarpa* soils, net ammonification rates tended to be higher in P-added soils (p < 0.1), but net nitrification rates showed no differences. In *Acacia auriculiformis, Acacia mangium, Eucalyptus camaldulensis*, and *Hopea odorata*, no differences



Fig. 1. Effects in different plantations of P addition on: (A) N_2O emissions; (B) CH₄ fluxes. *Above a column indicates significant differences between P-added soil and non-added control determined by paired *t*-test (p < 0.05). Error bars show mean \pm SE. AA, *Acacia auriculiformis*. AM, *Acacia mangium*. EC, *Eucalyptus camaldulensis*. HO, *Hopea odorata*. XX, *Xylia xylocarpa*.

were observed in the NH[‡] and NO³ contents, net ammonification rates, and net nitrification rates between the control and P-added soils (Table 2). P addition had no effects on the dissolved N and microbial biomass N, except that P addition tended to increase the microbial biomass N contents in *Acacia auriculiformis* soils (p < 0.1, Table 3). P addition significantly reduced the soil pH in *Acacia mangium* and *Hopea odorata* soils, but the decrease was very small (Table 3). In *Xylia xylocarpa* soils, N₂O emissions were negatively correlated with net ammonification rates, and the slope was lower in P-added soils (Fig. 2).

An increase in the N₂O emissions by P addition was in accordance with reports by Mori et al. (2010; 2013a), where P addition increased the N₂O emissions from an Acacia mangium plantation soil. The suggested mechanisms by Mori et al. (2010, 2013a) were: 1) P addition stimulated whole N cycling including N mineralization, providing more N for nitrifying or denitrifying processes or both; 2) P addition directly activated nitrifying or denitrifying bacteria or both by alleviating P limitation; and 3) P addition stimulated O₂ consumption by heterotrophic activities and created a more reductive condition, which was suitable for denitrifying bacteria and stimulated denitrification. The results from the present study suggested that P addition stimulated whole N cycles for two reasons. First, P addition tended to increase the net ammonification rates in Xylia xylocarpa soils (Table 2). Second, P addition reduced the slope of the regression line between N₂O emissions and net ammonification rates (Fig. 2). Since net ammonification is the sum of the NH $^{+}$ production (ammonification) and NH $^{+}$ consumption (NH[‡] immobilization and nitrification), the negative correlation between N₂O emissions and net ammonification rates was most probably because of the more-active nitrification in the soils with lower net ammonification rates (larger NH⁺₄ consumption by nitrification). A decrease in the slope by P addition indicates higher N₂O emissions in P-added soils at the same net ammonification rates, suggesting that the flow of N was accelerated (both NH₄⁺ production and consumption were stimulated) by P addition. Thus, it can be suggested that the stimulated whole N cycles caused higher N₂O emissions in the present study. Although two-way ANOVA using all samples showed that P addition increased CO₂ emissions (Mori et al., 2016), a paired t-test using Xylia xylocarpa samples alone did not show significant differences between the control and P-added soils. In Xylia xylocarpa soils, two of six replicates showed a decrease in CO₂ emissions after P-addition, and these two soils showed the largest increase of N2O after P addition. Thus we concluded that the promoted reductive condition was not the reason for the stimulated N₂O emissions by P addition in the present study.

P addition had no effects on N₂O emissions from Acacia auriculiformis, Acacia mangium, Eucalyptus camaldulensis, and Hopea odorata soils (Fig. 1A). Although insufficient data were available for a complete explanation, several mechanisms can be suggested. First, P addition may have improved the respiratory efficiency. Since nutrient shortage causes a lower efficiency of microbial respiration (López-Urrutia and Morán, 2007; Sinsabaugh et al., 2013), nutrient supply could increase respiratory efficiency conversely. P addition possibly improved nitrifying or denitrifying respiratory efficiency or both, reducing the emissions of N₂O, as a by-product and an intermediate of nitrifying and denitrifying respiration, and possibly offset the increased N₂O emissions deriving from the stimulated N cycling. Another suggested mechanism is that P addition stimulated mainly N immobilization, not nitrification or denitrification or both (Hall and Matson, 1999). Although P addition did not increase the microbial biomass N contents (Table 2), P addition may have also stimulated microbial lysis and transformed the microbial biomass N into organic N. In the present study, no effects of P addition on N₂O emissions were observed in Acacia mangium soils, while previous studies showed higher N₂O emissions from P-added

Table 2

Soil N contents for different plantation sites and treatments.

Site ^a	Treatment	NH4 (µg N/g soil)		NO_3^- (µg N/g soil)		Net ammonification rate (µg N/g soil/d)		Net nitrification rate (µgvN/g soil/d)	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE
AA	Control	17.6	1.2	21.6	1.4	1.1	0.8	2.2	0.4
	P-added	16.6	1.1	21.3	1.8	0.6	1.1	2.1	0.6
AM	Control	15.9	0.8	17.6	2.6	0.3	0.5	1.9	0.4
	P-added	16.7	0.9	17.1	2.2	0.7	0.9	2.1	0.2
EC	Control	18.3	2.0	12.4	2.6	0.3	0.4	0.7	0.0
	P-added	17.9	2.3	12.7	2.6	0.1	0.7	0.8	0.1
HO	Control	16.9	2.1	12.8	2.1	1.8	0.3	0.5	0.2
	P-added	16.0	2.6	12.7	2.0	1.4	0.4	0.5	0.2
XX	Control	13.6	0.6	14.1	0.5	-0.6	0.5	1.5	0.3
	P-added	15.2 ^b	1.0	14.1	0.5	0.2 ^b	0.2	1.5	0.2

^a AA, Acacia auriculiformis; AM, Acacia mangium; EC, Eucalyptus camaldulensis; HO, Hopea odorata; XX, Xylia xylocarpa.

^b Indicates the tendency of differences between P-added soils and non-added controls (p < 0.1, paired *t*-test).

Table 3 Dissolved nitrogen, microbial biomass nitrogen, and soil pH for different plantation sites and treatments.

Site ^a	Treatment	DN ^b (µg N/g soil)		MBN ^c (µg N/g	MBN ^c (µg N/g soil)		Soil pH	
		Aver.	SE	Aver.	SE	Aver.	SE	
AA	Control	39.9	1.6	50.6	6.3	5.02	0.1	
	P-added	39.4	1.7	56.1 ^e	6.2	4.99	0.1	
AM	Control	31.9	2.0	36.2	4.9	4.79	0.1	
	P-added	31.7	1.2	31.2	3.2	4.76 ^d	0.1	
EC	Control	29.1	1.2	38.8	5.1	4.97	0.1	
	P-added	29.9	1.0	37.3	5.6	4.93	0.1	
HO	Control	36.0	1.7	34.3	2.9	4.91	0.1	
	P-added	38.1	2.2	26.2	5.1	4.88 ^d	0.1	
XX	Control	27.4	1.5	34.9	1.5	5.29	0.2	
	P-added	28.0	1.8	34.2	2.5	5.27	0.1	

^a AA, Acacia auriculiformis; AM, Acacia mangium; EC, Eucalyptus camaldulensis; and HO, Hopea odorata; XX, Xylia xylocarpa.

^b DN, dissolved nitrogen.

^c MBN, soil microbial biomass nitrogen.

^d Indicates the significant differences between P-added soils and non-added controls (p < 0.05, paired *t*-test).

^e Indicates the tendency of differences between P-added soils and non-added controls (p < 0.1, paired *t*-test).



Fig. 2. Relationship between N₂O emissions and net ammonification rates in *Xylia xylocarpa* soils. In other soils, no significant relationships were observed. Dotted lines show equations. $R^2 = coefficient$ of determination.

soil taken from an *Acacia mangium* plantation in South Sumatra, Indonesia (Mori et al., 2010, 2013a), suggesting that the effects of P addition on N_2O emissions are different even among soils with the same trees planted.

In the present study, P addition had no effects on CH₄ uptakes. In previous reports, P application directly stimulated methanogenesis activities (Archer, 1985) or methanotrophic activities (Zhang et al., 2011; Song et al., 2012), or inhibited methanogenesis activities (Conrad et al., 2000; Song et al., 2012). It was possible that P addition stimulated both methanogenesis and methanotrophic activities, with each offsetting the other. It is suggested that the effects of P addition on N₂O and CH₄ fluxes in the current study site were not significant, at least under laboratory conditions.

Conflict of interest

None declared.

Acknowledgement

The authors thank all staff members of the Sakaerat Environment Research Station (SERS) for general support of this study and also thank Professor Kanehiro Kitayama, Professor Mamoru Kanzaki and Professor Kaoru Kitajima for their support in sample analysis. This study was financially supported by a grant from Grant-in-Aid for JSPS Fellows (number 252647).

References

- Aerts, R., Toet, S., 1997. Nutritional controls on carbon dioxide and methane emission from Carex-dominated peat soils. Soil. Biol. Biochem. 29, 1683–1690.
- Archer, D.B., 1985. Uncoupling of methanogenesis from growth of *Methanosarcina* barkeri by phosphate limitation. Appl. Environ. Microbiol. 50, 1233–1237.
 Baral, B.R., Kuyper, T.W., Van Groenigen, J.W., 2014. Liebig's law of the minimum
- Baral, B.R., Kuyper, T.W., Van Groenigen, J.W., 2014. Liebig's law of the minimum applied to a greenhouse gas: alleviation of P-limitation reduces soil N₂O emission. Plant. Soil 374, 539–548.
- Cleveland, C.C., Townsend, A.R., 2006. Nutrient additions to a tropical rain forest drive substantial soil carbon dioxide losses to the atmosphere. Proc. Natl. Acad. Sci. U.S.A. 103, 10316–10321.
- Cleveland, C.C., Townsend, A.R., Schmidt, S.K., 2002. Phosphorus limitation of microbial processes in moist tropical forests: evidence from short-term laboratory incubations and field studies. Ecosystems 5, 0680–0691.
- Conrad, R., Klose, M., Claus, P., 2000. Phosphate inhibits acetotrophic methanogenesis on rice roots. Appl. Environ. Microbiol. 66, 828–831.
- Elser, J.J., Bracken, M.E.S., Cleland, E.E., et al., 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecol. Lett. 10, 1135–1142.
- Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods, second ed. Soil Science Society of America, Madison, WI, USA, pp. 383–411.
- Hall, S.J., Matson, P.A., 1999. Nitrogen oxide emissions after nitrogen additions in tropical forests. Nature 400, 152.

- Ilstedt, U., Giesler, R., Nordgren, A., Malmer, A., 2003. Changes in soil chemical and microbial properties after a wildfire in a tropical rainforest in Sabah, Malaysia. Soil. Biol. Biochem. 35, 1071–1078.
- Ilstedt, U., Nordgren, A., Malmer, A., 2006. Soil chemical and microbial properties after disturbance by crawler tractors in a Malaysian forest plantation. For. Ecol. Manag. 225, 313–319.
- Jenkinson, D.S., Brookes, P.C., Powlson, D.S., 2004. Measuring soil microbial biomass. Soil Biol. Biochem. 36, 5–7.
- Keller, J.K., Bridgham, S.D., Chapin, C.T., Iversen, C.M., 2005. Limited effects of six years of fertilization on carbon mineralization dynamics in a Minnesota fen. Soil Biol. Biochem. 37, 1197–1204.
- Kuo, S., 1996. Phosphorus. In: Sparks, D.L. (Ed.), Methods of Analysis. Part 3. Chemical Methods. Soil Science Society of America, Madison, WI, USA, pp. 869–919.
- Le Mer, J., Roger, P., 2001. Production, oxidation, emission and consumption of methane by soils: a review. Eur. J. Soil. Biol. 37, 25–50.
- Liu, L., Gundersen, P., Zhang, T., Mo, J., 2012. Effects of phosphorus addition on soil microbial biomass and community composition in three forest types in tropical China. Soil Biol. Biochem. 44, 31–38.
 López-Urrutia, Á., Morán, X.A.G., 2007. Resource limitation of bacterial production
- López-Urrutia, Å., Morán, X.A.G., 2007. Resource limitation of bacterial production distorts the temperature dependence of oceanic carbon cycling. Ecology 88, 817–822.
- Lund, M., Christensen, T.R., Mastepanov, M., Lindroth, A., Ström, L., 2009. Effects of N and P fertilization on the greenhouse gas exchange in two northern peatlands with contrasting N deposition rates. Biogeosciences 6, 2135–2144.
- Mori, T., Ohta, S., Ishizuka, S., Konda, R., Wicaksono, A., Heriyanto, J., Hardjono, A., 2013a. Effects of phosphorus application on root respiration and heterotrophic microbial respiration in *Acacia mangium* plantation soil. Tropics 22, 113–118.
- Mori, T., Ohta, S., Ishizuka, S., Konda, R., Wicaksono, A., Heriyanto, J., Hardjono, A., 2013b. Effects of phosphorus addition with and without ammonium, nitrate, or glucose on N₂O and NO emissions from soil sampled under *Acacia mangium* plantation and incubated at 100% of the water-filled pore space. Biol. Fertil. Soils 49, 13–21.
- Mori, T., Ohta, S., Ishizuka, S., Konda, R., Wicaksono, A., Heriyanto, J., 2014. Phosphorus application reduces N₂O emissions from tropical leguminous plantation soil when phosphorus uptake is occurring. Biol. Fertil. Soils 50, 45–51.
- Mori, T., Ohta, S., Ishizuka, S., Konda, R., Wicaksono, A., Heriyanto, J., Hardjono, A., 2013c. Effects of phosphorus application on CH₄ fluxes in an *Acacia mangium* plantation with and without root exclusion. Tropics 22, 13–17.
- Mori, T., Ohta, S., Ishizuka, S., Konda, R., Wicaksono, A., Heriyanto, J., Hardjono, A., 2013d. Soil greenhouse gas fluxes and C stocks as affected by phosphorus addition in a newly established *Acacia mangium* plantation in Indonesia. For. Ecol. Manag. 310, 643–651.

- Mori, T., Ohta, S., Konda, R., Ishizuka, S., Wicaksono, A., 2010. Phosphorus limitation on CO₂, N₂O, and NO emissions from a tropical humid forest soil of South Sumatra, Indonesia. In: 2010 International Conference on Environmental Engineering and Applications. Singapore, pp. 18–21.
- Mori, T., Wachrinrat, C., Staporn, D., Meunpong, P., Suebsai, W., Matsubara, K., Boonsri, K., Lumban, W., Kuawong, M., Phukdee, T., Srifai, J., Boonman, K., 2016. Contrastive effects of inorganic phosphorus addition on soil microbial respiration and microbial biomass in tropical monoculture tree plantation soils in Thailand. Agric. Nat. Resour. 50, 327–330.
- Potter, C.S., Davidson, E.A., Verchot, L.V., 1996. Estimation of global biogeochemical controls and seasonality in soil methane consumption. Chemosphere 32, 2219–2246.
- Sinsabaugh, R.L., Manzoni, S., Moorhead, D.L., Richter, A., 2013. Carbon use efficiency of microbial communities: stoichiometry, methodology and modelling. Ecol. Lett. 16, 930–939.
- Song, C., Yang, G., Liu, D., Mao, R., 2012. Phosphorus availability as a primary constraint on methane emission from a freshwater wetland. Atmos. Environ. 59, 202–206.
- Vitousek, P.M., Farrington, H., 1997. Nutrient limitation and soil development: experimental test of a biogeochemical theory. Biogeochemistry 37, 63–75.
- Vitousek, P.M., Porder, S., Houlton, B.Z., Chadwick, O.A., 2010. Terrestrial phosphorus limitation: mechanisms, implications, and nitrogen-phosphorus interactions. Ecol. Appl. 20, 5–15.
- Walker, T.W., Syers, J.K., 1976. The fate of phosphorus during pedogenesis. Geoderma 15, 1–19.
- Wrage, N., Velthof, G.L., Van Beusichem, M.L., Oenema, O., 2001. Role of nitrifier denitrification in the production of nitrous oxide. Soil. Biol. Biochem. 33, 1723–1732.
- Yamashita, N., Ohta, S., Sase, H., Luangjame, J., Visaratana, T., Kievuttinon, B., Garivait, H., Kanzaki, M., 2010. Seasonal and spatial variation of nitrogen dynamics in the litter and surface soil layers on a tropical dry evergreen forest slope. For. Ecol. Manag. 259, 1502–1512.
- Yamashita, N., Ohta, S., Sase, H., Kievuttinonc, B., Luangjamea, J., Visaratanac, T., Garivaitd, H., 2011. Seasonal changes in multi-scale spatial structure of soil pH and related parameters along a tropical dry evergreen forest slope. Geoderma 165, 31–39.
- Zhang, T., Zhu, W., Mo, J., Liu, L., Dong, S., 2011. Increased phosphorus availability mitigates the inhibition of nitrogen deposition on CH₄ uptake in an old-growth tropical forest, southern China. Biogeosciences 8, 2805–2813.
- Zhang, W., Zhu, X., Luo, Y., Rafique, R., Chen, H., Huang, J., Mo, J., 2014. Responses of nitrous oxide emissions to nitrogen and phosphorus additions in two tropical plantations with N-fixing vs. non-N-fixing tree species. Biogeosciences 11, 1413–1442.