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RESEARCH ARTICLE

Nutrient dynamics through fine litterfall in three plantations in Sabah, Malaysia, in relation to nutrient supply to surface soil

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Abstract To investigate soil amelioration effects by older tropical fast-wood plantations, we examined the fine litterfall and accompanying nutrient flux of a 20-year-old *Acacia mangium* site over 3 years under a wet tropical climate in Sabah, Malaysia. The litterfall of a *Swietenia macrophylla* site and an *Araucaria cunninghamii* site was also examined for comparison. Annual nitrogen (N) flux through litterfall (kg N ha^{-1}) was larger in *A. mangium* (207–223) than in *S. macrophylla* (126–153) or *A. cunninghamii* (72–94), whereas annual phosphorus (P) flux through litterfall (kg P ha^{-1}) was considerably smaller in *A. mangium* (2.7–3.4) than in *S. macrophylla* (7.5–15.6) or *A. cunninghamii* (7.8–9.2). N flux through litterfall, forest floor N, and N concentration in topsoil (0–5 cm) were in the order of *A. mangium* > *S. macrophylla* > *A. cunninghamii*, but other element fluxes were not related to concentrations in soils. Our findings suggest that topsoil N increased because of a large N flux from litterfall. We conclude that these plantation trees, including *A. mangium* have the potential to produce a N flux in litterfall for the rapid return of organic N to soils larger than or equivalent to that in adjacent primary forests. However, the litterfall of a single species may lead to deficits of a particular element and cause nutrient imbalances. Using a mixture of fertilizer tree species or applying mixed litter might be a better solution.

Keywords Element flux · Tropical plantations · Soil amelioration · Old fast-wood plantation · Leguminous trees

Introduction

Acacia mangium is a major tropical and subtropical fast-wood plantation species in Asia and is also planted in Africa and Central and South America (CAB International 2005). In Sabah State in Borneo, Malaysia, exotic fast-growing species were introduced for plantations in the 1960s, and more than 100,000 ha had been planted by 2003 (Sabah Forestry Department 2005). *A. mangium* is one of the best performers in short-rotation forestry in the humid tropics and constitutes more than half of exotic plantation trees in Sabah. *A. mangium* can survive degraded site conditions (Srivastava 1993; Yang et al. 2009), even

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in acidic sandy sites with low nutrient content (Norisada et al. 2005). However, such fast-growing, monoculture plantations have been criticized because they may lead to plant disease (Cossalter and Pye-Smith 2003), lower biodiversity (Lugo 1997; Cossalter and Pye-Smith 2003), and rapid removal of resources (Fölster and Khanna 1997; Yamashita et al. 2008). Today, some projects are converting existing monoculture plantations into mixed forests, including through agroforestry using indigenous species (JIRCAS 2007; Abdu et al. 2008; Sakai et al. 2009).

Despite the problems of monoculture plantation, *A. mangium* can be used as a nurse tree in mixed planting because of its tolerance for and adaptation to severe site conditions (Kamo et al. 2002; Norisada et al. 2005; Abdu et al. 2008; Yang et al. 2009). Although some researchers and policy-makers also expect to use N_2-fixing trees to replenish soil N levels (Khanna 1998; Schroth et al. 2001), nutrient supply effects of legumes on mixed planting are not fully understood, and in situ examination of this is under way in some regions (reviewed by Forrester et al. 2006; Laclau et al. 2008; Siddique et al. 2008).

Understanding of the effect of N_2-fixing trees, particularly *A. mangium*, on soil conditions has recently improved (Fisher 1995; Bernhard-Reversat 1996; Majalap 1999; Li et al. 2001; Garay et al. 2004; Jang et al. 2004; Xue et al. 2005; Kimaro et al. 2007; Abdu et al. 2008; Macedo et al. 2008; Yamashita et al. 2008; Kunhamu et al. 2009). Some studies have found more organic matter and N accumulation in soils of *A. mangium* stands than in those of non-legume tree stands. However, few studies have examined the relationship between soil nutrient quantity and quality of litterfall in *A. mangium* stands (Bernhard-Reversat 1996; Majalap 1999; Kunhamu et al. 2009). In addition, *A. mangium* tends to be logged in a short rotation of less than 10 years, mainly for pulpwood production (Srivastava 1993); thus, nutrient dynamics in older stands have not yet been studied. However, *A. mangium* has the potential to produce lumber (Groome 1991) on longer rotations, requiring an understanding of nutrient dynamics of older stands for efficient timber production and soil conservation. Older stands may also provide information on facilitating better nutrient conditions for the growth of other plants in some intercropping systems.

In this study, nutrient dynamics through litterfall in a 20-year-old *A. mangium* stand were investigated for 3 years and compared with those of stands of two major tropical plantation species, *Swietenia macrophylla* and *Araucaria cunninghamii*, at the same location. The aim was to examine the potential of tree plantations for soil amelioration with respect to nutrient fluxes through litterfall in older stands. The nutrient flux of these plantations was also compared with that of primary forests (Dent et al. 2006) that would once have covered the research site. We discuss the function of the amelioration of soil nutrient content by *A. mangium* in light of our own data and those from previous studies.

Methods

Research area

This study was conducted at the Gum Gum Forest Reserve in Sandakan, Sabah, Malaysia (5°52′N, 117°54′E; Fig. 1). The forest reserve was once covered by lowland dipterocarp forest and was conventionally logged several times between the 1920s and 1960s (Sabah Forestry Department 2009). A plantation program was started in 1964. Precipitation and temperature data for the measurement period were obtained from Sandakan airport about 20 km from the research station recorded in the Global Historical Climatology Network (Point No. 50596491, National Climatic Data Center 2009). Average annual precipitation was 2,572 mm, and mean temperature was 27.9°C during the measurement period. This area has a wet tropical climate, with no month receiving less than 100 mm rain long-term average (Dent et al. 2006). Fluctuation in the mean monthly temperature is less than ±1.5°C, and no obvious long drought has occurred. The research sites were on gently sloping alluvial plains at an altitude of less than 40 m asl. The soil is Haplic Alisol (Alumic, Hyperdystric, Clayic; IUSS Working Group WRB 2007). Soil properties of the representative profile are described in Table 1.

Litterfall was collected at three sites: 20–22-year-old *Acacia mangium* Willd., 34–36-year-old *S. macrophylla* King, and 27–29-year-old *Araucaria cunninghamii* Sweet., located within 1 km of one another. *A. mangium* is a N_2-fixing evergreen tree from northern Australia and Papua New Guinea, *S. macrophylla* is a non-N_2-fixing evergreen tree from Central

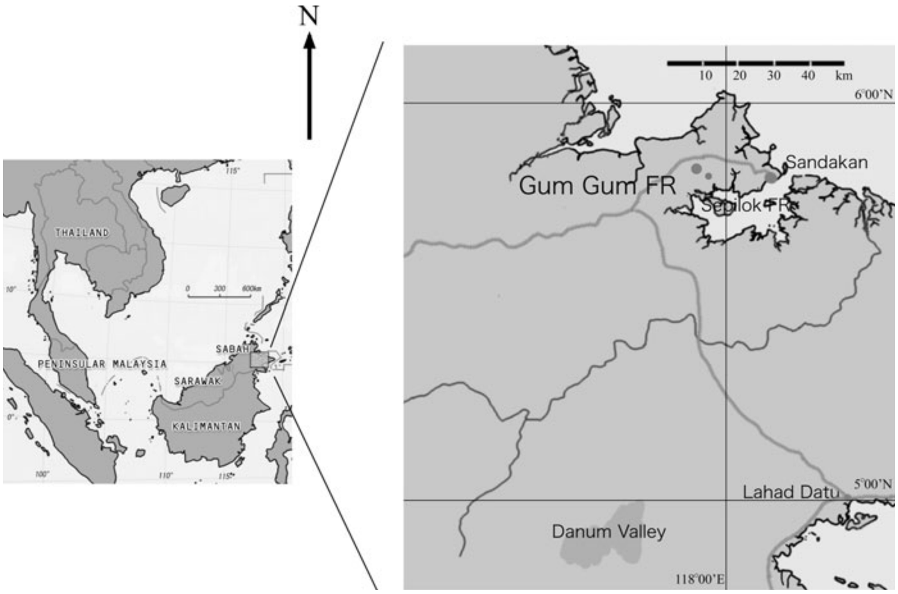

Fig. 1 Location of the research station

Table 1 Soil properties of a soil profile from the *Araucaria cunninghamii* site

Horizon	Depth (cm)	pH (H_2O)	OC (%)	TN (%)	CEC	Clay (%)	Silt (%)	Sand (%)	Texture (FAO)
Ah	0–9,11	3.92	1.18	0.14	15.7	31	27	42	CL
E	9,11–23	3.76	0.50	0.08	17.0	38	26	36	CL
EB	23–39	3.60	0.31	0.06	22.6	50	29	21	C
Bt1	39–57	3.63	0.26	0.06	21.9	53	31	17	C
Bt2	57–90	4.25	0.12	0.06	22.6	53	33	14	C
Bg	90–115	4.14	0.05	0.05	20.3	52	29	19	C
Cg	115–145(+)	4.62	0.13	0.06	25.5	57	39	7	C

pH was measured with a glass electrode, organic C by the Walkley–Black method, total N by the Kjeldahl method, cation exchange capacity (CEC) by the NH_4-Ac extraction method, and soil texture by the pipette method

and South America, and *A. cunninghamii* is a conifer from Australia and Papua New Guinea. Stand conditions were described in a previous report (Inagaki et al. 2009). Basal areas at *A. mangium*, *S. macrophylla*, and *A. cunninghamii* sites were 40, 59, and 54 m^2 ha^{-1}, respectively.

Table 2 Plot sizes and numbers of litter traps at the three sites

Site	Year planted	Plot size	No. of traps
Acacia mangium	1982	20 m × 50 m	12
Swietenia macrophylla	1968	25 m × 50 m	12
Araucaria cunninghamii	1975	40 m × 40 m	16

Litterfall sampling and analysis

Litterfall samples were collected from March 2002 to February 2005 (3 years), twice per month on the 1st and 15th days, using 1 m × 1 m square litter traps made with PVC pipe and polyethylene net. The litter traps were randomly placed at each site, with about one trap per 0.01 ha (Table 2). According to Finotti et al. (2003), the coefficient of variance of litterfall mass becomes stable with more than 10 traps per 0.64 ha. Litter samples were dried at 70°C until constant weight and separated into five fractions: species leaves, other leaves, fine wood (<20 mm in diameter), reproductive parts, and miscellaneous organic matter that could not be categorized into other fractions (Cuevas and Lugo

1998). Species leaves of *A. mangium* were phyllodes; those of *A. cunninghamii* included needles attached to final order branches. Large wood samples (>20 mm) were omitted from the analysis because of large fluctuations in values.

Samples were ground in an agate motor grinder (RT-100, Retsch, Haan, Germany) after being cut with a mill (A11, IKA, Konigswinter, Germany). Total C and N concentrations were measured by the dry combustion method (NC-22F, Sumitomo Chemical, Tokyo, Japan). For P, K, Ca, Mg, Fe, and Mn analysis, samples were analyzed by ICP-AES (Optima 4300 DV, PerkinElmer, Waltham, MA, USA) using the wet combustion method (Yamasaki 1997), with nitric and perchloric acid for digestion. For species leaves, we analyzed C and N concentrations monthly and P, K, Ca, Mg, Fe, and Mn bimonthly. For other litter fractions, we analyzed composite samples of 1 year from March to February in the next year. Values for samples missing due to destruction of traps were estimated using the average of adjacent collections.

Sampling and analysis of soil and organic matter at forest floor

Chemical conditions in the surface soil (0–5, 5–15, and 15–30 cm) and the forest floor of these stands were as previously reported in Inagaki and Titin (2009), and these data were used for analysis. Sampling was conducted in September 2002. We randomly selected six sampling points at each site (Table 2). At each sampling point, soil samples were taken using core samplers (Split tube sampler, Eijkelkamp, Giesbeek, The Netherlands) from four ridges 2 m × 2 m square, separated into three depth ranges, 0–5, 5–15, and 15–30 cm, and then merged into one sample for each depth range. Six forest floor samples were taken from inside 50 cm × 50 cm squares located at the center of the soil sampling quadrats.

Soil samples were measured for organic C by the Walkley–Black method, total N by the Kjeldahl method, exchangeable cations by the NH4-Ac extracted method using AAS, and available P by the Bray II method. Forest floor samples were also analyzed for organic C, total N, and total cations after wet combustion.

Statistical analysis

The total nutrient fluxes in litterfall were compared between species and years using repeated measures analysis of variance (ANOVA); a post hoc Tukey's honestly significant difference (HSD) test was used to compare means ($P < 0.01$). Two fixed factors were considered, site (between subjects) and measurement year (within subjects). The means of the nutrient fluxes were also compared between litter fractions, species and year using repeated measures ANOVA and a post hoc Tukey's HSD test. In this analysis, litter fractions nested within sites were included as a third fixed factor. We treated the individual traps as a random site effect in the mixed-effect model using restricted maximum likelihood (REML). The data on levels of elements in the forest floors and soil from a previous report (Inagaki and Titin 2009) were also analyzed by one-way ANOVA and post hoc Tukey's HSD test. All statistical analysis was performed using JMP 6.0.3 (SAS Institute, Inc., Cary, NC, USA).

Results

Mean annual litterfall dry mass was similar in *Acacia mangium* (12.8–13.5 Mg ha^{-1}) and *S. macrophylla* (12.5–14.1 Mg ha^{-1}) but lower in *Araucaria cunninghamii* (6.2–7.4 Mg ha^{-1}; Table 3). Annual fluctuation in dry mass in the 3-year study period was not significant. Annual C flux through litterfall exhibited a similar tendency as dry mass.

Annual N flux from litterfall in *A. mangium* (207–223 kg N ha^{-1}) was 1.6-fold higher than in *S. macrophylla* (126–153 kg N ha^{-1}), and that of *A. cunninghamii* was lowest (72–94 kg N ha^{-1}). In contrast, annual P flux was smaller in *A. mangium* (2.7–3.7 kg P ha^{-1}) than in *A. cunninghamii* (7.8–9.2 kg P ha^{-1}) and *S. macrophylla* (7.5–15.6 kg P ha^{-1}). Annual flux of base cations and Fe was largest in *S. macrophylla*, and at least 1.5 times greater than those of the *A. mangium* and *A. cunninghamii* sites. Annual Mn flux showed a different tendency from that of Fe: it was much smaller in the *S. macrophylla* site and was 1.5-fold higher in the *A. mangium* site than in the *A. cunninghamii* site.

In the *A. cunninghamii* site, most litterfall fractions were species leaves (Fig. 2) because needles of *A. cunninghamii* were attached to final order branches

Table 3 Mean annual fluxes of elements in litterfall over 3 years and effects of site and year on annual element flux in litterfall

Site	Year	Dry mass (Mg ha^{-1} year^{-1})		Total C (Mg ha^{-1} year^{-1})		Total N (kg ha^{-1} year^{-1})		Total P (kg ha^{-1} year^{-1})		Total Ca (kg ha^{-1} year^{-1})		Total Mg (kg ha^{-1} year^{-1})		Total K (kg ha^{-1} year^{-1})		Total Fe (kg ha^{-1} year^{-1})		Total Mn (kg ha^{-1} year^{-1})	
A. mangium	2002	12.8^{a} (0.39)	A	6.9^{a} (0.21)	A	223^{a} (6.1)	A	3.4^{a} (0.12)	C	137^{a} (4.3)	B	26^{a} (0.8)	C	38^{a} (1.0)	B	1.1^{b} (0.03)	B	5.1^{a} (0.17)	A
	2003	13.5^{a} (0.61)		7.4^{a} (0.33)		220^{a} (9.0)		3.7^{a} (0.15)		116^{b} (4.7)		26^{a} (1.0)		41^{a} (1.7)		1.3^{ab} (0.05)		3.9^{b} (0.16)	
	2004	13.0^{a} (0.73)		7.1^{a} (0.39)		207^{a} (11.0)		2.7^{b} (0.18)		95^{c} (4.9)		23^{a} (1.1)		46^{a} (2.4)		1.3^{a} (0.07)		3.2^{c} (0.15)	
S. macrophylla	2002	12.9^{a} (0.42)	A	6.8^{a} (0.22)	A	132^{b} (3.2)	B	15.6^{a} (0.54)	A	179^{b} (4.5)	A	50^{a} (1.5)	A	107^{a} (3.9)	A	1.7^{a} (0.05)	A	0.4^{a} (0.026)	C
	2003	14.1^{a} (0.42)		7.4^{a} (0.22)		153^{a} (4.3)		10.0^{b} (0.37)		252^{a} (7.6)		53^{a} (1.3)		73^{b} (3.5)		1.9^{a} (0.07)		0.1^{b} (0.002)	
	2004	12.5^{a} (0.62)		6.5^{a} (0.32)		126^{b} (4.9)		7.5^{c} (0.40)		189^{b} (6.9)		40^{b} (1.5)		72^{b} (5.0)		1.8^{a} (0.06)		0.2^{b} (0.009)	
A. cunninghamii	2002	7.4^{a} (0.28)	B	4.0^{a} (0.15)	B	94^{a} (3.6)	C	9.2^{a} (0.35)	B	102^{a} (3.9)	C	36^{a} (1.3)	B	45^{a} (1.6)	B	0.6^{a} (0.02)	C	2.7^{a} (0.10)	B
	2003	6.2^{a} (0.31)		3.4^{a} (0.16)		72^{b} (3.6)		7.8^{a} (0.36)		86^{a} (4.3)		31^{b} (1.5)		43^{a} (2.0)		0.5^{a} (0.02)		2.6^{a} (0.13)	
	2004	6.4^{a} (0.29)		3.4^{a} (0.15)		80^{ab} (3.8)		8.6^{a} (0.39)		91^{a} (4.3)		38^{a} (1.8)		35^{b} (1.6)		0.6^{a} (0.03)		2.6^{a} (0.13)	
Fixed factor	df	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Site	2	124.62	**<0.001**	122.21	**<0.001**	218.00	**<0.001**	198.08	**<0.001**	264.71	**<0.001**	96.14	**<0.001**	143.79	**<0.001**	369.22	**<0.001**	328.52	**<0.001**
Year	2	2.84	0.065	3.31	0.042	7.70	**<0.001**	107.44	**<0.001**	29.22	**<0.001**	12.02	**<0.001**	29.63	**<0.001**	6.04	**0.004**	108.27	**<0.001**
Site × year	4	4.08	**0.005**	4.67	**0.002**	8.34	**<0.001**	66.01	**<0.001**	42.47	**<0.001**	23.44	**<0.001**	31.17	**<0.001**	8.27	**<0.001**	62.34	**<0.001**

Year indicates the measurement period from March of that year to February of the next year. Numbers in parentheses indicate standard error of the mean (SEM). *Different capital letters* indicate significant inter-site differences according to repeated measures ANOVA and a post hoc Tukey's HSD test ($P < 0.01$). *Different small letters* indicate significant inter-annual differences according to repeated measures ANOVA and a post hoc Tukey's HSD test ($P < 0.01$)

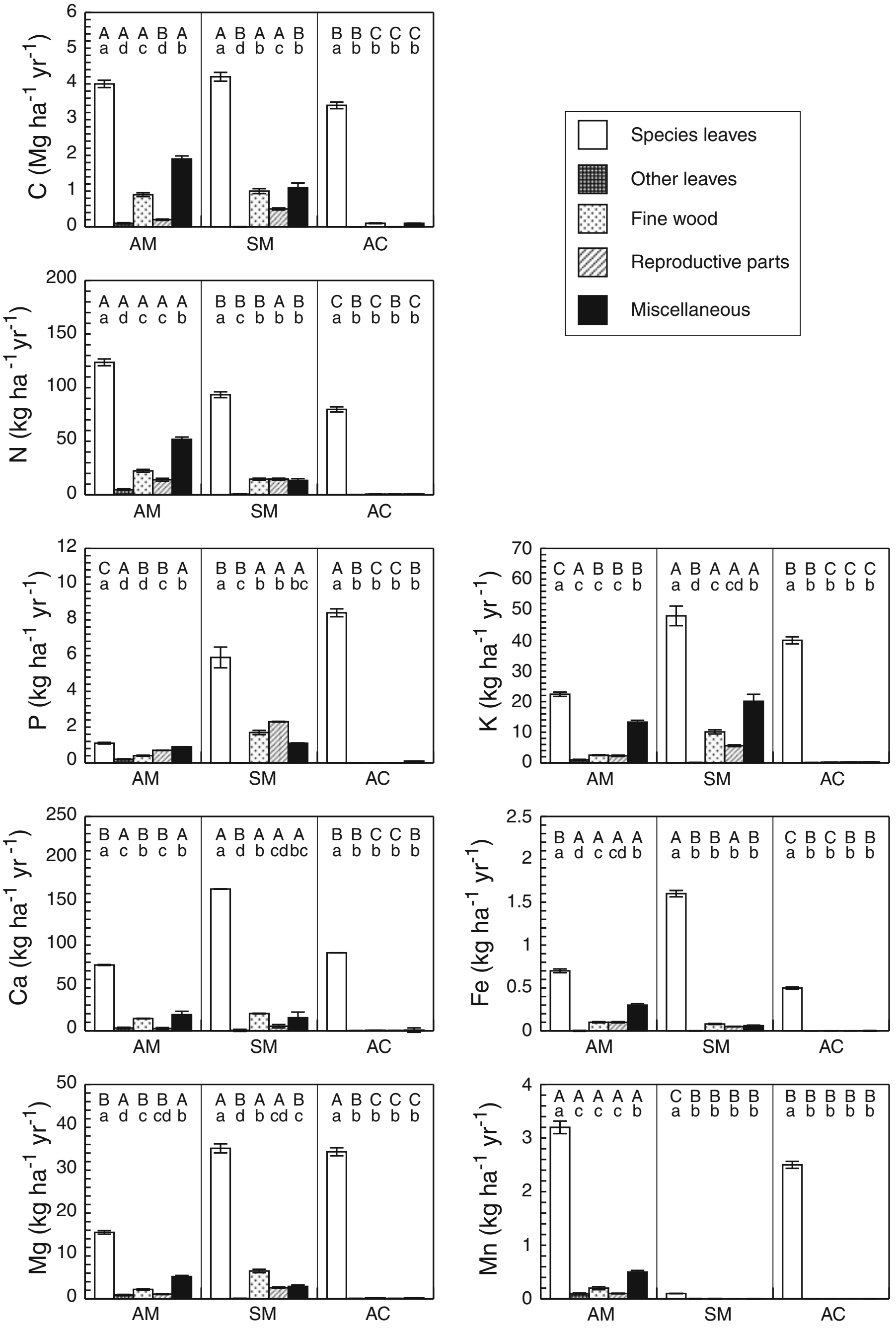

Fig. 2 Mean annual nutrient flux of five litterfall fractions. AM, SM, and AC indicates *A. mangium*, *S. macrophylla* and *A. cunninghamii*, respectively. *Error bar* indicates standard error of the mean (SEM). *Different capital letters* indicate significant differences between species in a post hoc Tukey's HSD test ($P < 0.01$). *Different small letters* indicate significant differences between fractions in a post hoc Tukey's HSD test ($P < 0.01$)

and were difficult to separate, as described by Bubb et al. (1998). At the other two sites, nutrient content in species leaves differed by element. Mean annual N fluxes of species leaves were 124, 93, and 80 kg N ha^{-1} at the *A. mangium*, *S. macrophylla*, and *A. cunninghamii* sites, respectively. Although these fluxes were significantly different (Table 4; Fig. 2), these differences in N flux in species leaves were smaller than those in total litterfall

Table 4 Effects of site, year and fraction on the annual element flux in each litter fraction

Fixed factor	*df*	Dry Mass		C		N		P		Ca		Mg		K		Fe		Mn	
		F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Sites	2	254.66	**<0.001**	256.07	**<0.001**	539.99	**<0.001**	391.73	**<0.001**	381.58	**<0.001**	178.04	**<0.001**	254.21	**<0.001**	702.24	**<0.001**	831.09	**<0.001**
Year	2	1.88	0.154	2.15	0.117	4.87	**0.008**	70.80	**<0.001**	18.24	**<0.001**	6.86	**<0.001**	18.79	**<0.001**	4.15	0.163	35.03	**<0.001**
Site × year	4	2.70	0.030	3.03	0.017	5.27	**<0.001**	43.49	**<0.001**	26.51	**<0.001**	13.38	**<0.001**	19.76	**<0.001**	5.68	**<0.001**	20.17	**<0.001**
Fraction	12	724.51	**<0.001**	748.42	**<0.001**	933.26	**<0.001**	977.24	**<0.001**	1293.22	**<0.001**	1334.19	**<0.001**	567.03	**<0.001**	1647.60	**<0.001**	1274.62	**<0.001**
Fracion × year	24	4.85	**<0.001**	5.13	**<0.001**	6.04	**<0.001**	50.07	**<0.001**	14.45	**<0.001**	7.76	**<0.001**	27.36	**<0.001**	5.95	**<0.001**	7.88	**<0.001**

Repeated measures ANOVA was used for three years of element flux in the litterfall fractions

(Table 3). Unlike total litterfall P, the P flux of species leaves was significantly larger in *A. cunninghamii* (8.4 kg P ha^{-1}) than in *S. macrophylla* (5.9 kg P ha^{-1}), and that of *A. mangium* site (1.1 kg P ha^{-1}) was only one-third of the total litterfall P. The miscellaneous fraction made a large contribution to the C, N, P, and K fluxes (16–27%, 10–24%, 10–27%, and 24–32%, respectively), and reproductive parts made a large contribution to the P flux at both the *A. mangium* and *S. macrophylla* sites (both 21%).

Very high C, N, and P fluxes in litterfall were observed at the *S. macrophylla* site a few months after March, when the rainy season ends (Fig. 3). At the *S. macrophylla* site, monthly element fluxes were very large during these months but very small in other months. In particular, the P flux at the *S. macrophylla* site was smaller than at the *A. mangium* site, where annual P flux was smallest for several months. At the *A. mangium* site, C, N, and P fluxes in litterfall were highest in June and July, but were not as distinct as in *S. macrophylla*. Monthly changes in C, N, and P fluxes in litterfall were less distinct at the *A. cunninghamii* site than at the other two sites.

We compared the element flux in litterfall with elements on the forest floor and in soils down to 30 cm (Fig. 4). Total N content, flux in litterfall and mass on the forest floor, and concentration in topsoil (0–5 cm) decreased in the order *A. mangium* > *S. macrophylla* > *A. cunninghamii*. N flux in litterfall and topsoil N concentration were significantly correlated ($r = 0.99$, $P = 0.005$), but no such correlations were observed in the other elements. Organic C in litterfall was larger at the *A. mangium* and *S. macrophylla* sites than at the *A. cunninghamii* site, but organic C on the forest floor was similar in all stands. Apart from N, only Ca content on the forest floor followed the same species order as Ca flux in the litterfall. The amounts of Ca on the forest floor and Ca concentrations in surface soil were unrelated. Mg and K fluxes in litterfall differed between species; however, those on the forest floor and in the soil did not differ.

Discussion

Nutrient flux through litterfall

Litterfall production of the *Acacia mangium* and *S. macrophylla* sites was larger than in previous

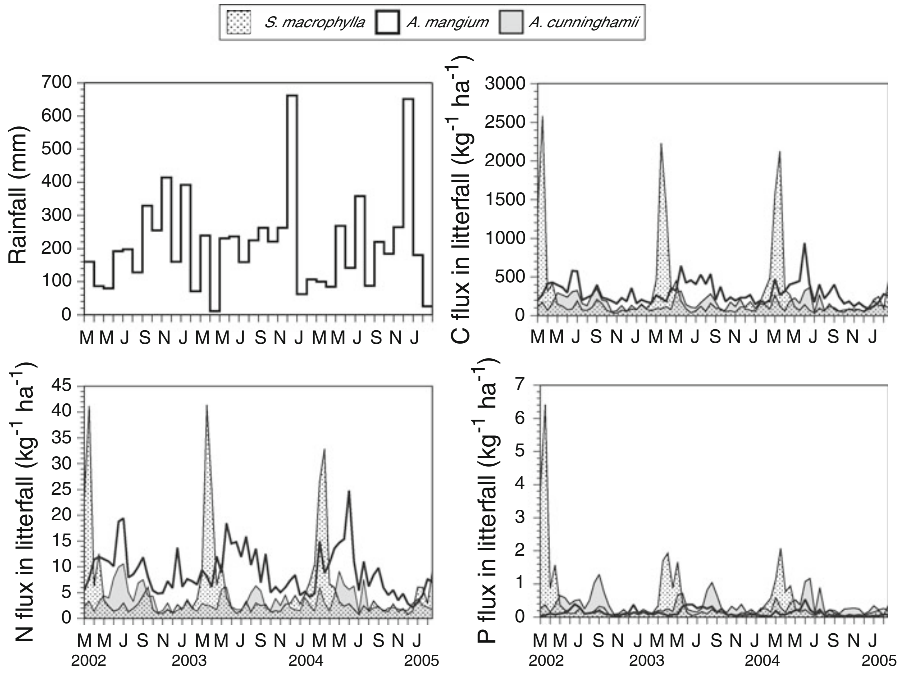

Fig. 3 Monthly rainfall, and C, N, and P fluxes in litterfall at the three sites during the measurement period. Rainfall data were obtained from GHCN-Monthly 2

results, and that of the *Araucaria cunninghamii* site was equivalent to results in its original habitat, Queensland, Australia (Brasell et al. 1980; Bubb et al. 1998; Table 5). Litterfall mass at the *A. mangium* site was considerably larger than that of some younger stands (Saharjo and Watanabe 2000; Bouillet et al. 2008b) and slightly larger than that of 10-year-old stands (Lim 1988; Bernhard-Reversat 1993; Majalap 1999; Kamo et al. 2008; Kunhamu et al. 2009). One explanation for these differences might be the contribution of stand necromass to the litterfall, since 14% of trees in the *A. mangium* site were dead during the measurement period (Kamo et al. unpublished data). The stand growth of fast-growing tree species showed an early peak and then a decline (West 2006). The growth peak appeared at age 4.5 years in an *A. mangium* stand near the research site (Kamo and Jamalung 2005). *A. mangium* stands in Indonesia also showed growth peaks at age 4–6 years (Heriansyah et al. 2007). These results, together with the appearance of dead trees at the *A. mangium* site, suggest that the 20-year-old *A. mangium* research stand had already matured. Despite this later stage of forest development, individual trees were still growing (Kamo et al. unpublished data). Another possible reason for the discrepancy in findings is differences in site fertility. High litterfall production was reported even in younger *A. mangium* stands (Hardiyanto and Wicaksono 2008). Litterfall mass at the *S. macrophylla* site was larger than that found in previous studies (Lugo 1992; Cuevas and Lugo 1998; Isaac and Nair 2006), although these studies did not include juvenile stands of less than 10 years of age (Table 5). Our results for the *S. macrophylla* site might reflect the fertile alluvial soils at the site.

N flux in litterfall at the *A. mangium* site was considerably larger than that of *S. macrophylla*, even though their litterfall dry mass was similar (Table 3). This is possibly due to symbiotic N fixation, estimated to be more than 30 kg N ha^{-1} year^{-1} in some *A. mangium* stands in Brazil (Bouillet et al. 2008a), and/or higher N demand by legumes. Legumes may be higher N_2-demanding species (McKey 1994) because they tend to have a higher N concentration in leaves regardless of whether they fix atmospheric N_2. The difference in litterfall N likely explains the higher N accumulation in biomass due to the higher N demand of *A. mangium* (Inagaki et al. 2009).

According to a tropical and subtropical litterfall data set including both natural and plantation forests ($n = 135$) assembled by Dr. K.V. Sankaran (Binkley et al. 1997), annual N flux at the *A. mangium* site was

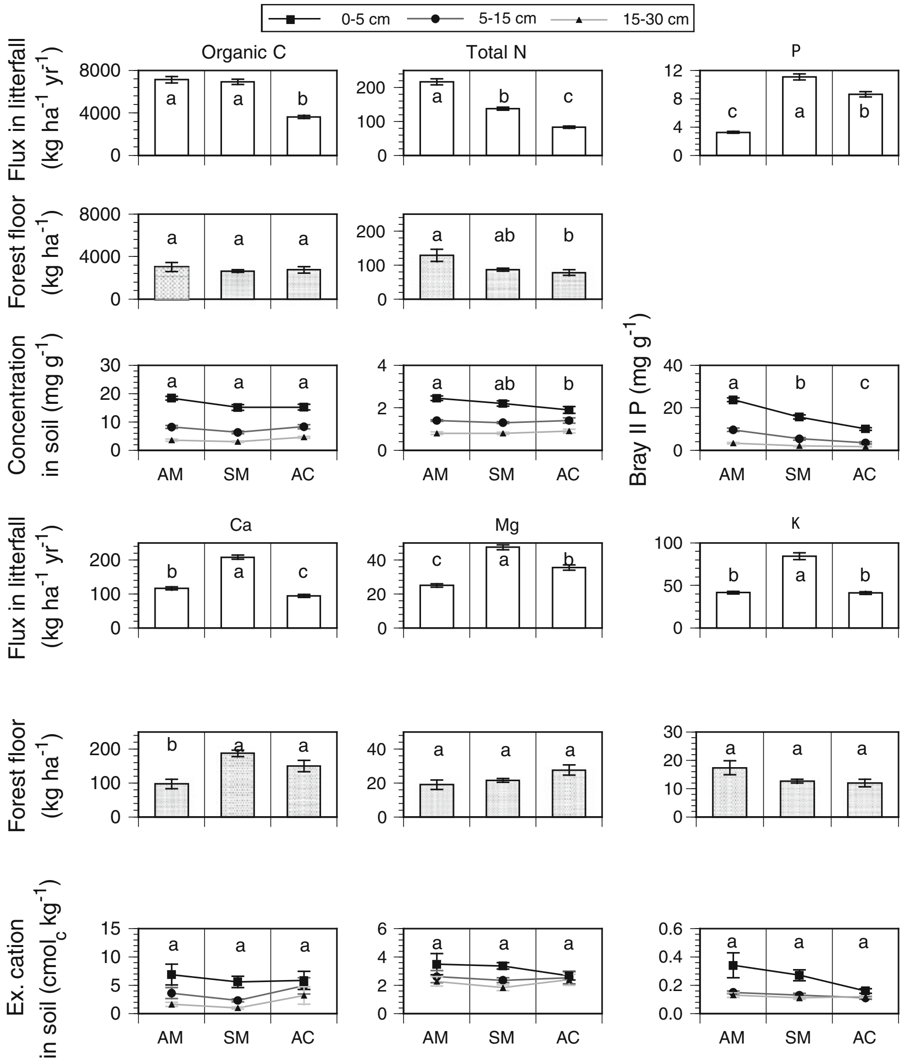

Fig. 4 Nutrient fluxes through litterfall, nutrients on the forest floor, and nutrient concentration in the surface soil. AM, SM, and AC indicates *A. mangium*, *S. macrophylla* and *A. cunninghamii*, respectively. Fluxes in litterfall are 3-year averages. *Error bars* indicate the standard error of the mean (SEM). *Different letters* indicate significant inter-site differences according to ANOVA and post hoc Tukey's HSD test ($P < 0.01$). Total P values on the forest floor were not available

above the 95% percentile and that at the *S. macrophylla* site was also above average. Large N fluxes of more than 200 kg N ha^{-1} year^{-1} were also reported in other tropical plantations of N$_2$-fixing trees (Binkley et al. 1992; Swamy and Proctor 1997; Jamaludheen and Kumar 1999). The *A. mangium* site not only produced the largest annual N flux compared with other tropical forests (Binkley et al. 1997) but also supplied the flux each month, unlike *S. macrophylla* (Fig. 3).

Compared to previous results, annual N fluxes of *A. mangium* in this study were larger, whereas annual P fluxes were similar (Table 5). N concentration per total litter mass in our study was similar to the results of Bernhard-Reversat (1993, 1996; 17 mg g^{-1}), and litter production was larger than in other studies. Hence, a large N flux in litterfall was recorded in our study. Annual N fluxes were not correlated with stand age (Table 5). In the case of leguminous *Paraserianthes falcataria* plantations in Hawaii, the annual N flux in litterfall was 240 kg ha^{-1} year^{-1} at 6 years of age (Binkley et al. 1992) but smaller in older stands (141 kg ha^{-1} year^{-1} at 14–16 years; Binkley and Ryan 1998). In these studies, total N concentrations in litter were similar in the two age groups (13 and

Table 5 Litterfall amounts and accompanying nutrient input per year for the three study species based on the literature and the present study

Species	Study site	Stand age	Soil type	Dry mass (Mg ha^{-1} year^{-1})	N (kg ha^{-1} year^{-1})	P (kg ha^{-1} year^{-1})	K (kg ha^{-1} year^{-1})	Reference
A. mangium	Pahang, Malaysia	4	N.A.	8.6–9.3	N.A.	N.A.	N.A.	Lim 1988
	Pointe Noire, Congo	5–7	Arenosols	9.7	170	N.A.	N.A.	Bernhard-Reversat 1993, 1996
	Sumatra, Indonesia	6–7	N.A.	5.9–6.0	N.A.	N.A.	N.A.	Saharjo and Watanabe 2000
	Sabah, Malaysia	7–10	Alisols	11.9	155	3.1	55.7	Majalap 1999
	São Paulo, Brazil	1.5–2.5	Ferralsols	6.1	90	N.A.	N.A.	Bouillet et al. 2008b
	Sakaerat, Thailand	12–13	Acrisols/ Podozols	7.5–9.8	N.A.	N.A.	N.A.	Kamo et al. 2008
	Sumatra, Indonesia	2–4	Acrisols	9.4–12.5	137.3–146.6	1.6–3.0	17.8–27.3	Hardiyanto and Wicaksono 2008
	Kerala, India	9	Acrisols	5.7–11.2	42.1–82.9	1.8–3.3	36.2–71.9	Kunhamu et al. 2009
	Sabah, Malaysia	20–22	Alisols	12.8–13.5	207–223	2.7–3.4	38–46	This study
S. macrophylla	Laquillo, Puerto Rico	17, 49	Acrisols/ Ferralsols	10.0–10.7	33–43	1.1–4.5	5.0–5.2	Lugo 1992
	Laquillo, Puerto Rico	26	Acrisols	9.8	74.3	2.7	74.3	Cuevas and Lugo 1998
	Kerala, India	N.A.	N.A.	6.4	68	4.2	26	Issac and Nair 2006
	Sabah, Malaysia	34–36	Alisols	12.5–14.1	126–153	7.5–15.6	72–107	This study
A. cunninghamii	Queensland, Australia	42–44	Krasnozems	5.1–12.7	78–109	9–13.1	37.0–66.8	Brasell et al. 1980
	Queensland, Australia	10–62	Krasnozems/ Podzolic soil	6.0–10.9	28.1–60.6	4.4–6.2	N.A.	Bubb et al. 1998
	Sabah, Malaysia	27–29	Alisols	6.4–7.4	72–94	7.8–9.2	35–45	This study

15 mg g^{-1}, respectively). Kunhamu et al. (2009) reported a lower N concentration in *A. mangium* litter (6–9 mg g^{-1}) and soil total N concentrations (0.07–0.42 mg g^{-1} at 0–15 cm) that were one order lower than those of soils at 5–15 cm in our study sites (1.2–1.4 mg g^{-1}; Inagaki and Titin 2009). The difference in total N concentration in litterfall would be determined by N availability, and both stand production and N availability would probably determine N flux in litterfall.

The P flux in litterfall was very low in *A. mangium*, considering its mass and high N flux (Table 3). A small P flux in contrast with a large N flux in litterfall has also been reported in other *A. mangium* stands (Majalap 1999; Hardiyanto and Wicaksono 2008), and was due to high P resorption before leaf fall (Hardiyanto and Wicaksono 2008; Inagaki et al. in preparation) and allocation to reproductive parts (Inagaki et al. in preparation). According to the global data set (Binkley et al. 1997), the annual P flux in litterfall at the *A. mangium* site was below average, and those at the other two sites were above average. The *S. macrophylla* site had a better supply of P with respect to annual flux. However, this flux was only larger than that at the other sites from February to April, at the end of the rainy season, as observed in

Puerto Rico, the original habitat of *S. macrophylla* (Lugo 1992; Cuevas and Lugo 1998). Palm (1995) emphasized the importance of nutrient release timing for crops in agroforestry systems; however, such intense nutrient flux as seen in *S. macrophylla* cannot provide successive nutrient releases throughout the year.

Other litterfall fractions besides species leaves made considerable contributions to the total element flux in litterfall (Fig. 2). Cuevas and Lugo (1998) reported that other fractions apart from species leaves made up more than 50% of total N and P flux in some plantations.

We compared our results with the litterfall of primary forests under similar edaphic conditions. Dent et al. (2006) investigated the litterfall of primary vegetation in the Sepilok Forest Reserve, about 5 km from our research sites (Fig. 1). The alluvial forest was the most fertile of four different types of forest they measured; we assumed it to be the original vegetation type of our sites because of the similarity in soil characteristics (Table 1). The mean litterfall mass in the alluvial forest was 7.7 Mg ha^{-1} year^{-1} for 2 years of measurement, which is similar to that of the *A. cunninghamii* site and smaller than those of the *A. mangium* and *S. macrophylla* sites. The annual N fluxes in litterfall at the present study sites, lowest at the *A. cunninghamii* site, were slightly smaller than that of alluvial forest (103 kg N ha^{-1} year^{-1}) and larger than those of infertile primary forests (from 47.6 to 56.9 kg N ha^{-1} year^{-1}). Except in *A. mangium*, annual P fluxes in litterfall at our sites were also larger than that of alluvial forest (5.41 kg P ha^{-1} year^{-1}), and our annual K fluxes in litterfall were almost equivalent to or larger than that of the alluvial forest (29.9 kg K ha^{-1} year^{-1}). Nutrient fluxes through species leaves and fine wood litterfall in the three plantation forests were 80–140% for N, 30–160% for P, and 80–190% for K compared to those of the most fertile site in the nearby primary forest (Dent et al. 2006). In terms of nutrient cycling, greater production and accompanying nutrient return to the forest floor occurred in the plantation sites than in the natural forests. In general, the N pool on the forest floor of primary wet tropical forests is high (e.g., Vitousek and Sanford 1986), and our results indicate that plantation forests can also provide a rich N pool.

Effect of element flux in litterfall on soil chemistry

We assumed that the subsurface soils of the three study sites were similar because chemical properties (Fig. 4) and topographic conditions were consistent across the sites.

Our results show that higher N flux in litterfall occurred at the *A. mangium* site, and the N mass on the forest floor and in the topsoil (0–5 cm) was proportional to the N flux in litterfall (Fig. 4). Based on the present results and those from nine other sites, including seven sites from two other research stations (Inagaki and Titin 2009), forest floor N and topsoil (0–5 cm) N were significantly positively correlated (12 sites; $r = 0.61$, $P < 0.05$; Fig. 5). *A. mangium* sites had also higher forest floor N levels as well at the other research stations. Therefore, the larger N input from more than 200 kg ha^{-1} of litterfall could enrich topsoil N and forest floor N. The subsurface soil (5–20 cm) N mean concentration in fertile primary forest (1.0 mg g^{-1}; Dent et al. 2006) was similar to that at our sites (1.2–1.4 mg g^{-1}; at 5–15 cm); the mean concentration of topsoil (0–5 cm) N in fertile primary forest (1.6 mg g^{-1}; Dent et al. 2006) was also similar to that in *A. cunninghamii* soil (1.9 mg g^{-1}; Fig. 4), and both N fluxes in litterfall were similar. Therefore,

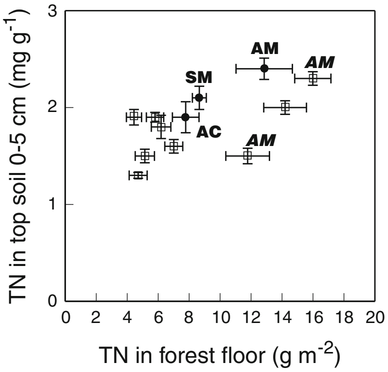

Fig. 5 Relationship between forest floor N and topsoil (0–5 cm) N concentration at 12 sites. AM, SM, and AC indicates *A. mangium*, *S. macrophylla* and *A. cunninghamii*, respectively. *Italic AMs* indicate *A. mangium* sites at another research stations. The correlation between the two axes was significant ($r = 0.61$, $P = 0.035$). *Error bars* indicate the standard error of the mean (SEM) for both axes. Data for the forest floor and soil from the 9 sites not part of the present study, indicated by *open square*, are also from Inagaki and Titin (2009)

the degree of N flux in litterfall is likely to affect the N concentration of topsoil.

The effects of *Acacia* plantations on soils have been investigated in many studies, especially recently. Some studies have reported positive effects on topsoil of N accumulation (Fisher 1995; Bernhard-Reversat 1996; Majalap 1999; Garay et al. 2004; Jang et al. 2004; Xue et al. 2005; Kimaro et al. 2007; Macedo et al. 2008; Kunhamu et al. 2009) and/or N mineralization (Majalap 1999; Li et al. 2001; Kimaro et al. 2007). Vitousek et al. (2002) pointed out the importance of N_2 fixation as a source of N cycling in tropical ecosystems, and a large organic N flux through litterfall is likely to enhance N availability in tropical forest plantations. The relationships between large N flux in litterfall, large N stock on the forest floor, and soil N have also been studied. More than 150 kg N ha^{-1} $year^{-1}$ in litterfall (Bernhard-Reversat 1996; Majalap 1999) and large forest floor mass (Garay et al. 2004) or forest floor N of more than 100 kg ha^{-1} (Xue et al. 2005; Macedo et al. 2008) resulted in larger N concentrations or mineralization of topsoil than in controls. Garay et al. (2004) also found a higher percentage of soil aggregates containing more organic C and nutrients than fine soil, in *A. mangium* soil than in *Eucalyptus* soil. Using the Soil Fertility Index (SFI) proposed by Moran et al. (2000), Abdu et al. (2008) found that SFI values were higher in an *A. mangium* intercropping forest than in a secondary forest. These results suggest that a large organic matter input leads to N accumulation and ameliorates soil conditions. Some studies have observed soil N enrichment to a depth of 30 cm (Jang et al. 2004; Macedo et al. 2008), whereas examination of N was limited to 0–5 cm in our study (Inagaki and Titin 2009). This could be attributed to differences in soil type, depth of the A horizon, original soil condition, and years since planting. Our study site was secondary forest before planting, and soil degradation might have been little in contrast to the study sites of Jang et al. (2004) and Macedo et al. (2008); furthermore, these studies compared *A. mangium* sites with considerably degraded land. Although the soil N stock of our *A. mangium* study site was not enhanced in deeper soil horizons, the large N flux in litterfall is likely to enhance the available N pool, which would be labile on the forest floor and in surface soil. Therefore, older *A. mangium* stands would have an advantage in providing a larger N pool. In addition to the aboveground litterfall, belowground litterfall would also contribute to soil amelioration because belowground litterfall is expected to show large production and rapid turnover, although the amounts and functions of belowground litterfall are still uncertain, particularly in tropical forest ecosystems (Graefe et al. 2008).

As for other elements (C, P, Ca, Mg, and K), there were no significant relationships between litterfall and soil. Litterfall P at the *A. mangium* site was lower than at the other two sites, even though topsoil P as measured by the Bray II method was high (Fig. 4). According to our results (Inagaki and Titin 2009), soil P at two *A. mangium* sites at two other research stations was not higher than that at other species sites. Soil P as measured by the Bray II method had no relationship to litterfall P in this study. Methods of measuring plant available P in soil are still under discussion because extraction methods for soil P reveal only a part of the total plant available P (Tiessen and Moir 2008). The significance of the relationship between litterfall P and soil P depended on soil P fractions (Cuevas and Lugo 1998), or plant species (Watanabe et al. 2009). Available nutrients in pools and demand by plants could vary, particularly for P (Binkley et al. 2000; Inagaki et al. 2009). To better understand P management in plantations, further studies are needed on soil P fractions and growth and demand of plantation trees.

Ca and Mg are relatively immobile elements. The Ca flux in litterfall and on the forest floor was similar even though other elements were reduced (Fig. 4). In a 26-year-old *S. macrophylla* site in Puerto Rico, Ca in the forest floor (Lugo et al. 1990) was twofold larger than litterfall Ca flux (Cuevas and Lugo 1998). Ca from litterfall is likely to stay longer on the forest floor than other elements. During litter decomposition in a primary forest in Borneo, Ca remained at almost 100% on a mass basis over a period of a few months in some species, but the process differed by species and litter characteristics (Hirobe et al. 2004).

The Mn flux in litterfall was extremely low at the *S. macrophylla* site. This may cause lower decomposition rates and affect surface soil conditions. Metallic elements such as Mn and Fe have a positive effect on the decomposition of litter or dissolved organic matter and act like catalysts (Berg et al. 2000; Davidson et al. 2003). Because of the difference in vegetation, concentrations of certain elements might be altered. Jobbágy and Jackson (2004) reported that an *Eucalyptus* plantation accumulates more Mn in the surface soil than grassland by uplifting it from deeper soil horizons. Such differences in the flux of key elements by plant activities might alter the decomposition process and the nutrient dynamics of forest plantation ecosystems.

Conclusion

We evaluated nutrient supply through litterfall in an older *Acacia mangium* site and two other plantation sites. Annual N flux at the *A. mangium* site was more than 200 kg N ha^{-1} because of a large litterfall mass and higher N concentration. The large litterfall mass could have been enhanced by standing necromass because of the age of the stand, and the higher N concentration could have been caused by the N-fixing of legumes. Soil N availability would also affect these factors. Species leaves accounted for more than 50% of the total N flux, with significant amounts in other fractions. We considered that such a large N flux enriched topsoil N of the *A. mangium* site relative to that of the other sites. However, P flux through litterfall was very small compared to that of the other two stands. Of the three species studied, *A. mangium* was the best supplier of N to the forest floor, but not the best supplier of P. The *S. macrophylla* site had larger element fluxes, except for N and Mn, than the other sites. However, because of its high litterfall flux within a few months, nutrient supply is inconstant, which may lead to inadequate nutrient release. The Mn flux in litterfall at the *S. macrophylla* site was very small. The nutrient fluxes of plantation sites, even of the *Araucaria cunninghamii* site, were equivalent to or larger than those of nearby fertile primary forests.

For the purpose of rapid organic N supply, *A. mangium* has a great potential to produce a large N flux through litterfall. However, the litterfall of a single species may cause deficits of particular elements (e.g., P in *A. mangium* and Mn in *S. macrophylla*) and/or inconstant litter supply (as shown in *S. macrophylla*) and might cause a nutrient imbalance in soils. Fast-wood plantations have potential as fertilizer trees, but foresters should pay attention to maintaining nutrient balance in soils. Using a mixture of fertilizer tree species or applying a mixed litter might be a better solution.

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