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POTASSIUM AND MAGNESIUM IN LEAF AND TOP SOIL AFFECTED BY TRIPLE SUPERPHOSPHATE FERTILISATION IN AN *ACACIA MANGIUM* PLANTATION

Mori T[1, 2, *], Ishizuka S[3], Konda R[1], Genroku T[1], Nakamura R[1], Kajino H[1], Wicaksono A[4], Heriyanto J[4], Hardjono A[4] & Ohta S[1, 5]

[1]*Graduate School of Agriculture, Kyoto University, Kitashirakawa Oiwake-cho Sakyo-ku, Kyoto 606-8502, Japan*
[2]*Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China*
[3]*Department of Forest Soils, Forestry and Forest Products Research Institute, Matsunosato 1, Tsukuba, Ibaraki 305-8687, Japan*
[4]*PT Musi Hutan Persada, Muara Enim 31172, South Sumatra, Indonesia*
[5]*Japan International Forestry Promotion and Cooperation Center, Koraku 1-7-12, Bunkyo-ku, Tokyo 112-0004, Japan*

**taikimori7@gmail.com*

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Since nutrients have either synergetic or antagonistic effects, fertilisation has potential to change harvest export of other nutrients present in plantations. In the present research, we investigated the effects of triple superphosphate (TSP) fertilisation on Mg and K contents of leaf and soil pools in a monoculture *Acacia mangium* plantation in South Sumatra, Indonesia. TSP fertilisation reduced leaf K concentration, but leaf K content per stand area did not show any difference between control and fertilised plots because of the offset by stimulated biomass increment following fertilisation. TSP fertilisation significantly elevated both leaf Mg concentration and leaf Mg content per stand area, indicating the stimulated Mg uptakes by trees. Despite the stimulated uptakes, soil Mg pools were not affected by the fertilisation. It was possibly because the decrease in soil Mg pools during the experimental period was much greater than the stimulated Mg uptakes deriving from the fertilisation. Although the soil nutrient pools were not affected by TSP fertilisation in the present study, our results of the increased leaf Mg contents and the estimated future harvest export of Mg suggest that unbalanced fertilisation can accelerate nutrient export from plantation soils through harvesting.

Keywords: Calcium, stimulated biomass increment, phosphorus, South Sumatra, Indonesia

INTRODUCTION

As the global natural forest area continues to decline, tree plantations have an increasing role to provide industrial pulp and timber (Payn et al. 2015). Planted forest area has increased from 167.5 to 277.9 M ha from 1990 to 2015, offsetting the pressure and negative impacts on natural forests (Payn et al. 2015). Tropical plantations with fast-growing tree species as *Acacia mangium* have increased substantially (Nambiar 2004) due to its rapid growth, good quality of wood and tolerance for nutrient-poor acidic soils (Cole et al. 1996, Norisada et al. 2005). These plantations contribute not only to the wood production but also to providing ecosystem services (Nambiar 2004), including increasing forest surface (Wang et al. 2010) and sequestrating carbon (C) (Zhang et al. 2012), although some plantations have been established in areas previously occupied by native forests (Cossalter & Pye-Smith 2003).

One of the biggest concerns in the fast-growing tree plantations is their sustainability (Mackensen & Folster 2000, Cossalter & Pye-Smith 2003), because the management practice in tree plantations reduces soil nutrients, especially through harvest, erosion, slash and burn and leaching. Fast-growing tree plantations usually follow short rotations, which make the decline of soil nutrients more serious due to repeated harvesting in short cycles (Mackensen et al. 2003, Gonçalves et al. 2004, 2008).

Since lowland tropical forest ecosystems are poor in phosphorus (P) availability (Vitousek & Sanford 1986, Elser et al. 2007), P fertilisers (most cases in the form of calcium phosphate) are often used to compensate the P shortage in tropical tree plantations (Hardiyanto et al. 2004, Uddin et al. 2007, 2009). However, P fertilisation containing calcium (Ca) may affect other nutrient uptakes such as potassium (K) and magnesium (Mg). According to the Mulder's chart, P has antagonistic effects on K uptake and synergetic effects on Mg uptake, and Ca has antagonistic effects on both K and Mg uptake (Osman 2013). Following this theory, P (and Ca) fertilisation in plantations of fast-growing trees influences the harvest by reducing K uptakes and elevating or reducing Mg uptakes. However, to our knowledge, the effects of P (and Ca) fertilisation on Mg and K uptakes were tested mostly in agronomy and have not been reported in tree plantations, despite the importance of altered nutrient losses from plantation soils through harvest. In addition, field observation in agronomic research sometimes reported inconsistent results with the theory (Murthy 2006, Islam et al. 2008). In this report we investigated the effects of TSP (triple super phosphate, containing both P and Ca) fertilisation on leaf and top soil contents of Mg and K in a monoculture *A. mangium* plantation in South Sumatra, Indonesia.

MATERIALS AND METHODS

Study plot

The field experiment was conducted at an *A. mangium* plantation site managed by a plantation company (Musi Hutan Persada) in South Sumatra, Indonesia (Figure 1). The plantation was established on *Imperata cylindrica* grasslands containing degraded secondary forests at the beginning of the 1990s (Hardjono et al. 2005, Yamashita et al. 2008). The climate of the study site is humid tropical with a seasonality of relatively dry condition from June till September and wetter condition from November till April, although the difference is not prominent. Mean annual temperature is 27.3 °C and average annual precipitation is 2750 mm (Hardjono et al. 2005). The soils in the area are Acrisols developed from tertiary sedimentary rock.

Three 1-ha plots were established at different locations (3° 32' S, 105° 4' E; 3° 43' S, 104° 1' E and 3° 42' S, 104° E) in September 2007. Each site had experienced the first rotation for 8 years and trees were harvested in July 2007. At each location, we established six control subplots and four TSP-added subplots (12 m × 12 m). Each subplot was at least 9 m apart from one another. TSP was applied by hand at a rate of 100 kg P ha^{-1} at the end of September 2007. *Acacia mangium* seedlings were planted at 3 m × 3 m intervals at the beginning of February 2008 as the second rotation of the plantation. TSP fertilisation had no effects on soil pH (H_2O) during the whole period of the experiment (Mori et al. 2013).

Sampling and chemical analysis

We collected fresh leaf samples in March 2009. Twelve leaves from four trees (three from each tree) in the middle of each subplot were collected. We combined the 12 leaves and obtained a composite sample from each subplot (n = 18 in control plots and 12 in TSP-added plots). After the samples were air-dried, they

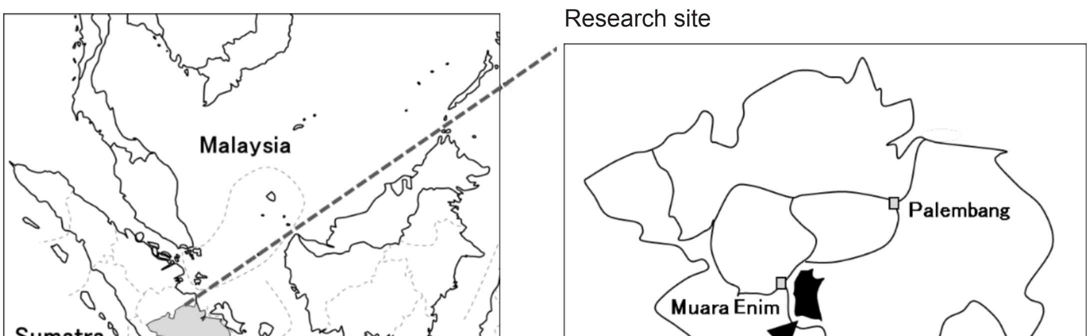

Figure 1 Location of research site

were finely smashed and subjected to microwave digestion with 9 mL of concentrated HNO_3 and 2 mL of H_2O_2 (EPA 1996). Concentrations of K, Mg and Ca in the solutions were determined using inductively coupled plasma atomic emission spectrometer.

Two soil cores per subplot were taken at a depth of 0–5 cm using 100-mL cylinders (20 cm^2 × 5 cm) for chemical analysis at approximately 90-day intervals from the end of September 2007. We composited the soil cores taken from the same location (12 cores from control subplots and 8 cores from TSP-added subplots) after passing through a 2-mm sieve and removing roots. There were three composite samples at each sampling time. Exchangeable base cations (exchangeable K and Mg) were extracted with 1 M ammonium acetate buffered at pH 7. Soils were digested using the same method as leaf digestion (EPA 1996) after finely ground. Although this method was used to determine the total amount of soil K and Mg, silicate may not be digested in the present study because we omitted to add hydrofluoric acid for digestion. Instead we used the HNO_3-digested K and Mg as indicators of non-exchangeable fractions, which contribute to land sustainability by providing exchangeable fractions through equilibrium (Surapaneni et al. 2002). Concentrations of K and Mg were determined using an inductively coupled plasma atomic emission spectrometer. Total C and N contents in soils and litter layers, and fresh leaves were already reported in the study by Mori et al. (2013) and summarised in Table 1.

Calculation and statistical analysis

We estimated the leaf K and Mg contents per ha using leaf biomass data from literature (4.84 t ha^{-1}, at a 14-month-old stand in the same plantation site, Hardiyanto et al. 2004) and data of leaf K and Mg concentrations from the present study. The increase in leaf biomass by TSP fertilisation was estimated using the same increment rate as aboveground biomass increment by TSP fertilisation at 9-month-old stands (171% from 2.1 to 3.6 t ha^{-1}, Mori et al. 2013). The potential exports of K and Mg through tree harvest were calculated to ascertain the effects of TSP fertilisation. We assumed that changes in K and Mg concentrations in the stem after TSP fertilisation were the same as in the leaf. There are no reports on effects of TSP fertilisation on stem nutrient contents in tree plantations. Stem biomass increment caused by TSP fertilisation were assumed to be the same as those of aboveground biomass in a 20-month-old stand (Mori et al. 2013). We used data on stem (> 8 cm) K (59.7 kg ha^{-1}) and Mg (17.6 kg ha^{-1}) contents taken from a 10-year-old stand of the first rotation in another stand at our study site (Hardiyanto & Nambiar 2014).

The level of significance was examined by unpaired t-test (for comparing leaf nutrient contents) or two-way (fertilisation vs time after fertilisation) ANOVA followed by Tukey's HSD test for assessing the effects of TSP fertilisation on soil nutrient contents. We assumed normal distribution and homoscedasticity of the data. All statistical analyses were performed using Excel 2013 with statistical add-in software (SSRI).

RESULTS AND DISCUSSION

We found clear effects of TSP fertilisation on leaf concentrations of both K and Mg (Figures 2a and b). K concentration in the leaf was significantly reduced by TSP fertilisation (Figure 2a). Thus, the theory that P and Ca have antagonistic effects on K uptake (Mulder's chart, Osman 2013) is true in *Acacia mangium* monoculture plantation. Greater biomass in TSP-fertilised plots offset the decrease in K concentration in the leaf, resulting in insignificant difference in leaf K content per stand area between control and TSP-fertilised plots (Figure 3c). Due to this offset, TSP fertilisation did not change the estimated K export (59.7 and 59.1 kg K ha^{-1} in control and TSP-fertilised plots respectively). Contrary to K, Mg uptakes were stimulated by TSP fertilisation (Figure 2b). The synergetic effect of P on Mg uptakes was stronger compared with Ca antagonism with Mg (Mulder's chart, Osman 2013). TSP fertilisation also increased the estimated leaf Mg content per stand area (Figure 2d). The potential export of Mg through tree harvest stimulated by P addition was 18.6 kg Mg ha^{-1}. This result suggested that TSP fertilisation has potential to stimulate the harvest export of Mg substantially, and the impact may not be negligible because this value is large enough when compared with soil exchangeable fractions of Mg in another plantation stand in our study site (18 kg Mg ha^{-1} at 0–40 cm depth, Hardiyanto & Wicaksono 2008) and annual nutrient inputs through rainfall values observed in lowland forests and lower montane forests (0.2–19.8 kg Mg ha^{-1}, Proctor 1987). Fertilisation

Table 1 Tree sizes and aboveground biomass, chemical factors of soil, leaf, and litter during the experimental period

Age	Treatment	Tree diameter (cm)	Tree height (m)	Aboveground biomass ($Mg\ ha^{-1}$)	Soil TC ($kg\ C\ m^{-2}$)	Soil TN ($g\ N\ m^{-2}$)	Litter layer TC ($kg\ C\ m^{-2}$)	Litter layer TN ($g\ N\ m^{-2}$)	Leaf TC ($mg\ C\ g^{-1}$ leaf)	Leaf TN ($mg\ N\ g^{-1}$ leaf)
9 months	Control	4.3 (0.1)	3.2 (0.1)	2.1 (0.1)	-	-	-	-	-	-
	TSP-added	5.1 (0.2)	3.4 (0.1)	3.6 (0.2)	-	-	-	-	-	-
		***	***	***						
20 months	Control	9.6 (0.1)	7.0 (0.2)	44.6 (2.5)	-	-	-	-	-	-
	TSP-added	10.3 (0.2)	7.2 (0.3)	69.0 (5.5)	-	-	-	-	-	-
		**		**						
2 years	Control	-	-	-	2.01 (0.06)	138.5 (3.4)	0.76 (0.06)	34.6 (2.8)	537.0 (1.8)	30.4 (0.3)
	TSP-added	-	-	-	1.87 (0.06)	126.8 (4.2)	0.70 (0.05)	31.7 (2.2)	535.7 (2.4)	31.3 (0.2)
					**		***			

From Mori et al. 2013; values of tree sizes and aboveground biomass are means (± standard errors); significant difference between control plots and TSP-added plots using Mann–Whitney's U-test (** = $p < 0.01$, *** = $p < 0.001$); values of chemical factors are means (± standard errors) of 24 samples (3 composite samples from control plots were taken at every 3 months for 2 years; TC = total carbon contents. TN = total nitrogen content, TSP = triple superphosphate, TC = total carbon, TN = total nitrogen; ** = $p < 0.01$ and *** = $p < 0.001$

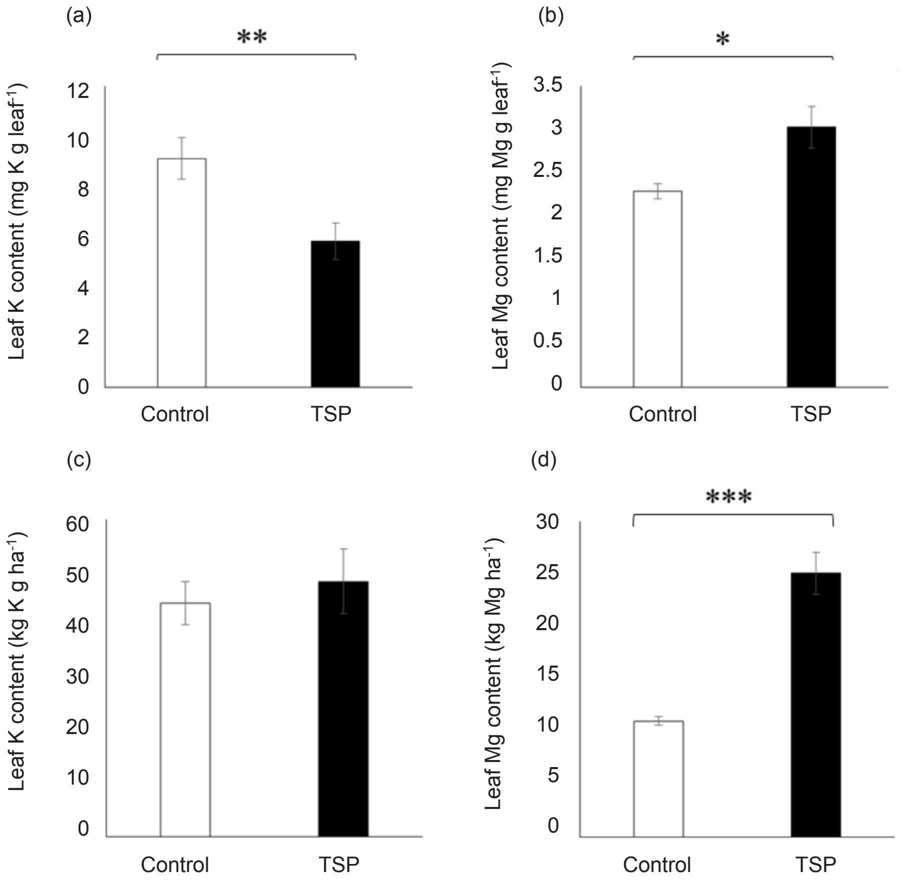

Figure 2 Effects of TSP-fertilisation on concentrations of (a and c) K and (b and d) Mg in leaf and per stand area respectively; error bars indicate standard errors, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$; TSP = triple superphosphate

also increased leaf Ca concentration significantly, i.e. from 10.5 to 14.2 mg Ca g leaf^{-1}, $p < 0.01$, paired t-test), most probably because of the Ca contained in TSP fertiliser.

Despite significant differences in Mg content in leaf samples, its content in the top soil was not affected by TSP fertilisation. Fertilisation had no significant effects both on exchangeable K and exchangeable Mg (Figures 3a and c), and HNO_3-digested K and Mg (Figures 3b and d). Although time after fertilisation had significant effects on exchangeable Mg, Tukey's HSD test did not show any differences between sampling times. One year after planting, concentrations of HNO_3-digested K and Mg decreased significantly. This phenomenon could not be attributed only to the plant nutrient uptakes because the decrease in soil nutrients was greater than the nutrient (especially Mg) contained in tree biomass (Hardiyanto et al. 2004). *Acacia* roots may have obtained some unavailable form of nutrients by accelerating soil weathering as reported for other plants (Sugiyama & Ae 2000). The nutrients released from the unavailable fractions of mineral soils could be easily leached into the deeper layers in acidic soil conditions with low cation exchange capacity as suggested by the low pH in this study site (Mori et al. 2013). It is possible that the effects of fertilisation on soil Mg contents through stimulated Mg uptakes were masked by the large decrease in soil Mg pools during the experiment. Since we investigated soil nutrient pools only at the depth of 0–5 cm, more data including deeper soil layers are necessary to fully understand the effects of TSP fertilisation on soil K and Mg pools.

Fast-growing tree plantation management has potential to deplete plant-available K and Mg because the outflow of non-exchangeable fraction of K and Mg was probably beyond the supply from structural fraction of K and Mg (Figure 3). We also demonstrated that the exchangeable fraction had less temporal changes (Figures 3a and c) although non-exchangeable fractions decreased

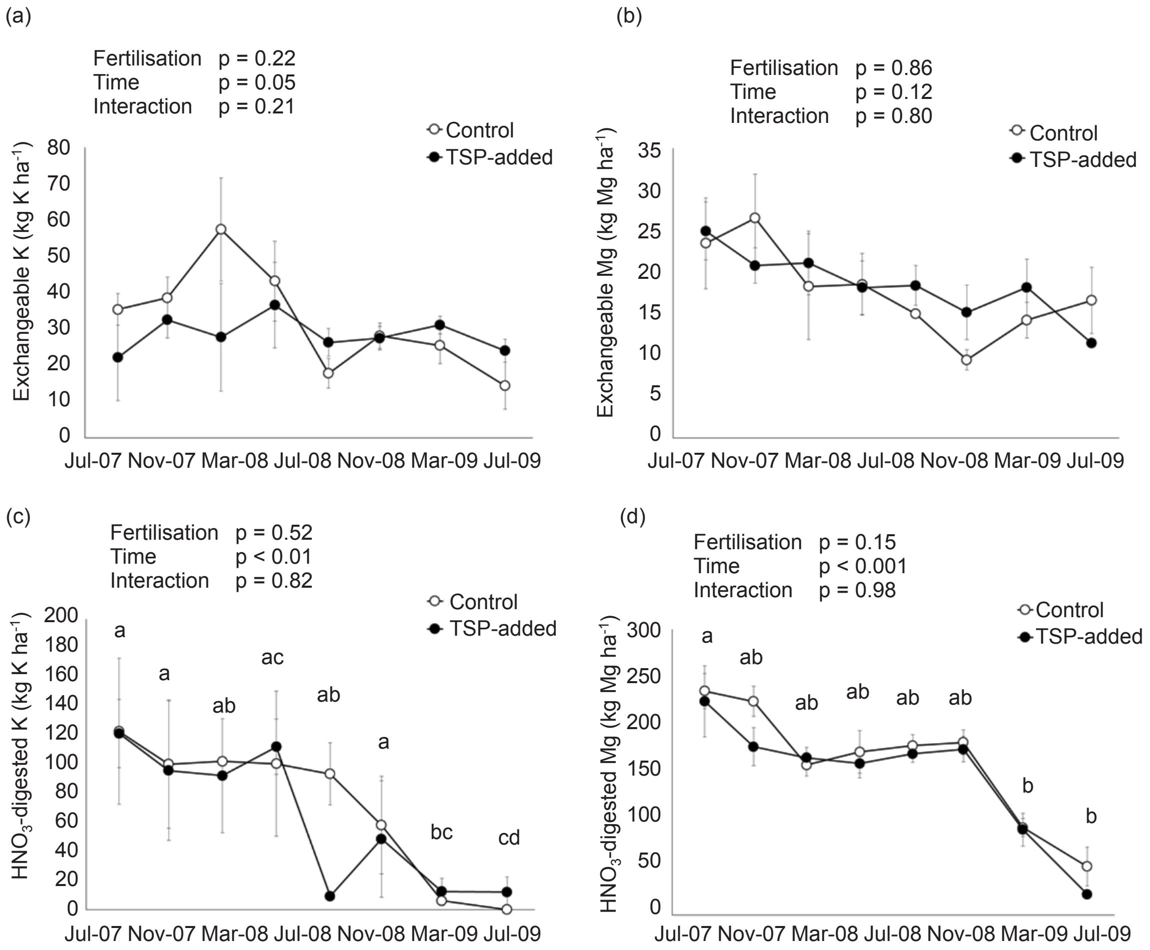

Figure 3 Effects of TSP fertilisation on soil exchangeable (a) K and (c) Mg, and HNO_3-digested (b) K and (d) Mg; different letters indicate significant differences at $p < 5\%$ or $p < 1\%$ (Tukey's HSD test), error bars indicate standard errors; TSP = triple superphosphate

substantially as time passed (Figures 3b and d). Quantifying non-exchangeable fraction is necessary to access the sustainability of tropical tree plantations in terms of soil nutrient supply, not only exchangeable fraction which most of the previous studies reported as an indicator of soil nutrient pools (Hardiyanto et al. 2004, Sankaran et al. 2008, Xu et al. 2008).

CONCLUSIONS

Soil nutrient pools were not affected by TSP fertilisation. However, fertilisation increased leaf Mg contents. Estimated export of Mg from plantation stands through tree harvest was also accelerated by TSP fertilisation. Longer monitoring, including during tree harvesting, is necessary to determine if the changes in Mg uptake affects soil Mg pool in the future. Quantifying non-exchangeable fractions, rather than exchangeable fractions, would better assess the sustainability of tropical tree plantations in terms of soil nutrient supply.

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