 DOI: 10.11598/btb.2022.29.1.1627

LITTERFALL, LITTER DECOMPOSITION AND NUTRIENT RETURN OF REHABILITATED MINING AREAS AND NATURAL FOREST IN PHANGNGA FORESTRY RESEARCH STATION, SOUTHERN THAILAND

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Received 3 August 2021 / Accepted 20 December 2021

ABSTRACT

Litterfall and litter decomposition play important roles in the maintenance of nutrient cycling and rehabilitation of degraded lands. Litterfall, litter decomposition and nutrient return were investigated in a 27-year-old *Acacia mangium* plantation on sandy and clay sites, and in a mixed plantation at the Phangnga Forestry Research Station, Phangnga Province, Thailand. Additionally, secondary and primary forests were investigated and compared with the values obtained from the *Acacia mangium* and the mixed plantations. The results indicated that litter production in *A. mangium* plantation on sandy and clay sites, and in mixed plantations (15.47, 11.68 and 7.89 t/ha/yr, respectively) was higher than that in the secondary and primary forests (6.34 and 6.92 t/ha/yr, respectively). The rate of litter decomposition was the greatest in the secondary forest (3.01/yr) and the lowest occurred in the primary forest (1.15/yr). The decomposition rate of the mixed leaf litter between native trees and *A. mangium* in plantations was higher than that of only *A mangium* leaf, except in the mixed plantations. A high initial nitrogen concentration in *A. mangium* could accelerate litter decomposition and improve litter quality in the mixed litter. In addition, the nutrient return in plantations was higher than that in the secondary and primary forests, especially for N. Increased litter production, high decomposition rate and nutrient return from *A. mangium* plantation had important roles in nutrient cycling, suggesting that a mixed plantation consisting of *A. mangium* and native trees should be considered for the reclamation of mining land.

Keywords: litter decomposition, litterfall, mining rehabilitation, nutrient return, tropical forest

INTRODUCTION

Mining operations have been undertaken on a global scale as the raw minerals obtained play an important role in economic and infrastructure development. A high level of mineral production has been reported in Asian countries (Reichl *et al.* 2017). The ill-effects of mining cause severe impacts on the ecosystem, including soil degradation, water and air pollution, and loss of wildlife habitat. The vegetation richness and soil properties are destroyed by mining activities, resulting in the degradation of the ecosystem (Bell & Donnelly 2006; Tripathi *et al.* 2016). Improving environmental conditions in mining areas using natural methods takes a long time (Oktavia *et al.* 2015). Barriers to natural regeneration include environmental factors such as water, soil pH and soil properties (Thaiutsa & Rungruangsilp 1990; Tripathi *et al.* 2016).

Forest plantations have been established on degraded lands to improve the soil properties and ecosystem function (Singh *et al.* 2004; Zhang *et al.* 2014; Oktavia *et al.* 2015). Rehabilitation in such areas by planting nitrogen-fixing trees has been recommended and they have been planted on many sites as

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they grow well and have a high aboveground biomass and litter production (Dutta & Agrawal 2003; Singh *et al.* 2004). *Acacia mangium* is the most preferred species for reclamation efforts in mining land (Martpalakorn 1990; Oktavia *et al.* 2015) and other degraded lands (Kamo *et al.* 2008). Soil properties and microclimate under such plantations are improved, resulting in the accelerated natural regeneration of native forest species (Parrotta 1999; Inagaki *et al.* 2010).

Litter production and decomposition play important roles in nutrient cycling and the improvement of soil fertility in terrestrial ecosystems (Goma-Tchimbakala & Bernhard-Reversat 2006; Paudel *et al.* 2015). On degraded lands, litterfall and litter decomposition are keys to restoring the ecology and soil properties because the litter is a nutrient source (Lugo 1992; Parsons & Congdon 2008). Nutrient contents of plants are closely related to tree species, especially nitrogen which is abundant in nitrogen-fixing trees (Parrotta 1999; Singh *et al.* 2004). Tree composition and forest type are the main factors influencing the quality of the litter produced (Parrotta 1999; Zhou *et al.* 2006; Tang *et al.* 2010; Paudel *et al.* 2015). In addition, climatic factors can significantly affect litterfall (Zhou *et al.* 2006; Scherer-Lorenzen *et al.* 2007; Triadiati *et al.* 2011). Litter fractions that fall onto the forest floor are decomposed by organisms living in the soil, and nutrients are subsequently released to the forest floor, resulting in the improved soil properties and a better forest community, which maintain forest function (Parrotta 1999). Litter quality and microclimate are related to the litter decomposed by soil microbes (Parsons & Congdon 2008; Cizungu *et al.* 2014; Zhong *et al.* 2017). Furthermore, litter decomposition varies depending on the tree species, successional stage, and forest type (Lugo 1992; Parsons & Congdon 2008; Tang *et al.* 2010).

The efficiency of plantations in degraded land rehabilitation not only builds productivity and improves forest structure but also increases forest function such as nutrient cycling (Lugo 1992; Parrotta 1999). A high litter decomposition rate and nutrient return encouraged natural succession and increased soil nutrients (Lugo 1992; Celentano *et al.* 2011), which reduced the time required for the restoration process. Therefore, the objective of the current study was to evaluate the potential of *A. mangium* plantation for mining rehabilitation, focusing on litter production, decomposition and nutrient return in comparison to secondary and primary forests. An effort has been made to compare the rehabilitated plantation area to secondary and primary forests.

MATERIALS AND METHODS

Study Sites

This study was carried out in an abandoned tin mining area, in the Phangnga Forestry Research Station, Phangnga Province, Southern Thailand (8°46′5″N, 98°16′7″E) (Fig. 1). Exotic trees, such as *Acacia mangium* and *Eucalyptus camaldulensis* were commonly planted for tin mining reclamation in Thailand. The mining was operated by the gravel pumping method. Landform after mining was divided into clay, sand, and gravel areas. Soil nutrients were observed to be very low (Thaiutsa & Rungruansilp 1990). The experimental plots were established in a 27-year-old *A. mangium* plantation, planted in a sandy soil area (AMS), in a clay soil area (AMC), and mixed plantation (MP). The planted trees in MP consisted of *A. mangium*, *Eucalyptus camaldulensis* and *Dipterocarpus alatus*.

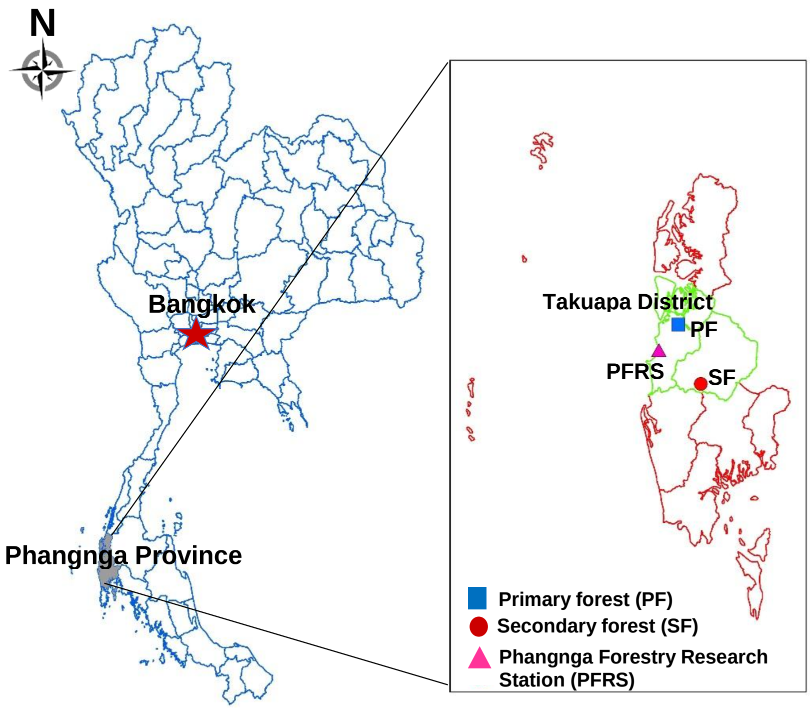

Figure 1 Location of study sites in Phangnga Province, Southern Thailand

In addition, the experimental plots were established in a secondary forest (SF, located at 8°39'28″ N, 98°24′35″ E) and a primary forest (PF, located at 8°51'11″ N, 98°20′5″ E) as reference sites. The SF plot was in an approximately 30-year-old site abandoned after shifting cultivation. The PF plot was classified as a low tropical rainforest. Dominant native trees in the 27-year-old plantations and the secondary forest were pioneer tree species including *Carallia brachiata*, *Aporosa planchoniana*, *Bridelia tomentosa*, *Vitex pinnata*, *Microcos paniculata* and *Eurya acuminata*. Meanwhile, dominant trees in PF were *Swintonia schwenckii*, *Dipterocarpus kerrii*, *Mesua ferrea*, *Hopea griffithii* and *Gluta elegans*. Tree composition and dominant trees in AMS, AMC, MP, SF and PF were reported by Wongprom *et al.* (2020).

Climatic conditions during the study were recorded at the climate station in the Takuapa District. The rainfall was 3,260.10 mm with the rainy season occurring from April to November and the dry season happening from December to March. The mean relative humidity was 83% and the mean temperature was 27.58 °C. Data on rainfall, mean temperature and relative moisture recorded during the study are shown in Figure 2.

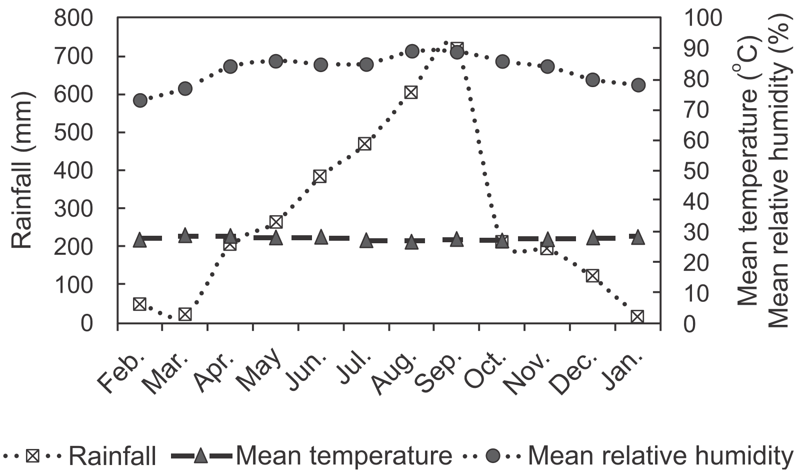

Figure 2 Climatic conditions at Takuapa District, Phangnga Province during the study

Litter Production

Three experimental plots (each 40 x 40 m) were established in each AMS, AMC, MP, SF, and PF for estimating the amount of litterfall production. Five litter traps (each 1 x 1 m) with a 2 mm mesh size were placed 1 m above the ground in each plot. Litterfall in the traps was collected monthly for 1 year. Litterfall samples were sorted into leaf, branches, reproductive parts and miscellaneous. *A. mangium* litter was separated from that of the other tree species. All samples were oven-dried at 80 °C for 48 h until reaching constant weight. The samples (leaf, branches, reproductive parts and miscellaneous) were analyzed during both the rainy and dry seasons. The organic debris obtained from each site was analyzed as a single sample, as it was difficult to identify the components as they were very small and had a similar texture.

Litter Decomposition and Nutrient Return

Nylon bags (50 x 50 cm) with a 2 mm mesh size were used for investigating litter decomposition. Leaf having the top five Importance Value Index (IVI) trees in AMS, AMC, MP and SF, and the top seven IVI trees of PF were selected to investigate litter decomposition. Litter decomposition was divided into two classes: 1) mixed leaf litter in AMS, AMC, MP, SF and PF; and 2) pure *A. mangium* leaf litter in AMS, AMC, and MP. In each case, 30 g samples of air-dried leaf litter were filled into the nylon bags according to the IVI ratio of the dominant trees for each site. The IVI of trees in AMS, AMC, MP, SF and PF was reported by Wongprom *et al.* (2020). The litter water content was determined by first, oven-drying subsamples of air-dried litter at 80 °C for 48 h to obtain the initial dry mass. Twelve litter bags from each treatment with three replications were randomly placed in each plot. Three samples of both mixed leaf litter and pure *A. mangium* leaf litter were retrieved monthly. The leaf litter remaining in each bag was brushed to remove any soil particles and roots. The remaining litter was oven-dried at 80 °C for 48 h until a constant weight was recorded.

The annual litter decomposition rate (k) was calculated according to the negative exponential decay model (Olson 1963) given as $k = \ln(X/X_0)/t$, where X_0 is the initial dry weight, X is the dry weight remaining at the end of the study, and t is the time period in years. Nutrient return (N, P, K, Ca, and Mg) to the forest floor (kg/ha) was estimated by multiplying the amount of litter production by the nutrient concentration of litter for each site.

Chemical Analysis of Litter

Nutrient concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) of leaf, branches, reproductive parts and miscellaneous obtained from the study sites were determined during the rainy (April to November) and dry (December to March) seasons. Samples of each litter type in the rainy and dry seasons were mixed and analyzed. The concentration of N was measured based on dry combustion using a CNHS analyzer, while the concentrations of P, K, Ca, and Mg were determined by wet washing with NHO_3-$HClO_4$ acid (HNO_3: $HClO_4$; 5: 2). The concentration of P was analyzed using the vanadomolybdate yellow color method with a spectrometer at a wavelength of 440 nm, while the concentrations K, Ca, and Mg were analyzed using atomic absorption spectrometry.

Data Analysis

Nutrient concentrations of each litter sample during the rainy and dry seasons were averaged to calculate the amount of nutrients return. The annual litter production, nutrient return and litter decomposition rate among sites were analyzed using a one-way ANOVA and the means were compared with the Tukey HSD test at a 5% probability level.

RESULTS AND DISCUSSION

Litter Production

The annual litter production was significantly different among sites ($P < 0.05$). AMS had the highest litterfall followed by AMC, MP, PF, and SF (Table 1).

Table 1 Litter production (leaf, branches, reproductive parts and miscellaneous) (t/ha/yr) of *A. mangium* (AM) and native trees and planted trees (NPT) in the 27-year-old *A. mangium* plantation in sandy soil area (AMS), clay soil area (AMC), mixed plantation (MP), secondary forest (SF), and primary forest (PF)

Site	Leaf		Branches		Reproductive parts		Miscellaneous	Total
	AM	NPT	AM	NPT	AM	NPT		
AMS	5.90^{a}	2.85^{b}	0.74	1.67	2.86^{a}	0.57	0.88^{a}	15.47^{a}
AMC	3.56^{ab}	3.83^{ab}	0.56	1.20	1.60^{b}	0.50	0.43^{b}	11.68^{b}
MP	1.52^{b}	2.86^{b}	0.59	1.06	0.84^{b}	0.51	0.51^{ab}	7.89^{c}
SF	-	4.12^{ab}	-	0.76	-	0.74	0.72^{ab}	6.34^{c}
PF	-	4.72^{a}	-	0.89	-	0.72	0.59^{ab}	6.92^{c}
F value	11.59**	8.03**	1.83^{ns}	0.87^{ns}	16.55**	2.02^{ns}	4.58*	27.21**

Notes: * = significant difference; ** = very significant difference; ns = non-significant difference; a - c = different superscripts in the same column indicate significant differences at $P < 0.05$.

Litter production peaked in the dry season (December to March) (Fig. 3), as a response to the water stress, which was similar to that of other tropical forests (Triadiati *et al.* 2011; Cizungu *et al.* 2014). Leaf component was the main litter falling onto the forest floor in AMS, AMC, MP, SF and PF, and made up around 54 to 62% of the total litter. However, the amount of reproductive parts in AMS and AMC was relatively high compared to branches, especially the reproductive parts of *A. mangium* as it fell almost all year. A large amount of litter from *A. mangium* in AMS was resulted from the high tree density and crown cover, while *A. mangium* in AMC and MP had a low crown cover due to the high mortality rate. Litters from other trees in AMS, AMC, and MP came from native tree species. Planted trees in MP such as *D. alatus* and *E. camaldulensis* were also a main source of litter. Leaf litter is a significant contributor of annual primary production and nutrient capital in a terrestrial ecosystem (Cizungu *et al.* 2014; Paudel *et al.* 2015).

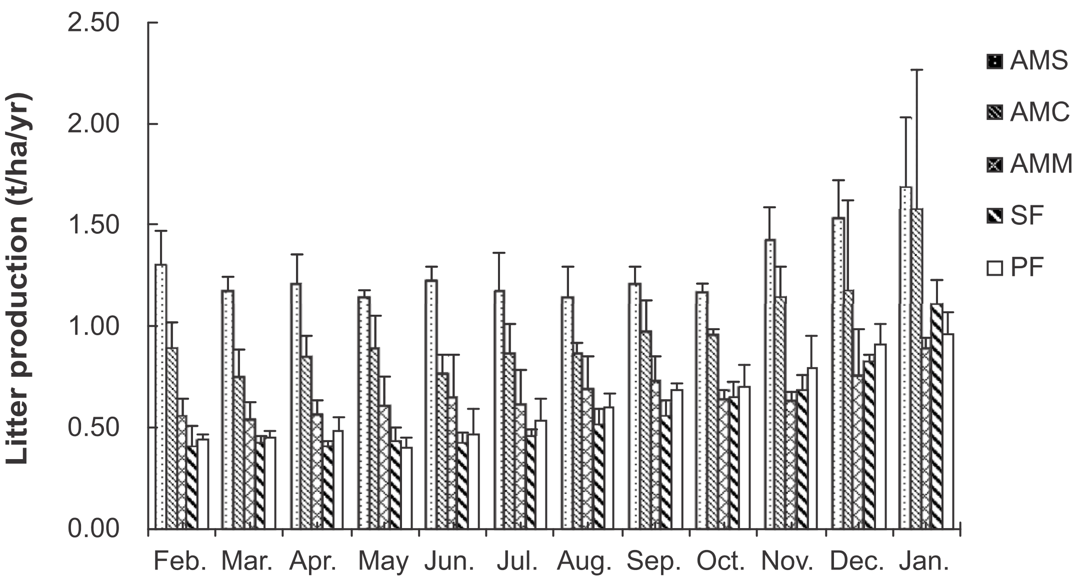

Figure 3 Total monthly litter production (t/ha/yr) of the 27-year-old *A. mangium* plantation in sandy soil area (AMS), clay soil area (AMC), mixed plantation (MP), secondary forest (SF), and primary forest (PF)

This study showed that the amount of litter production in AMS and AMC was higher than that in both SF and PF. A forest plantation with fast-growing trees is highly effective at building litter production compared to a natural forest (Goma-Tchimbakala & Bernhard-Reversat 2006) and secondary forest (Lugo 1992; Kamo *et al.* 2008). Post mining reclamation should focus on increasing the aboveground biomass and litter production to improve the ecosystem. *A. mangium* is one species recommended for degraded land restoration. Acacia grows well and has high aboveground biomass compared to native trees (Martpalakorn 1990; Kamo *et al.* 2008). However, the total litter production in MP was similar to that in PF and SF, although *A. mangium* had less litter production. The canopy cover of *A. mangium* can promote a high litterfall. Fast nitrogen-fixing tree plays important role in the early stage by rapid growth to create a canopy in order to suppress the weeds and shrubs that could obstruct the establishment of native tree understory vegetation and to increase nitrogen availability (Ingaki *et al.* 2010; Lanuza *et al.* 2018). However, the litterfall in AMS, AMC and MP was not only sourced from planted trees but also native trees through natural succession. Old plantations have high tree diversity and richness (Lugo 1992; Koonkhunthod *et al.* 2007), as litterfall is contributed to by native trees. Native tree species are usually pioneer trees having high growth rates (Chazdon 2014; Chen *et al.* 2017) and their litter production increases with succession age (Zhou *et al.* 2006; Feng *et al.* 2019). Litterfall production plays an important role in forest functions such as carbon and nutrient cycling (Moura *et al.* 2016; Paudel *et al.* 2015; Lanuza *et al.* 2018) because litter is a source of nutrient pools, which releases nutrient to the forest floor via litter decomposer activities (Lugo 1992; Fisher & Binkley 2000), suggesting that *A. mangium* should be recommended for reclamation in a mining area due to the capability of *A. mangium* in bringing out high litter production.

Litter production in the SF and PF study sites was not different, resulting from pioneer trees producing litter in natural succession. Forest structure and tree composition of succession forests affected litter biomass (Lanuza *et al.* 2018). Long-lived pioneer trees and high tree diversity were observed in SF. The litter production in the SF and PF study sites was similar to that in many evergreen forests in Thailand (6.42 to 7.85 t/ha/yr) (Bunyavejchewin 2001; Glumphabutr *et al.* 2007). However, litter production in our study was lower than that in other tropical forests (8.30 - 13.67 t/ha/yr) (Anderson *et al.* 1983; Tang *et al.* 2010; Triadiati *et al.* 2011; Paudel *et al.* 2015).

Litter Decomposition

Litter decomposition of pure litter and mixed litter was significantly different among treatments ($P < 0.05$). The litter decomposition rate (*k*) ranged between 1.15 and 3.01/yr, which was classified as medium to high levels. The decomposition rate in SF was the highest, indicating litters were rapid litter decay, but not different in AMC (2.91/yr) (Table 2).

The dominant trees in SF and AMC were pioneer tree species and were of similar tree composition (Wongprom *et al.* 2020), having thin and flexible leaves without a prominent skeleton, and so could decay easily. On the other hand, a low rate of decomposition was found in climax forest trees due to their thick, tough leaf and prominent midribs and veins. The leaf morphology of trees (leaf thickness, roughness, toughness) significantly affects the rate of litter decomposition (Liao *et al.* 2006; Cizungu *et al.* 2014). In addition, the chemical properties of leaf litter, including high N, N/P, low C/N and low lignin, are generally positive contributors to decomposition (Xuluc-Tolosa *et al.* 2003; Liao *et al.* 2006; Cizungu *et al.* 2014; Rai *et al.* 2016). Similarly, leaf litter in SF, AMS, AMC, and MP had a high nitrogen content, which could explain their faster rate of decomposition. Leaf litter in AMS, AMC, and MP was rich in nitrogen due to the litter produced by *A. mangium*. In addition, leaves of dominant pioneer trees in SF, AMS AMC and MP have thin and less rigid leaves leading to a high decomposition rate compared to PF. However, the litter decomposition of PF was of moderate level (1.15/yr), which was similar to other climax tropical forests (Hättenschwiler *et al.* 2011).

Table 2 Decomposition rate of pure *A. mangium* and the mixed leaf in the 27-year-old *A. mangium* plantation in sandy soil area (AMS), clay soil area (AMC), mixed plantation (MP), secondary forest (SF), and primary forest (PF)

Site	Type of leaf	*k* (constant)
AMS	Pure *A. mangium* leaf	1.56^{bc}
	Mixed leaf	1.64^{bc}
AMC	Pure *A. mangium* leaf	1.88^{bc}
	Mixed leaf	2.91^{a}
MP	Pure *A. mangium* leaf	2.05^{b}
	Mixed leaf	1.87^{bc}
SF	Mixed leaf	3.01^{a}
PF	Mixed leaf	1.15^{cd}
F value		7.905^{*}

Notes: * = significant difference; a - d = different superscripts in the same column indicate significant differences at $P < 0.05$.

Climate conditions and soil microbials significantly affect litter decomposition (Berg & McClaugherty 2008). This study indicated that rainfall and relative humidity in the study sites were of similar conditions. However, soil microbials could be different because soil properties in AMS, AMC, and MP were of poor soil compared to that in SF and PF, especially in terms of total N and OM (Wongprom *et al.* 2020), leading to low diversity and abundance of soil microbials (Zhang *et al.* 2016). Soil nutrients, N and P and Organic Matter (OM) are significantly correlated with soil microbials (Zhang *et al.* 2016; Ngugi *et al.* 2020). Low decomposition rate of litter was found in the PF study site. Microclimate conditions may slightly affect litter decomposition. Litter quality of the restored forest may significantly determine litter decomposition. Meanwhile, litter decomposition rate changes depending on successional stage and tree composition (Moura *et al.* 2016; Lanaza *et al.* 2018). A study conducted by Xuluc-Tolosa *et al.* (2003) indicated that pioneer trees in the early succession phase has a higher decay rate than tree species in the late succession phase because pioneer trees have a high initial N concentration and low C/N. Pioneer tree species have high nutrient resorption efficiency and high leaf nutritional quality, especially N concentration (Gomes & Luizão 2012). Our study showed that a litter mixture of *A. mangium* and native trees generally resulted in a faster decay than the decay of PF litter. This result could be affected by synergistic effects of mixed litter with high litter quality and a high initial N concentration. Mass loss is positively correlated with initial N concentration (Liu *et al.* 2016). Thus, poor litter quality is improved. Mixing litters from various trees accelerate the mass loss, enhance the nutrient release and nutrient cycling (Liu *et al.* 2016; Trogisch *et al.* 2016; Cizungu *et al.* 2016) and different litter components may change the litter chemical components and the decomposer community (Gartner & Cardon 2004).

Nutrient Concentration in Litter and Nutrient Return

Nutrient concentration in litter produced by *A. mangium* in this study varied among components (leaf, branches and reproductive parts). However, the N concentration was greater than that of P, K, Ca, and Mg (Fig. 4). Nutrient concentration in the leaf and branches litters of *A. mangium* in all sites followed the order of N>Ca>K>Mg>P, except for the reproductive parts, where the K concentration was higher than that of Ca.

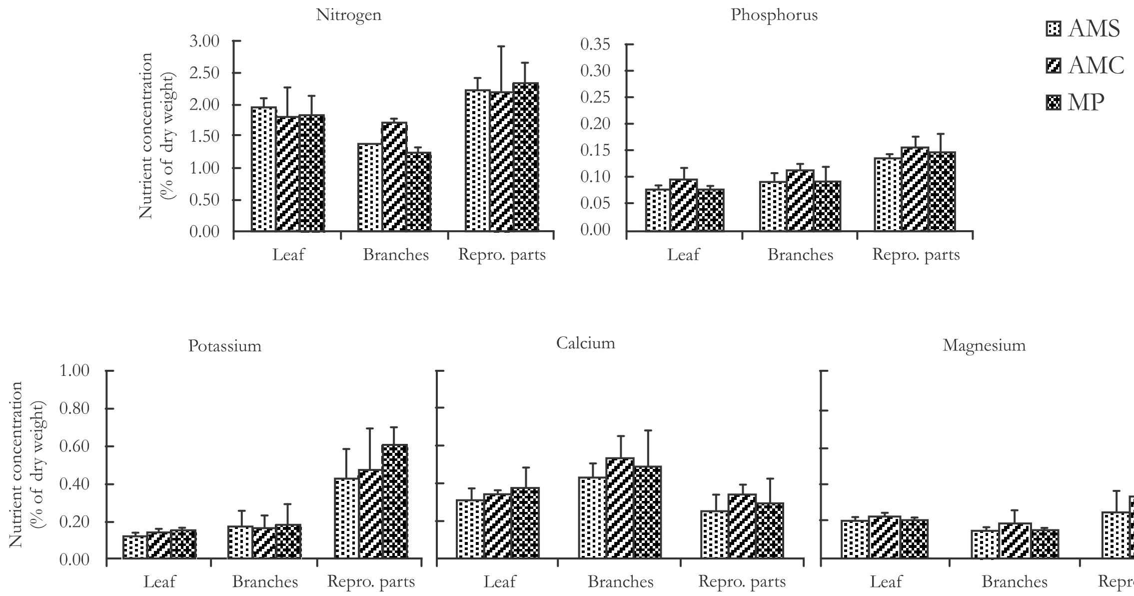

Figure 4 Nutrient concentration of pure *A. mangium* leaf, branches and reproductive parts of the 27-year-old *A. mangium* plantation in sandy soil area (AMS), clay soil area (AMC) and mixed plantation (MP)

N concentration in the litter of other trees (native tree species in AMS, AMC, MP, SF and PF, and planted trees in MP) was the highest for all litter components, and was especially high in the litter miscellaneous component. The P concentration was relatively high in the miscellaneous and reproductive parts components, while the concentrations were similar for K, Ca and Mg in the leaf, branches, reproductive parts and miscellaneous components. The nutrient concentration of leaf, branches, reproductive parts and miscellaneous for the other tree species in AMS, AMC, MP, SF, and PF are shown in Figure 5.

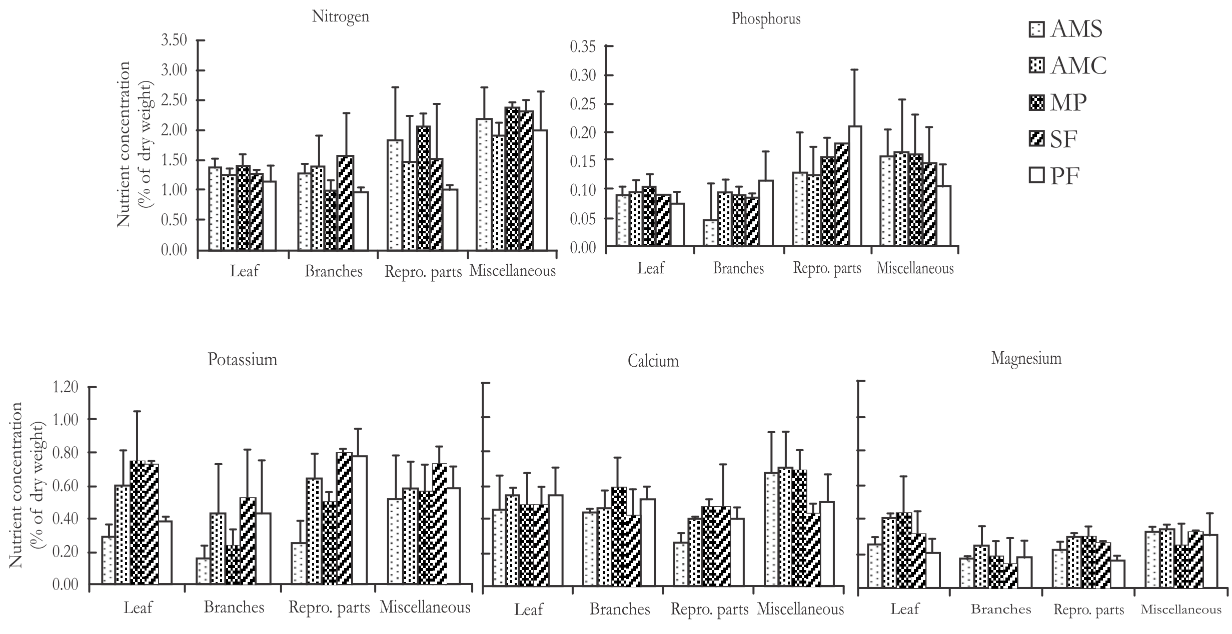

Figure 5 Nutrient concentration of mixed leaf, branches, reproductive parts and miscellaneous litter of native tree species in the 27-year-old *A. mangium* plantation in sandy soil area (AMS), clay soil area (AMC), secondary forest (SF), and primary forest (PF) and planted trees and native tree species in mixed plantation (MP)

The nutrient return of N, P, K, Ca and Mg from litters to forest floor was significantly different among sites. N contributed the highest nutrient return to the forest floor in all sites. The large amounts of N, P, K, Ca and Mg returned in AMS, AMC, and MP were mostly from the litter of the planted trees, especially *A. mangium* (Table 3).

A. mangium is the dominant tree with a large size and crown cover, although the tree density is low, particularly in the AMC and MP sites (Wongprom *et al.* 2020). Litters from planted trees in a plantation are still the main nutrient source to the forest floor, although the vegetation composition are shifted after restoration. Leaf litter was the main source of nutrient return in all sites. However, nutrient return from miscellaneous and reproductive parts of *A. mangium* was relatively high. The annual nutrient return of AMS, AMC and PF followed a pattern of N>Ca>K>Mg>P, while that of MP and SF followed a pattern of N>K>Ca>Mg>P (Table 4). The annual nutrient return of N, P, Ca and Mg to forest floor in AMS and AMC was significantly higher than that in SF and PF, especially for the nitrogen. Meanwhile, the annual nutrient return of N, P, Ca, and Mg in SF was similar to that in PF.

Forest community on a restored site and in a secondary forest can accelerate litter decomposition and nutrient cycling because the litter quality is improved. Nutrients returned to the forest floor can promote natural regeneration and tree growth, resulting in a complex forest structure in the long term, especially as N is a significant nutrient in developing a forest community and establishing seedlings and saplings during mining restoration and natural succession in a degraded land (Zhao *et al.* 2013; Lei *et al.* 2015). Fast litter decomposition of restored sites resulted in high nutrient depositions, especially N.

In the current study, N was the major nutrient return in AMS, AMC and MP, and was significantly higher than that in SF and PF. The high N return may be resulted from *A. mangium* due to the Acacia being a nitrogen-fixing tree. Moreover, the return of P, K, Ca and Mg to the soil of the rehabilitated sites was greater than that in PF. Soil nutrients of *A. mangium* plantation in an abandoned mining area are higher compared to that in an abandoned mining area without the *A. mangium* plantation, especially in terms of N and soil organic matter (Wongprom *et al.* 2020). Therefore, the study result indicated that *A. mangium* improves soil chemical properties through nutrient cycling processes. N flux of nitrogen-fixing tree plays an important role in the early succession (Moura *et al.* 2016).

Table 3 Nutrient return (kg/ha/yr) of *A. mangium* (AM) litter and native trees and planted trees (NPT) litter in the 27-year-old *A. mangium* plantation in sandy soil area (AMS), clay soil area (AMC), and mixed plantation (MP)

Site	N		P		K		Ca		Mg	
	AM	NPT	AM	NPT	AM	NPT	AM	NPT	AM	NPT
AMS	18.96^{a}	7.12	0.94^{a}	0.49	2.07^{a}	1.48^{b}	2.92^{a}	2.14^{ab}	1.91^{a}	1.20^{b}
AMC	10.97^{a}	6.52	0.68^{a}	0.52	1.37^{a}	2.93^{a}	2.08^{ab}	2.64^{a}	1.41^{a}	1.94^{a}
MP	5.47^{b}	6.42	0.30^{b}	0.49	0.85^{b}	2.73^{a}	1.11^{b}	1.91^{b}	0.62^{b}	1.56^{ab}
F value	26.37**	1.09^{ns}	18.39**	0.37^{ns}	14.95**	29.01**	14.48**	6.19*	15.66**	12.36**

Notes: * = significant difference; ** = very significant difference; ns = non-significant difference; a - b = different superscripts in the same column indicate significant differences at $P < 0.05$.

Table 4 Nutrient return (kg/ha/yr) of litter to the forest floor in the 27-year-old *A. mangium* plantation in sandy soil area (AMS), clay soil area (AMC), mixed plantation (MP), secondary forest (SF), and primary forest (PF)

Site	N	P	K	Ca	Mg
AMS	26.09^{a}	1.43^{a}	3.56^{b}	5.06^{a}	3.12^{a}
AMC	17.49^{b}	1.19^{a}	4.30^{a}	4.72^{a}	3.36^{a}
MP	11.89^{c}	0.79^{b}	3.58^{b}	3.03^{b}	2.18^{bc}
SF	8.26^{c}	0.63^{b}	4.21^{ab}	2.72^{b}	1.74^{bc}
PF	7.47^{c}	0.61^{b}	2.77^{c}	3.20^{b}	1.28^{c}
F value	53.60**	33.78**	15.87**	22.75**	34.63**

Notes: ** = significant difference; a - c = different superscripts in the same column indicate significant differences at $P < 0.05$.

Fast-growing tree plantations are commonly planted for wood production. However, they are also planted for forest restoration in degraded lands. High litter production and litterfall are significant parts in restoration processes (Parrotta 1999). The N nutrient returned to the forest floor from nitrogen-fixing tree plantations was significantly higher than that from a non-nitrogen-fixing tree plantations and for other nutrients (Bernhard-Reversat 1996). The litter decomposition of nitrogen-fixing trees positively affect the acceleration of nutrient release and nutrient deposition to promote vegetation development and improve soil properties (Lugo 1992; Ruiz-Jaén & Aide 2005; Lanuza *et al.* 2018), suggesting that *A. mangium* plantation should be used for improving nutrient cycling in mining reclamation. Nutrient cycling is a key process for mining rehabilitation, relating to vegetation succession and soil development in the mining area.

CONCLUSION

A. mangium plantation is an effective way for mining rehabilitation compared to the reference sites. *A. mangium* plantation showed relatively high litter production and litter decomposition rate which could modify the litter quality in the litter mixture. Mixed litter sourced from nitrogen-fixing trees and native trees in plantations can enhance litter decomposition, which can result in higher levels of soil improvement and revegetation. AMS, AMC and MP had high levels of nutrient return compared to that in SF and PF, leading to contributing high levels of soil nutrients to forest floor, particularly N. The litter mixture in MP decomposed more rapidly compared to that in PF with improved the litter quality. A mixed plantation consisting of *A. mangium* and native tree species could be considered for reclamation efforts in mining area and other similar degraded lands.

ACKNOWLEDGMENTS

Financial support for this study was provided by the Kasetsart University Research and Development Institute (KURDI) in Bangkok, Thailand. We are grateful to the staff at the Phangnga Forestry Research Station for their assistance during the field work.

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