Nutrient dynamics via litterfall and litter decomposition on the forest floor of an Acacia mangium Willd. stand in Sumatra

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ABSTRACT Nutrient inputs via litterfall and associated nutrient accumulations and releases in the litter layer were investigated in 7-year-old Acacia mangium Willd. plantation stands in Indonesia. Annual N, Mg, Ca and K inputs via litterfall were 230–235, 21–26, 157–179 and 131–157 kg ha⁻¹ yr⁻¹, respectively and the contributions of phyllode litterfall to these nutrient inputs were over 60%. Nutrient inputs via litterfall increased from dry to wet seasons being strongly associated with reproductive litterfall inputs as well as phyllode litterfall inputs. Annual mean N, Mg, Ca and K accumulations on the forest floor were 172–235, 12–14, 52–88 and 42–47 kg ha⁻¹, respectively. There were no clear seasonal variations in nutrient amounts on the forest floor. The peak of mass loss of phyllode litter was observed in the late wet seasons, and its seasonal change was coincided with the rainfall seasonality. Reflecting mass losses of reproductive and twig litters, however, seasonal variability in mass loss of whole litter became more complex. Nitrogen and Mg releases from litter layer tended to increase in the late wet seasons being affected by the retarded releases of these nutrients from fleshy fallen litters in addition to the increased mass loss of phyllode litter in the periods. Calcium releases from litter layer showed no significant seasonal variations reflecting the irregular seasonal changes in Ca release from twig litter rich in Ca. Meanwhile, the seasonal variation in K release from litter layer coincided with the seasonal changes in K inputs via litterfall.

Key words: Tropical fast growing tree plantation, N₂-fixing tree, Nutrient releases, Nutrient uptake efficiency, Seasonality of nutrient cycling

INTRODUCTION

Litterfall is a major pathway of nutrient input from trees to the forest floor, and litter decomposition releases most nutrients into the mineral soil. In tropical forest with low soil nutrient reserves, the forest floor is the major component associated with nutrient supply and cycling (e.g. Evans and Turnbull 2004, FAO 2001, Tobon et al. 2000). Seasonal variations in litterfall input and litter decomposition are affected by environment, species-specific phenology and litter quality (e.g. Jordan 1986, Swift et al. 1979, Vitousek 1984). This in turn can result in distinctive seasonal patterns of nutrient releases from litter layer. A synchronism between the nutrient demand by plants and the supply from decomposing litters is essential to minimize the nutrient loss from the forest system as well as the temporal plant nutrient deficiency.

In tropical Asia, the area of industrial tree plantations is rapidly increasing. One of the most common tree species planted in this region is Acacia mangium Willd., which is preferred because its fast growth is suitable for wood production with short rotations and it has high adaptability to various site conditions (Turnbull et al. 1998). Due to its rapid initial crown development and tolerance of very poor soil, A. mangium can effectively suppress Imperata grasses (Awang and Taylor 1993, Tilki and Fisher 1998, Turnbull et al. 1998) and provide a favorable condition for the growth of slow-growing tree species (Norisada et al. 2005, Otsamo 2000, Yang et al. 2009). Also the establishment of A. mangium plantations has beneficial effects on the stands such as increase in availability of soil nutrients, especially N (Bernhard-Reversat 1996, Franco and DeFaria 1997, Garay et al. 2004, Inagaki et al. 2010, Li et al. 2001, Majalap 1999, Schiavo et al. 2009, Yang et al. 2009) and improvement of soil structuration (Garay et al. 2004, He et al. 2007).

Despite the many beneficial and adverse effects, some researchers suggested that the low nutrient availability in soils, especially nutrient cations and phosphorus, could be induced by A. mangium stands due to the high rate of consumption of nutrients by this species and comparatively less nutrient returns to the mineral soil (Inagaki et al. 2010,
Majalap 1999, Nykvist 1996, 2000, Rathod and Devar 2003, Yamashita et al. 2008). Therefore, the maintaining and improving of their high productivity may depend strongly on the short-term or annual recycling of nutrients. However, few studies have been reported concerning seasonal nutrient dynamics in A. mangium stands (Majalap 1999), and the seasonality in nutrient releases from litter layer has not yet studied.

The aim of the present study was to clarify the qualitative and quantitative nutrient dynamics of above-ground litterfall, litter accumulation and decomposition, and potential nutrient release from decomposing litters on the forest floor to the mineral soil in A. mangium stands on Sumatra.

**MATERIALS AND METHODS**

**Study site**

The study was conducted at A. mangium stands in PT. Musi Hutan Persada, Muara Enim, South Sumatra Province (103°58' E, 3°52' S), Indonesia from October 2003 to February 2007. In September 2003, a study plot (plot C, 1.0 ha) was set up in a 7-year-old A. mangium plantation with spacing 3 x 3 m. Preparatory to clear-cut harvest conducted in plot C on August 2005, another plot (plot A, 1.2 ha) was set up in an adjacent 7-year-old A. mangium stand in September 2004. When the study plots were set up, the mean height, mean diameter at breast height and basal area of the site were 23.0 m, 20.8 cm and 25.5 m² ha⁻¹ in plot C; 23.7 m, 22.5 cm and 24.2 m² ha⁻¹ in plot A, respectively (Kaneko et al., personal communication). The stands were the first rotation plantation established on previously alang-alang (Imperata cylindrica (L.) P. Beauv.) grassland. The topography was flat with a slope of 0%–3%, and the altitude was approximately 165 m a.s.l. The soil at the study site was Oxisol (USD A Soil Taxonomy). The climate falls into Aw in Koppen’s classification. Annual temperature (2005–2006) was 24.9–25.4°C, and annual rainfall (2004–2006) was 2469–3786 mm. The wetter months from October to April had a monthly average of 298 mm in 2004, 355 mm in 2005 and 292 mm in 2006, while the drier months from May to September had a monthly average of 97 mm in 2004, 240 mm in 2005 and 75 mm in 2006. The study area experienced a prolonged drought in 2006 due to El Nino-Southern Oscillation and received less than 10 mm of rainfall in August.

**Field sampling**

**Litterfall**

Litterfall was measured using litter traps set up in 20 m x 20 m quadrates established in each study plot. Each litter trap consisted of a 2-mm nylon mesh with a surface area of 0.49 m² suspended on four wooden poles placed at 1.0 m above the ground level. Litterfall was collected every 10 days (three times per month) from 25 traps. Since the plot C was harvested, the investigation was conducted in plot C from October 2003 to July 2005 and in plot A from August 2005 to February 2007.

**Litter layer**

Litters on the forest floor were collected from 0.2 m² area with four replications every 2 months. Since the plot C was harvested, the investigation was conducted in plot C from December 2003 to August 2005 and in plot A from October 2005 to February 2007.

**Sample preparation and chemical analysis**

Litter samples were separated into phyllodes, reproductive organs, and twigs (<2.0 cm in diameter). Five monthly composite field samples for each component were prepared by combing every 10-day litterfall samples from 5 litter traps, and weighted after oven-drying at 70°C for 2 weeks. Phyllode fragments, insect frass, fine reproductive parts (<2.0 mm in diameter) and coarse woody materials (>2.0 cm in diameter) were not included.

Oven-dried litter samples were ground and passed through a 0.25-mm mesh sieve, and analyzed for C and N concentrations using a CN coder (JM1000CN; J-Science Lab, Yokohama, Japan) and Mg, Ca and K concentrations using an atomic absorption spectrometer (iCE 3300; Thermo Fisher Scientific, Yokohama, Japan) after wet digestion with a nitric, sulfuric and perchloric acid. For litterfall samples, we analyzed C, N, Mg, Ca and K for monthly composite samples of each litter component prepared by combing 5 monthly composite field samples. For litter layer samples, we analyzed C and N for 2 replicate samples of each litter component at every sample timing, and Mg, Ca and K for all 4 replicate samples.

**Data processing and statistical analysis**

**Nutrient inputs via litterfall and nutrient pools in litter layer**

Monthly nutrient inputs via each litterfall component were calculated by multiplying its monthly nutrient concentrations and mass. Nutrient pools of each component in the litter layer were calculated by multiplying its average
nutrient concentrations and mass. Annual mean nutrient concentrations of each component of litterfall and litter layer were calculated by dividing its total nutrient by its annual amount. Since the study plot was changed part way through a year, annual data for litterfall were calculated using the monthly values from October 2003 to September 2004 and October 2005 to September 2006, and for litter layer were calculated using the bimonthly values from December 2003 to November 2004 and December 2005 to November 2006.

Net mass loss and net nutrient release from litter layer

Since the study stand showed strong seasonal variations in litterfall inputs, net litter mass losses were calculated using the following equation for each litter component (UNESCO/UNEP/FAO 1978):

\[ \text{decay}_{t_2} = \text{FF}_{t_1} + \text{LF}_{t_2} - \text{FF}_{t_2} \]

where, FF and LF, and FF and LF, are masses of litter layer at dates \( t_1 \) and \( t_2 \), and LF is the litterfall input between \( t_1 \) and \( t_2 \). Annual net litter mass losses were calculated by summing the bimonthly values of decay.

Net mass loss and net nutrient release from litter layer were calculated using the bimonthly values of decay using each estimated net litter mass loss as follows:

\[ \text{N}_{t_2} = \text{FF}_{t_1} + \text{LF}_{t_2} - \text{FF}_{t_2} \]

where, FF and FF and FF and LF are the nutrient amounts in litter layer at dates \( t_1 \) and \( t_2 \), and LF is the nutrient input via litterfall between \( t_1 \) and \( t_2 \). Annual nutrient releases from decomposing litters on the forest floor were calculated by summing the bimonthly values of N.

A percentage of litter mass loss (\( k_\text{l} \)) was calculated using each estimated net litter mass loss as follows:

\[ k_\text{l} = \frac{\text{decay}_{t_2}}{\text{FF}_{t_1} + \text{LF}_{t_2}} \times 100 \]

A percentage of nutrient release (\( k_\text{n} \)) was also calculated as follows:

\[ k_\text{n} = \frac{\text{N}_{t_2}}{\text{FF}_{t_1} + \text{LF}_{t_2}} \times 100 \]

The annual decomposition coefficient (\( k_\text{a} \)) was calculated by dividing annual amount of net litter mass loss by annual mean amount of litter layer. The annual nutrient release constant coefficient (\( k_\text{a} \)) was calculated in the same manner as the \( k_\text{l} \). Residence times of each litter component and nutrients in each litter component were calculated as the inverse of \( k_\text{l} \) or \( k_\text{n} \).

The N input via litterfall was 230–235 kg N ha\(^{-1}\) yr\(^{-1}\), 70–72%, 21–22% and 7–8% of which via phyllode, reproductive and twig litterfall comprised 60–65%, 23–30% and 11–12% of the total litterfall, respectively (Table 1). Phyllode litterfall increased at the end of the dry season especially from July to October 2006, possibly due to water stress (Figure 1). Reproductive litterfall showed distinct increases at the beginning of wet seasons, concomitantly with fruit maturation. Twig litterfall tended to increase in wet seasons probably attributing to the effects of strong winds often observed during rainfall (plot C: \( r_1 = 0.433, p<0.05, n = 22 \), plot A: \( r_1 = 0.650, p<0.001, n = 28 \)).

Annual mean N, Mg and Ca concentrations were higher in order of phyllodes > reproductive organs > twigs, phyllodes > twigs > reproductive organs, and phyllodes > twigs > reproductive organs, respectively (Table 1 and Fig. 2). There were no clear seasonal variations in N, Mg and Ca concentrations in phyllodes and twigs, whereas the concentrations in reproductive organs significantly increased from late wet to middle dry seasons, reflecting the relatively large amounts of premature Acacia fruits. Annual mean K concentration was in the order of reproductive organs > phyllodes > twigs (Table 1), and the concentrations in all plant components clearly increased in dry seasons (Fig. 2).

The N input via litterfall was 230–235 kg N ha\(^{-1}\) yr\(^{-1}\), 70–72%, 21–22% and 7–8% of which via phyllode, reproductive and twig litterfalls in a year (Table 1), and it increased from dry to wet seasons, reflecting the increased inputs of phyllode and reproductive litterfalls (Fig. 1). Annual Mg, Ca and K inputs via litterfall were 18.2–25.8, 157–179 and 131–157 kg ha\(^{-1}\) yr\(^{-1}\), respectively, and contributions of phyllode litterfall to Mg, Ca and K inputs (69–71%, 76–79%, and 61–63%, respectively) were much higher than those of reproductive (19–21%, 7–13%, and 33–35%, respectively) or twig (8–12%, 12–14%, and 5%, respectively) litterfalls. Mg, Ca and K inputs via total
Table 1. Annual nutrient concentrations, C/N ratios and nutrient inputs of phyllode, reproductive and twig (<2 cm) litterfalls in *A. mangium* stands in South Sumatra, Indonesia.

<table>
<thead>
<tr>
<th>Age (yr)</th>
<th>Litterfall mass (Mg ha(^{-1}))</th>
<th>Nutrient concentrations in litterfall (mg g(^{-1}))</th>
<th>Nutrient fluxes via litterfall (kg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>Mg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mg</td>
<td>mg</td>
</tr>
<tr>
<td>phyllodes</td>
<td></td>
<td>19.9</td>
<td>1.67</td>
</tr>
<tr>
<td>reproductive organs</td>
<td>7</td>
<td>16.5</td>
<td>1.32</td>
</tr>
<tr>
<td>twigs</td>
<td></td>
<td>10.0</td>
<td>1.58</td>
</tr>
<tr>
<td>total litterfall</td>
<td></td>
<td>13.0</td>
<td>1.58</td>
</tr>
<tr>
<td>phyllodes</td>
<td></td>
<td>16.8</td>
<td>1.85</td>
</tr>
<tr>
<td>reproductive organs</td>
<td>8</td>
<td>9.92</td>
<td>1.12</td>
</tr>
<tr>
<td>twigs</td>
<td></td>
<td>8.79</td>
<td>1.16</td>
</tr>
<tr>
<td>total litterfall</td>
<td></td>
<td>13.9</td>
<td>1.56</td>
</tr>
</tbody>
</table>

Data for the 7-year-old stand were obtained in plot C from October 2003 to September 2004 and for the 8-year-old stand were obtained in plot A from October 2005 to September 2006.

Litterfall also increased from dry to wet seasons associated with increased amounts of phyllode and reproductive litterfalls (Fig. 1).

**Litter layer**

The amount of annual mean litter layer was 8.77–11.3 Mg ha\(^{-1}\), and phyllodes, reproductive organs and twigs comprised 41–47%, 20–24% and 33–34% of the total amount of litter layer, respectively (Table 2). Total litter amounts showed tendencies to increase in the beginning of wet seasons, reflecting the increased amounts of phyllodes and reproductive organs (Fig. 3).

The N concentration was in the order of phyllodes > reproductive organs > twigs (Table 2 and Fig. 4), and those in all litter components were virtually constant throughout the period (Fig. 4). The Mg concentrations were higher in phyllode litter than other litter components, and the concentrations did not show clear seasonal variations for all litter components. The Ca concentration in litter layer was higher in the order of twigs > phyllodes > reproductive organs, and the concentrations increased in the dry seasons for phyllode and reproductive litters, but not for twig litter. The K concentration was in the order of reproductive organs > phyllodes > twigs, and the concentrations were clearly higher in dry seasons for phyllode and reproductive litters, but not for twig litter.

The annual mean N amount in litter layer was 172–235 kg N ha\(^{-1}\), and phyllodes, reproductive organs and twigs comprised 53–61%, 19–25% and 23–26% of the total N amount, respectively (Table 2). The N amount tended to increase from dry to wet seasons. Annual mean amounts of Mg, Ca and K in litter layer were 12.0–14.4 kg ha\(^{-1}\), 51.9–88.0 kg ha\(^{-1}\), and 41.8–47.1 kg ha\(^{-1}\), respectively, and phyllodes, reproductive organs and twigs constituted 53–57%, 20–24% and 27–28% to the total Mg amount in litter layer, 47–48%, 11–12% and 42–46% to the total Ca amount in litter layer, and 52%, 30–31% and 22–23% to the total K amount in litter layer, respectively. Mg and K amounts also showed slight and prominent increases during the beginning of wet seasons, but Ca did not.

**Decomposition and nutrient releases in litter layer**

Reproductive litter had the shortest residence time (RT), followed by phyllode litter. Twig litter was 3–6 times longer in RTs than the other litter components (Table 2). RTs of all nutrient elements in each component showed the similar trend as the mass (reproductive organs > phyllodes > twigs), except for Ca (phyllodes < reproductive organs < twigs). RTs of nutrient elements in phyllode and reproductive litters were in the order K < Ca < Mg < N and in twig litter were (K <) Ca < Mg (K <) N. RTs for N in all litter components were longer than those for masses. Meanwhile, RTs for other nutrient elements in each litter component were shorter than or nearly similar to those for masses.

Percentages of litter mass loss (k) tended to decrease in dry seasons, reflecting the decreased mass loss of phyllode litter (Fig. 5). Contrarily, mass loss of twig litter tended to increased in the middle to late dry seasons. Mass loss of reproductive litter increased in the transition from dry to wet seasons. k of N and Mg reached their peaks in the late wet seasons and decreased in dry seasons, reflecting the seasonal changes in phyllode litter mass losses (Fig. 5).
Nutrient dynamics via litterfall and litter decomposition on the forest floor of an *Acacia mangium* Willd. stand on Sumatra

Fig. 1. Monthly variations in amounts of dry masses and nutrient inputs of phyllode, reproductive and twig litterfalls in *A. mangium* stands in South Sumatra, Indonesia. Data were obtained in plot C from October 2003 to July 2005 and in plot A from August 2005 to February 2007.
Although $k_c$ of Ca also tended to decrease in the middle dry seasons, there were no clear seasonal variations, reflecting the irregular seasonal change of Ca releases from twig litters rich in Ca. Meanwhile, $k_c$ of K peaked at the beginning of wet seasons, reflecting the increased K releases from phyllode and reproductive litters rich in K.

**DISCUSSION**

**Litterfall amounts and nutrient inputs via litterfall in the *A. mangium* plantation**

The annual litterfall amounts in this study were in the upper range of other *A. mangium* stands (Table 4). The higher litterfall amounts in our study site compared to young immature stands were partly due to the higher amounts of reproductive and twig litterfalls associated with
Nutrient dynamics via litterfall and litter decomposition on the forest floor of an Acacia mangium Willd. stand on Sumatra.

The clear seasonality of litterfall inputs has prominent droughts, the seasonal variations in N inputs via litterfall in our stand compared to young immature stands. Due to the very low Ca concentration in reproductive litterfall, the seasonal variation in Ca inputs via litterfall was less pronounced although it still tended to increase at the end of dry seasons, reflecting the increased phyllode litterfall inputs during the periods.

The annual K inputs via litterfall in this study were much higher than those in other A. mangium stands (Table 4) primarily due to the higher K input via phyllode litterfall associated with its extremely high K concentration. The higher K concentrations in phyllode litterfall in our stands may become more pronounced in mature stands associated with the development of reproductive organs.

Reflecting higher litterfall production, annual Mg inputs via litterfall in our stand were in the upper range of other A. mangium stands (Table 4). The seasonal variation in Mg input via litterfall in this study coincided with the increase in Mg inputs via reproductive litterfall, indicating that the seasonality in Mg inputs via litterfall may become more pronounced in mature stands than in young immature stands as in the case of N.

The annual Ca inputs via litterfall in this study were much higher than those in other A. mangium stands (Table 4) primarily due to the higher Ca input via phyllode litterfall associated with its higher Ca concentration. As in the case of Mg, the higher Ca concentration in phyllode litterfall in South Sumatra sites than in other A. mangium stands did not reflect soil exchangeable Ca status (Fig. 7), but it may possibly reflect rapid Ca release from decomposing litters and simultaneously reuptake by planted trees. And also the increased Ca inputs via twig litterfall rich in Ca could contribute importantly to the higher Ca inputs via litterfall in our stand compared to those in young immature stands. Due to the very low Ca concentration in reproductive litterfall, the seasonal variation in Ca input via litterfall was less pronounced although it still tended to increase at the end of dry seasons, reflecting the increased phyllode litterfall inputs during the periods.

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The annual K inputs via litterfall in this study were much higher than those in other A. mangium stands (Table 4) primarily due to the higher K input via phyllode litterfall associated with its extremely high K concentration. The higher K concentrations in phyllode litterfall in our stands may become more prominent in mature stands associated with the development of reproductive organs.
Fig. 3. Seasonal variations in amounts of dry masses and nutrient accumulations of phyllode, reproductive and twig litters on the forest floor in *A. mangium* stands in South Sumatra, Indonesia. Data were obtained in plot C from December 2003 to June 2005 and in plot A from August 2005 to February 2007.
Nutrient dynamics via litterfall and litter decomposition on the forest floor of an *Acacia mangium* Willd. stand on Sumatra

**Fig. 4.** Seasonal variations in nutrient concentrations in phylloide, reproductive and twig litters on the forest floor in *A. mangium* stands in South Sumatra, Indonesia. Data were obtained in plot C from December 2003 to June 2005 and in plot A from August 2005 to February 2007.

...could reflect the higher soil exchangeable K status (Fig. 7). Also the K concentrations in reproductive litterfalls were correlated with the surface soil K levels ($y = 2.66 + 22.7x$, $r^2 = 0.795$, $p < 0.05$, $n = 5$), suggesting that the K inputs via litterfall in *A. mangium* stands may depend strongly on soil K status, irrespective of stand maturation. While, the seasonal variation in K inputs via litterfall may become much more pronounced in mature stands than in young immature stands associated with the increase in K input via reproductive litterfall, which had a clear seasonal variation with a peak at the beginning of the wet seasons. The seasonality in K inputs via litterfall became clearer in a dry year due to additional non-senesced phylloides inputs at the end of dry period.

**Residence times of nutrients and nutrient release patterns in litter layer in the *A. mangium* plantation**

A large fluctuation in RTs of whole litter was observed in this study possibly due to both the stand specific differences and the interannual rainfall variability, and the range of RTs for litter mass in our study site was including those in Pahang and Sabah sites (Table 5). The much longer...
RTs in the Congo and Brazil with the relatively large amounts of litters on the forest floor may be explained by slower litter decomposition due to the low fertility sandy soil and/or the low rainfall. Seasonal variation in phyllode litter mass loss in this study coincided with the rainfall seasonality ($r_s = 0.943$, $p<0.01$, $n = 6$), indicating that in situ moisture condition may strongly control phyllode litter decomposition in litter layer. Reflecting mass losses of reproductive and twig litters, however, mass loss of whole litter showed a more complex seasonal variability.

There was also a large intersite difference in RTs for N in this study, and there did not appear to be clear regional trends (Table 5). In all *A. mangium* stands, the RTs for N were longer than those for litter mass, indicating the slow N release from litter layer except Sabah site. The relatively long RTs for N could be partly attributed to the repeated N immobilization by microbes in decomposing litters in litter layer. N concentrations in litter layer of these stands (17.9–19.6 mg g$^{-1}$) were 1.1–1.4 times higher than those in litterfall (14.6–17.9 mg g$^{-1}$). This increase in N concentration is a general phenomenon during litter decomposition (e.g. Berg and Theander 1984, Melillo et al. 1982, O’Connell 1988, Staaf and Berg 1982), also described as a decrease in the C/N ratio. It was, however, difficult to explain the inconsistent result found in Sabah site due to lack of information about contributions of respective litter components.

Seasonal variation in N release from litter layer strongly linked to its release from phyllode litter, which increased concomitantly with the distribution of rainfall ($r_s = 0.829$, $p<0.05$, $n = 6$). Therefore, N release from litter layer may increase in synchrony with increasing N demands of trees although N inputs via litterfall increased during the dry to wet transition periods (Fig. 1 and 5). This delayed release of N from decomposing litters on the forest floor indicated that the N immobilization may be superior to the release in the initial phase of litter decomposition.

The RTs for Mg in this study were longer than that in Pahang, but shorter than that in Sabah (Table 5), partly reflecting the different contributions of woody litters to litterfall inputs. The much longer RT for Mg in Brazil may be strongly affected by the slower litter decomposition under drier climate and/or poor soil conditions. Seasonal variation in Mg release from litter layer was also strongly affected by its release from phyllode litter, which coincided with the rainfall seasonality ($r_s = 0.943$, $p<0.01$, $n = 6$). Therefore, Mg release from litter layer may increase in synchrony with increasing in requirements for plant uptake as in the case of N.

The RTs for Ca in our stand were much shorter than those in other stands, which were comparable to RTs for mass loss (Table 5). Generally, Ca is an essential structural component of cell walls and an immobile cation firmly fixed in plant tissues (e.g. Raven et al. 1999), and thus it may be released from decomposing litters associated with litter mass loss. However, in our stand the RTs for Ca were much shorter than those for litter mass, indicating a rapid Ca release from litter layer which could be related to the relatively high Ca concentration in phyllode litterfall in our stand. The less seasonal variation in Ca releases from phyllode litter may indicate that Ca is principally supplied constantly from litter layer to mineral soil throughout the

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Table 3. Estimates of residence times for dry masses and nutrients in phyllode, reproductive organs and twig (<2 cm) litters on the forest floor in *A. mangium* stands in South Sumatra, Indonesia.

<table>
<thead>
<tr>
<th>Age</th>
<th>Residence times</th>
<th>Mass</th>
<th>N</th>
<th>Mg</th>
<th>Ca</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>yr</td>
<td>yr</td>
<td>yr</td>
<td>yr</td>
<td>yr</td>
<td>yr</td>
<td>yr</td>
</tr>
<tr>
<td>phyllodes</td>
<td>0.684</td>
<td>0.927</td>
<td>0.560</td>
<td>0.248</td>
<td>0.294</td>
<td></td>
</tr>
<tr>
<td>reproductive organs</td>
<td>0.538</td>
<td>0.751</td>
<td>0.520</td>
<td>0.392</td>
<td>0.292</td>
<td></td>
</tr>
<tr>
<td>twigs</td>
<td>7</td>
<td>3.08</td>
<td>36.5</td>
<td>1.65</td>
<td>1.25</td>
<td>2.72</td>
</tr>
<tr>
<td>total</td>
<td>0.860</td>
<td>1.15</td>
<td>0.670</td>
<td>0.394</td>
<td>0.363</td>
<td></td>
</tr>
<tr>
<td>phyllodes</td>
<td>0.417</td>
<td>0.665</td>
<td>0.398</td>
<td>0.208</td>
<td>0.184</td>
<td></td>
</tr>
<tr>
<td>reproductive organs</td>
<td>0.340</td>
<td>0.547</td>
<td>0.391</td>
<td>0.314</td>
<td>0.174</td>
<td></td>
</tr>
<tr>
<td>twigs</td>
<td>8</td>
<td>1.14</td>
<td>1.88</td>
<td>1.29</td>
<td>1.13</td>
<td>0.916</td>
</tr>
<tr>
<td>total</td>
<td>0.498</td>
<td>0.752</td>
<td>0.491</td>
<td>0.345</td>
<td>0.220</td>
<td></td>
</tr>
</tbody>
</table>

Data for the 7-year-old stand were obtained in plot C from December 2003 to November 2004 and for the 8-year-old stand were obtained in plot A from December 2005 to November 2006.
year. However, the irregular seasonality in Ca releases from twig litter, especially the substantial increase in the late dry seasons, may result in the asynchronous Ca supply to plants. The irregular seasonal variation in Ca release from litter layer may become more pronounced in mature stands, reflecting the increasing in twig litter inputs with stand age.

The RTs for K in this study were shorter than those in other *A. mangium* stands, reflecting the greater K inputs via litterfall. Since K is the most mobile cation and shows a rapid initial release from decomposing litters (e.g. Berg and Staat 1987, Cortina and Vallejo 1994, Parker 1983, Swift et al. 1981), the RTs for K were much shorter than those for litter mass in all *A. mangium* stands.

The seasonal variation in K release from litter layer was strongly affected by the seasonality of K releases from reproductive litter as well as phylloide litter, indicating that it may become more pronounced in mature stands. There were no time lags between K inputs via litterfall and K releases from litter layer, which increased from dry to wet seasons (Fig.1 and 5). The leaching potential of K during
the transition from dry to wet seasons may be enhanced by the increased K accumulation on the forest floor during rainless periods. The flush of K release from decomposing litters during the transition periods may occur asynchronously with K uptake by plants, resulting in the increased risk of leaching loss of this element from the plantation stands. Particularly after prolonged droughts, the potential risk of leaching loss may become more pronounced because plant uptake may be restricted by reduced phyllode amounts. In addition to P deficiency (e.g. Inagaki et al. 2009, Otsumo 2001, Wan Rasidah et al. 1988), K can also act as a major limiting factor to growth and productivity for *A. mangium* (Simpson 1992 in Srivastava 1993). Since droughts may become more severe and frequent in the future, it is crucial to pay more attention to K uptake efficiency in *A. mangium* stands.

**CONCLUSION**

Nutrient inputs via litterfall and nutrient releases from litter layer in *A. mangium* stands were significantly different among site locations and were primarily linked to site productivity. Under similar locational conditions, however, nutrient inputs via litterfall and nutrient releases from litter layer may depend strongly on stand maturity associated with the increased reproductive and twig litterfall inputs. Also seasonal variations in nutrient inputs via litterfall may become more pronounced with stand maturity. Meanwhile, seasonal variations in nutrient releases from litter layer

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The table below provides annual dry masses of phyllode, reproductive and total litterfalls, nutrient concentrations in phyllode litterfall and nutrient inputs via total litterfall in some *A. mangium* plantations.

**Table 4.** Annual dry masses of phyllode, reproductive and total litterfalls, nutrient concentrations in phyllode litterfall and nutrient inputs via total litterfall in some *A. mangium* plantations.

<table>
<thead>
<tr>
<th>Location (Soil type)</th>
<th>RF</th>
<th>Temp Age</th>
<th>Phyllode litterfall mass (Mg ha⁻¹ yr⁻¹)</th>
<th>Reproductive litterfall mass (Mg ha⁻¹ yr⁻¹)</th>
<th>Total litterfall mass (Mg ha⁻¹ yr⁻¹)</th>
<th>Phyllode litterfall concentration (mg g⁻¹)</th>
<th>Nutrient inputs via litterfall and nutrient releases from litter layer (kg ha⁻¹ yr⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Sumatra, Indonesia (Oxisols)</td>
<td>2420–3682</td>
<td>5.2 yr</td>
<td>7.849</td>
<td>2.99</td>
<td>13.0</td>
<td>19.9</td>
<td>6.69</td>
<td>This study</td>
</tr>
<tr>
<td>South Sumatra, Indonesia (Ultisols)</td>
<td>1816–3513</td>
<td>29.0 yr</td>
<td>8.94</td>
<td>4.85</td>
<td>16.5</td>
<td>16.8</td>
<td>9.75</td>
<td>Hardiyanto et al. (2008)</td>
</tr>
<tr>
<td>Pointe Noire, Congo (Psamments)</td>
<td>1250</td>
<td>25.0 yr</td>
<td>7.90</td>
<td>1.00</td>
<td>9.70</td>
<td>16.2</td>
<td>25.8</td>
<td>Bernhard-Reversat (1993, 1996)</td>
</tr>
<tr>
<td>Rio de Janeiro, Brazil (Alfisols)</td>
<td>1250</td>
<td>16.0–32.0 yr</td>
<td>6.39</td>
<td>2.10</td>
<td>9.13</td>
<td>17.1</td>
<td>5.01</td>
<td>Andrade et al. (2000)</td>
</tr>
<tr>
<td>Sabah, Malaysia (Ultisols)</td>
<td>2808</td>
<td>7–11 yr</td>
<td>7.41</td>
<td>2.65</td>
<td>11.9</td>
<td>13.0</td>
<td>6.03</td>
<td>Majalap (1999)</td>
</tr>
<tr>
<td>Sabah, Malaysia (Ultisols)</td>
<td>2572</td>
<td>27.1–22 yr</td>
<td>12.8–13.5</td>
<td>12.8–13.5</td>
<td>21.8</td>
<td>17.4</td>
<td>10.8</td>
<td>Inagaki et al. (2010)</td>
</tr>
<tr>
<td>Pahang, Malaysia (Ultisols)</td>
<td>2100</td>
<td>27.0–33.0 yr</td>
<td>9.26</td>
<td>0.89</td>
<td>10.5</td>
<td>14.8</td>
<td>6.20</td>
<td>Lim (1988a)</td>
</tr>
</tbody>
</table>

**Fig. 6.** Relationships between the annual litterfall amounts and the stand age in some *A. mangium* stands. The solid line indicates the regression using the data of South Sumatra sites (r² = 0.833, p < 0.05, n = 5).
Fig. 7. Relationships between the N, Mg, Ca and K concentrations in surface mineral soils and the respective nutrient concentrations in phyllole litterfalls in some *A. mangium* stands. A solid line represents the best fit linear regression ($y = -0.486 + 23.3x$, $r^2 = 0.912$, $p < 0.01$, $n = 6$). The values for surface soil N, Mg, Ca and K concentrations were 2.58 mg g$^{-1}$, 0.865, 2.43 and 0.412 cmolc kg$^{-1}$ (at 0–15 cm) in this study site (Yamashita unpublished data 2008), 2.29 mg g$^{-1}$, 0.321, 0.710 and 0.142 cmolc kg$^{-1}$ (at 0–15 cm) in South Sumatra (Hardiyanto et al. 2004), 1.40 mg g$^{-1}$, 1.71, 2.52 and 0.210 cmolc, kg$^{-1}$ (at 0–15 cm) in Sabah (Majalap 1999), 1.73 mg g$^{-1}$, 2.89, 4.69 and 0.213 cmolc, kg$^{-1}$ (at 0–15 cm) in Sabah (Inagaki & Titin 2009), and 0.300 mg g$^{-1}$, 0.600, 0.600 and 0.0200 cmolc, kg$^{-1}$ (at 0–20 cm) in Rio de Janeiro (Andrade et al. 2000), respectively. If values at corresponding soil depth (0–15 cm) were not presented in literatures, volume-weighted mean concentrations were calculated.

Table 5. Amounts of dry mass and N accumulation on the forest floor and residence times for dry mass and nutrients in litter layer in some *A. mangium* plantations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Soils type</th>
<th>RF</th>
<th>Temp</th>
<th>Age</th>
<th>Litter layer amounts</th>
<th>Residence times*</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Sumatra, Indonesia</td>
<td>Oxisols</td>
<td>2420–3682</td>
<td>25.2</td>
<td>7</td>
<td>11.3 235</td>
<td>0.860 0.15 0.670 0.394 0.363</td>
<td>This study</td>
</tr>
<tr>
<td>Pointe Noire, Congo</td>
<td>Psamments</td>
<td>1250</td>
<td>25.0</td>
<td>8</td>
<td>8.8 172</td>
<td>0.498 0.752 0.491 0.345 0.220</td>
<td>Bernhard-Reversat (1993, 1996)</td>
</tr>
<tr>
<td>Rio de Janeiro, Brazil</td>
<td>Alfsols</td>
<td>1250</td>
<td>16.0–32.0</td>
<td>4</td>
<td>13.6 251</td>
<td>1.24 1.31 – – –</td>
<td>Andrade et al. (2000)</td>
</tr>
<tr>
<td>Sabah, Malaysia</td>
<td>Ultisols</td>
<td>2572</td>
<td>27.9</td>
<td>20</td>
<td>10.0 129</td>
<td>0.784 0.576 0.731 0.710 0.458</td>
<td>Inagaki &amp; Titin (2009) Inagaki et al. (2010)</td>
</tr>
<tr>
<td>Pahang, Malaysia</td>
<td>Ultisols</td>
<td>2100</td>
<td>27.0–33.0</td>
<td>4</td>
<td>7.06 128</td>
<td>0.690 0.840 0.324 0.597 0.534</td>
<td>Lim (1988a)</td>
</tr>
</tbody>
</table>

*: If residence times are not available, values are obtained from amounts of dry masses or nutrient inputs via litterfall and amounts of dry masses or nutrient accumulations in litter layer.
were considerably different depending on each nutrient element. N and Mg releases from litter layer increased in synchrony with increasing nutrient demands in rainy seasons, irrespective of stand maturity. While, the irregular seasonal pattern of Ca release from litter layer may become more pronounced with stand age associated with the increasing woody litterfall inputs. Also the K release from litter layer may become apparent with stand maturity reflecting the increasing reproductive litterfall rich in K. The increased K release from dry to wet seasons may pose a potential risk of temporal asynchrony between K supply and demand for plants.

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