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Contribution of Harvest Residues to Nutrient Cycling in a Tropical *Acacia mangium* Willd. Plantation

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Abstract: Harvest residues can play a crucial role in conserving nutrients for recycling in forests, but little is known about the rates of decomposition and nutrient release from these residues following logging in tropical acacia plantations. In this study, we examined the biomass and nutrient content of harvest residue components (bark, leaves, and branches) using the litterbag technique for a 1.5-year-period following harvest of a seven-year-old *Acacia mangium* plantation in Northern Vietnam. At harvest, the total dry biomass of harvest residues was 18 t ha^{-1} comprising bark (8.9 t ha^{-1}), branches (6.6 t ha^{-1}), and leaves (2.5 t ha^{-1}). The retained bark on site conserved 51% N, 29% P, 32% K, 64% Ca, and 24% Mg content from harvest residues for recycling. Decomposition rate of the leaves was the most rapid (k = 1.47 year^{-1}; $t_{0.5}$ = 0.47 year), then branches (k = 0.54 year^{-1}; $t_{0.5}$ = 1.29 year), and bark (k = 0.22 year^{-1}; $t_{0.5}$ = 3.09 year). During decomposition, the loss of nutrients from harvest residues was K ≈ Ca > N > P > Mg. Decomposition of harvest residues and the associated rate of nutrient release can potentially supply a significant amount of nutrients required for stand development in the next rotation.

Keywords: nutrient loss; mass loss; nutrient release; nutrient dynamics; decay constant; residue half-life; nutrient cycling; tropical plantation

1. Introduction

In Vietnam, plantations are typically clear-felled at the end of the rotation. The stemwood that is down to 3 cm in diameter (over bark) is exported from the site as a harvest product [1,2]. Bark is often removed from the site with the commercial logs and sold for the production of charcoal, tannin, and garden compost [3–5], or is stripped after harvesting at the edge of the site or in a nearby wood yard, and not distributed over the logging area. The non-commercial logs and branches may be collected by locals for firewood, and the site subsequently burnt [6]. There are concerns that these practices may degrade the productive potential of the site over successive rotations [6–9]. While burning can initially improve soil fertility, it can also lead to large losses of N via volatilisation [10–13], and P, Ca, and K through leaching, as well as water and wind erosion [13–15]. Retention of harvest residues, especially bark, acts to conserve nutrients and leads to their controlled release in a way that minimizes losses from leaching and potentially supplies the amount of nutrients required for stand development

in the next rotation [16–20]. Hence, understanding decomposition rates and nutrient release from harvest residues, including bark, is important for informing residue and nutrient management over successive rotations.

Management of residues after harvesting has been shown to improve site fertility [6,13,21–23]. For example, retention of harvest residues, including bark, branches, and leaves of a *Eucalyptus grandis* Hill ex Maiden plantation in Brazil, resulted in soil organic carbon (TC) and soil nitrogen (TN) (0–5 cm soil depth) that were 33% and 43% higher, respectively, seven years after all harvest residues were removed [13]. Similarly, TC and TN (0–10 cm soil depth) increased by 17% and 11%, respectively, in a two-year-old *A. mangium* plantation in Sumatra, Indonesia, when harvest residues were retained rather than removed [21]. This is because decomposing harvest residues can provide a significant source of nutrients to the soil [16,17,23]. For example, harvest residues potentially contributed 176 kg ha^{-1} of N, 15 kg ha^{-1} of P and 276 kg ha^{-1} of K to soil fertility during the first year following harvest in a *Eucalyptus globulus* Labill. plantation in Western Australia [16], and 176, 20, 375, 460, and 92 kg ha^{-1} of N, P, K, Ca, and Mg, respectively, during the first two years following harvest in a *Eucalyptus dunnii* Maiden plantation in Uruguay [17]. Retention of harvest residues, therefore, can conserve nutrients for recycling.

Fast-growing short-rotation plantation species generally require large amount of nutrients to optimize yield [24]. The amount of nutrient uptake by tropical acacia trees is generally highest during the first three years after planting [1,21]; approximately 180, 7, 80, 90, and 23 kg ha^{-1} $year^{-1}$ of N, P, K, Ca, and Mg were respectively accumulated in the above-ground stand biomass of *A. mangium* at two years old [21]. Although the demand for P appears to be low in Vietnam, plantation soils are characteristically very low in soil P [1,25,26] and most forest growers can only afford to apply a small dose of fertilizer at planting [6,26,27]. As deficiency in P could be a concern in successive rotations of acacia [1,21], retention of harvest residues may provide a sufficient source of P as well as other nutrients which, given the limited soil nutrient pool, could support a demand that results in commercial rates of growth.

Harvesting of short-rotation plantations can be associated with the export of large quantities of organic matter and nutrients from the site [1,22,24]. For example, removal of stemwood without bark from a six-year-old *Acacia auriculiformis* A. Cunn. ex Benth. plantation in Southern Vietnam, led to the export of 135.2, 47.3, 115.3, and 15.7 kg ha^{-1} of N, P, K, and Ca, respectively [1]. Retention of bark on-site is potentially important, with the quantities of nutrients extracted by harvesting increasing to 256.5, 55.7, 155.6, and 41.1 kg ha^{-1} of N, P, K, and Ca, respectively, in the same plantation if stemwood with bark had been removed. Similarly, in a 10-year-old *A. mangium* plantation in Sumatra, Indonesia, harvesting stemwood with, rather than without bark, would have increased the export of N, P, K, Ca, and Mg by 55%, 15%, 52%, 97%, and 48%, respectively [21]. Although the bark of acacia trees represents only 9–10% of the total aboveground stand biomass (AGB) when trees are harvested, it contributed 19–24% of N, 7–11% of P, 15–17% of K, 30–36% of Ca, and 7–15% of Mg in the above studies [1,21]. As debarking on site at harvesting can substantially reduce the export of nutrients [1,21], the retention of bark and its even distribution across the site may potentially reduce the costs of fertilizer application in the next rotation.

Given that decomposition and nutrient release from plant materials are largely influenced by environment [28] and substrate quality [29–31], materials of lower nutrient content generally decompose more slowly, immobilize more nutrients during decomposition, and have slower rates of net mineralization than nutrient-rich materials [32]. Acacias are a N-fixing species, and therefore the concentration of N in a given material is generally higher in acacias than in other genera, such as eucalypts [33,34]. This may lead to different activities of microbial decomposers, and thus rates of decomposition and nutrient release. As little is known about the dynamics of nutrient release from the decomposition of acacia harvest residues, particularly bark residue [33–36], it is crucial to measure rates of decomposition and nutrient release from its various components, especially in tropical environments where the area of acacia plantation estates has grown rapidly.

Acacia plantations, including *A. mangium*, *A. auriculiformis*, and their hybrid, currently represent a significant proportion of the commercial forest in Vietnam [37] and are managed on a rotation length of 5–8 years for both pulp and timber production [6]. Most of the resource is currently in the second and third rotation, and their productivity varies from 10 to 25 m^3 ha^{-1} $year^{-1}$ [6,27], depending on site condition as well as management inputs. Sustaining the productivity of these plantations will rely on maintaining, and if possible increasing, the nutrient capital of the current forestry land base [6,37]. The objectives of this study were to evaluate the contribution of harvest residues, particularly the bark component, to nutrient cycling in these intensive short-rotation plantation systems. To this end, decomposition rates of harvest residues of *A. mangium* were quantified. The results from this study are expected to assist with optimizing residue management of short-rotation tropical acacia plantations.

2. Materials and Methods

2.1. Location and Site Description

The study site was located at Phuc, a commune in the Yen Binh district of Yen Bai province in Northern Vietnam (21°51′ N, 105°00′ E; 100 m above sea level). The climate is tropical with four distinct seasons. During the study period, the mean monthly temperatures ranged from 15 to 28 °C (average 22 °C), and the mean monthly rainfall ranged from 6.1 to 375 mm (average 144 mm) (Figure 1).

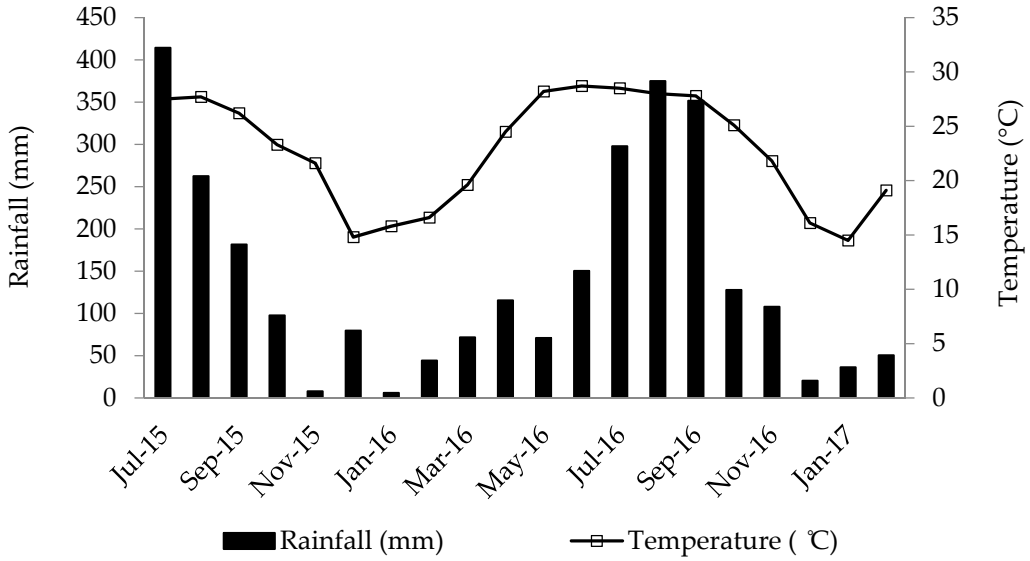

Figure 1. Average monthly temperatures (*continuous line*) and monthly rainfall (*vertical bars*) near the site during the experimental period.

The site is characterized by steep slopes that range from 10° (at the top of the hill) to 30°–40° (in the middle and at the bottom of the hill). The soil is classified as a Ferric (Ferralic) Acrisol [38] with a depth of ~0.5 m (in the middle and bottom of the hill) to 1 m (on top of the hill). The topsoil (0–10 cm depth) is acidic with a pH (1:5 water) of 3.8, a Bray extractable P of 4.04 mg kg^{-1} and soil organic carbon (TC) of 44 g kg^{-1} (Table 1). A more detailed description of soil properties is provided in Bich et al. [39].

Table 1. Soil chemical properties at the experimental site in Northern Vietnam. Standard errors are shown in parentheses (n = 5).

Soil Depth	pH	Total C	Total N	Total P	Bray Extractable P	Exchangeable Cations ($cmol_c$ (+) kg^{-1})		
(cm)	(1:5 Water)	g kg^{-1}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	K	Ca	Mg
0–10	3.79	44.36	2.10	0.09	4.04	0.12	0.70	0.45
	(0.03)	(2.57)	(0.09)	(0.00)	(0.51)	(0.01)	(0.11)	(0.09)
10–30	3.94	27.80	1.54	0.08	2.21	0.08	0.57	0.40
	(0.08)	(2.14)	(0.07)	(0.00)	(0.37)	(0.02)	(0.13)	(0.07)

In the 1980s, the area was converted from secondary forest (degraded natural forest) to a native tree plantation of *Styrax tonkinensis* (Pierre) Craib. Two successive rotations of *A. mangium* were then planted in 2000 and 2008. The second rotation was planted at a spacing of 2 m × 2.5 m and mixed with NPK fertilizer (17 kg ha^{-1} N, 15 kg ha^{-1} P, and 8 kg ha^{-1} K) at planting. During the April 2015 harvest, trees were aged seven years and had a mean annual increment (MAI) of 13.3 ± 2.3 m^3 ha^{-1} $year^{-1}$ based on measurements made on surface area rather than horizontal-projected area (noting that the horizontal projected area is less than the ground surface area because of the slope of the plots). The total aboveground stand biomass (AGB) was 60.8 t ha^{-1}, comprising stemwood (70%), bark (15%), branches (11%), and leaves (4%). The understory vegetation was high and dense, and dominated by woody shrubs and grass.

2.2. Estimation of Biomass and Nutrients in Harvest Residues, Litter and Understory Vegetation

In February 2015, 16 representative plots of 750 m^2 were established to determine stand growth and biomass accumulation in the second rotation. Height (H, m) and diameter (DBH, cm) at breast height (1.3 m) of all trees in the plots were measured. A total of 30 trees, covering the range of five diameter classes i.e., 6–9, 10–13, 14–17, 18–21, and 21–24 cm (six trees per diameter class), were randomly sampled for each diameter class to develop predictive models for calculating the biomass and nutrient content of the stand. The method for measuring the components of stand biomass is described in Huong et al. [1]. Briefly, after felling the tree, DBH and H (to a top end diameter of 3 cm) were measured. The tree was divided into five equal-length sections based on the tree height up to 3 cm in diameter over bark. Fresh biomass of stemwood, stem bark (manually stripped), branches, and leaves were weighed at the site and subsamples were then dried to a constant weight at 65 °C.

Forest floor litter and understory vegetation were assessed by sampling all biomass within five randomly located quadrats (16 m^2) in each plot. Litter was separated into woody (branches, stemwood plus bark) and non-woody (leaves, reproductive parts) materials, and the understory into woody and non-woody plants. Each part of the material (woody or non-woody) of the litter and understory vegetation component was weighed and a combined subsample of about 200 g from each part (woody or non-woody) of the components was selected for each plot (total of 32 subsamples per component). The subsamples were oven-dried at 65 °C to a constant weight.

The dry mass ratio of tree, litter, and understory components were used to calculate the total dry mass of each component. Subsamples of biomass components from two trees per diameter class (a total of ten trees) and of litter (16 subsamples of each woody and non-woody part), and understory vegetation (16 subsamples of each woody and non-woody plants) were ground to 0.02 mm particle size for nutrient analyses.

To estimate the biomass of harvest residue components, allometric relationships (equations) between DBH and biomass components of living trees were established (see Supplementary Figure S1) for bark ($y = 0.0208 \times DBH^{2.3914}$, $r^2 = 0.92$), branches ($y = 0.0044 \times DBH^{2.8555}$, $r^2 = 0.81$), and leaves ($y = 0.0020 \times DBH^{2.7966}$, $r^2 = 0.89$). Based on the allometric equations, biomass components were estimated for each individual tree in sample plots and were then summed to give plot totals and then expressed as total biomass per ha.

2.3. Rate of Decomposition and Nutrient Release of Harvest Residues (Branches, Leaves, and Bark)

The experimental site was initially established in a third rotation of the *A. mangium* plantation in June 2015 to examine the effect of residue management treatments and fertilizer application at planting on growth and soil properties. The details of the experimental design are presented in Bich et al. [39]. In brief, the design was 20 plots based on a randomized complete block design with five replications. Each replicate occupied a similar position in the landscape, with plots grouped according to elevation: top-hill, middle-hill, and bottom-hill. This study used only the five plots that combined residue retention and fertilizer as 17 kg ha^{-1} of N, 15 kg ha^{-1} of P, and 8 kg ha^{-1} of K applied in the base of the planting hole at planting. All harvested stemwood without bark down to 3 cm in diameter over bark had been exported from the site. All other harvested tree components, bark, branches, and leaves, as well as forest floor components, were retained as residues and distributed evenly across the site prior to application of treatments. Each plot contained 6 × 6 trees and was surrounded by two rows of buffer trees. Trees had a spacing of 2.5 m × 3 m (1333 trees ha^{-1}).

Decomposition of harvest residues from the *A. mangium* stand excluding litter and understory vegetation was measured by the mesh bag method [40]. Briefly, 10 kg sample of leaves, branches (<3 cm in diameter, ~10 cm lengths), and bark were collected randomly across the site immediately after clear-felling in April 2015 and air-dried at room temperature. The mesh bags—30 cm × 28 cm in size with 2 mm mesh—were used to minimize leakage of small fragments while allowing access by decomposer organisms [41]. Each bag was packed with the air-dried residues, either 40 g leaves, 100 g bark, or 100 g branches. Additional samples were oven dried at 65 °C and weighed to establish moisture content and dry weight before grinding for nutrient analysis.

A total of 21 mesh bags comprising nine of leaves and six each of branches and bark were located randomly within each of the five plots (a total of 105 bags) on 25 July 2015. Bags were positioned on top of the litter layer to simulate the position and microclimate representative of the majority of the harvest residues. For the leaf component, one bag from each plot was collected every 60 days until 540 days after the bags were first placed in the plot (1 sample per plot × 5 plots per collection time × 9 times = 45 samples); for the bark and branch components, one bag of each was collected every 90 days during the same period (1 sample per plot × 5 plots per collection time × 6 times = 30 samples per component). The bags were air dried, and the contents brushed free of soil, insect frass, and other debris, oven dried at 65 °C and weighed to determine dry weight loss. Oven-dried samples were ground ($\leq$0.02 mm particle size) for nutrient analysis.

2.4. Plant Nutrient Analysis

Oven-dried biomass samples of tree components, litter, understory, and decomposing harvest residues from mesh bags were digested in concentrated sulphuric acid with 30% hydrogen peroxide; all nutrients were measured from that digest. Total N was analyzed by Automatic Kjeldahl distillation (UDK 149, PLT Scientific SDN BHD, Puchong Selangor Darul Ehsan, Malaysia), P by spectrophotometry (Jasco 7800 spectrophotometer-JASCO International Co., Ltd, Tokyo, Japan), K by flame photometry (Model 410 Flame Photometer Range—Sherwood Scientific Ltd, Cambridge, UK), and Ca and Mg by atomic absorption spectroscopy [42]. The initial nutrient content of each stand biomass component was calculated from nutrient concentrations multiplied by dry weight while the nutrient content of residues from the mesh bags was calculated as the product of the dry weight remaining and the relevant nutrient concentration.

2.5. Statistical Analysis

Long-term patterns of mass loss (up to 10 years) can be analyzed by a range of decay models [43]. However, given that this decomposition study was only 1.5 years long, a single exponential decay model [44] was used to fit the mass loss of each residue component (bark, leaves, and branches) as a function of time as follows: $M_t = M_0 \times e^{-kt}$, where M_t is residue dry weight at time t, M_0 is the

initial residue dry weight at time 0, k is exponential decay coefficient (day^{-1}), and t is time in days. The exponential decay equation was converted to a linear form ($\ln[M_t] = \ln[M_0] - kt$) before the regression procedures were performed. Linear regression of ln [% mass remaining] versus time t was used to determine the decay constant k; the time required for the decomposition of half of the initial residue weight ($t_{0.5}$) was then calculated as $t_{0.5} = 0.693/k$ [44]. Analysis of covariance was conducted to test whether these decomposition rates differed among leaf, branch, and bark; that is, the regression lines of the three separate components were compared to see if they had the same slope. The statistical analyses were conducted with SPSS for Windows version 22.0 (IBM Corp, Armonk, NY, USA, 2013).

3. Results

3.1. Biomass and Nutrient Content of Harvest Residues, Litter and Understory Vegetation

The total initial dry weight of all residues (from harvest and forest floor) following logging was 27.2 t ha^{-1}, comprising 66% harvest residues and 34% forest floor (Table 2). The total initial amounts of N, P, K, Ca, and Mg maintained on the site were 439.6, 14.8, 60.7, 185.0, and 20.1 kg ha^{-1}, respectively. Harvest residues alone accounted for 60% of N, 61% of P, 43% of K, 64% of Ca, and 24% of Mg (Table 2).

Table 2. Initial dry weight and nutrient content of harvest residues and forest floor on the site following harvest of a seven-year-old *A. mangium* plantation in Northern Vietnam. Standard errors are shown in parentheses (n = 16). DM is dry matter.

Components	Dry Weight	Nutrient Content (kg ha^{-1})				
	(t DM ha^{-1})	N	P	K	Ca	Mg
Harvest residue components						
Bark	8.9 (0.3)	133.4 (5.2)	2.6 (0.1)	8.4 (0.3)	76.5 (3.0)	1.2 (0.1)
Branches	6.6 (0.3)	53.9 (1.8)	1.9 (0.1)	4.9 (0.1)	28.9 (1.3)	0.9 (0.1)
Leaves	2.5 (0.1)	76.0 (3.3)	4.5 (0.2)	13.1 (0.6)	13.7 (0.6)	2.8 (0.1)
Subtotal	18.1 (0.7)	263.4 (10)	9.0 (0.3)	26.4 (1.0)	119.2 (4.9)	4.9 (0.2)
Forest floor residue components						
Litter	5.8 (0.6)	128.9 (13.3)	5.1 (0.5)	31.6 (3.3)	45.4 (4.7)	13.7 (1.4)
Understory	3.3 (0.4)	47.3 (5.6)	0.7 (0.1)	2.7 (0.3)	20.4 (2.4)	1.5 (0.2)
Subtotal	9.1 (0.6)	176.2 (12)	5.9 (0.5)	34.4 (3.1)	65.8 (4.3)	15.2 (1.3)
Total residue with bark	27.2 (0.9)	439.6 (15)	14.8 (0.6)	60.7 (3.2)	185.0 (6.3)	20.1 (1.2)
Total residue without bark	18.2 (0.7)	306.1 (12)	12.2 (0.5)	52.3 (3.1)	108.5 (4.5)	18.9 (1.3)

3.2. Decomposition of Harvest Residue Components

A single exponential decay model explained the decomposition of each of the harvest residue components very well (Figure 2; Table 3). The half-lives for leaf, branch, and bark dry weight were 0.47, 1.29, and 3.09 years, respectively (Table 3). The slopes of the regression lines indicate that the decomposition rates of bark and branches were significantly lower than that of leaves ($p < 0.05$; Figure 2; Table 3). The decomposition of leaf dry weight was the fastest throughout the study period with only 10% remaining after 540 days, as compared to 47% and 72% for branches and bark, respectively (Table 3).

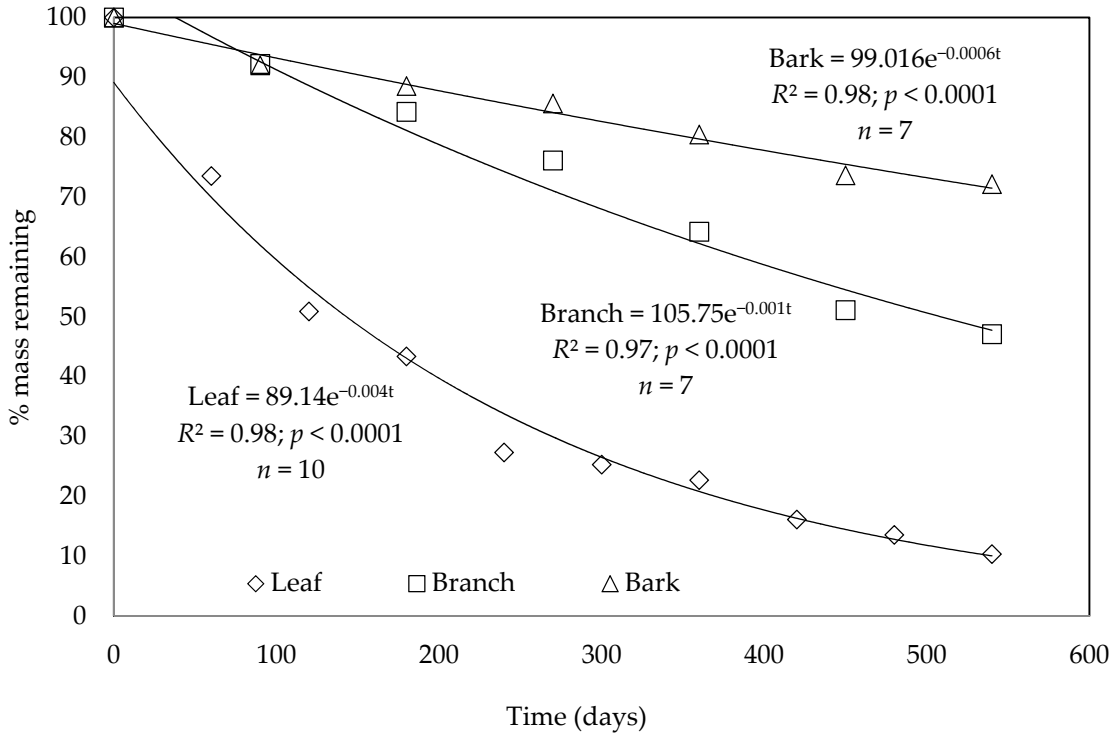

Figure 2. Exponential decay functions fitted to dry weight loss of harvest residue components of *A. mangium* in Northern Vietnam during decomposition for 540 days.

Table 3. Loss of dry weight (%) over the 540-day period, decomposition constant (k, year^{-1}), the proportion of explained variation (R^2), root mean squared error (*RMSE*), and half-life ($t_{0.5}$, year) of harvest residue components of *A. mangium* in Northern Vietnam. N = 10 collection times for leaves and 7 for branches and bark.

Component	Dry Weight Loss (%)	k (Year^{-1})	R^2	*RMSE*	p-Value	$t_{0.5}$ (Year)
Leaves	90	1.47	0.98	0.10	<0.0001	0.47
Branches	53	0.54	0.97	0.05	<0.0001	1.29
Bark	28	0.22	0.98	0.02	<0.0001	3.09

3.3. Nutrient Release During Decomposition of Harvest Residues

Among the harvest residue components, leaves consistently contained the highest concentration of N, P, K, and Mg, but not Ca during decomposition (Figure 3). Leaves also showed the fastest release of nutrients (Figure 4) as described by the single exponential model (see Supplementary Table S1).

N release from decomposing harvest residue components was similar to their dry weight loss over time (Figure 4), as their N concentration remained relatively stable during the study period (Figure 3a). In contrast, the K and Ca release from all residue components was more rapid; the Mg and P release was less rapid than the dry weight loss (Figure 4).

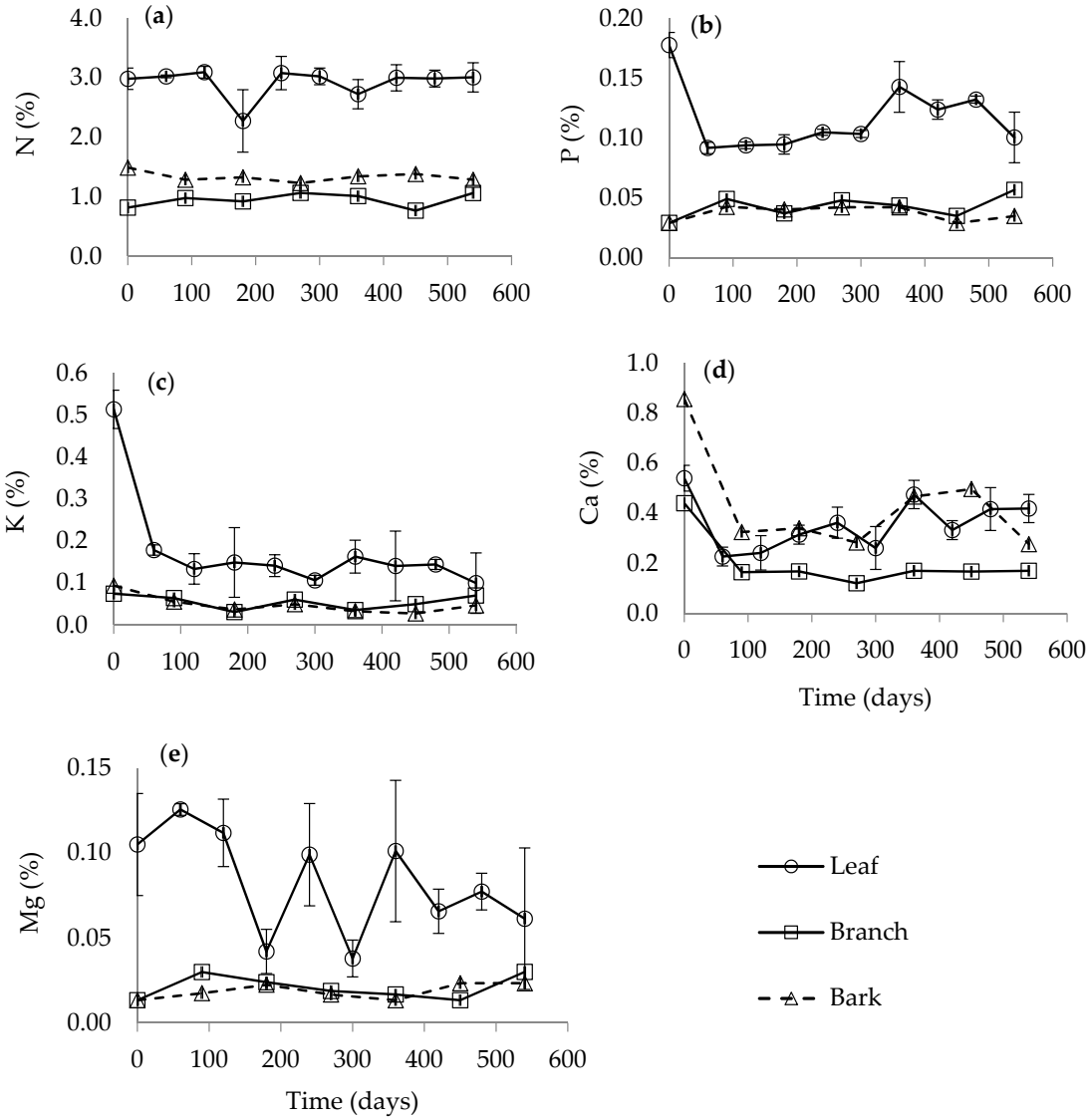

Figure 3. Dynamics of (**a**) N, (**b**) P, (**c**) K, (**d**) Ca, and (**e**) Mg concentration in harvest residues of *A. mangium* during the 540-day period of decomposition in Northern Vietnam. Vertical bars indicate standard errors for each sampling (n = 5).

Throughout the study period, the loss of Ca in all the residue components was rapid; 92%, 82%, and 76% was lost in leaves, branches, and bark, respectively (Figure 4). The losses of K were of similar magnitude to that of Ca with 98%, 56%, and 63% being lost in leaves, branches and bark, respectively (Figure 4). In contrast, there was an accumulation of P and Mg, particularly in the bark and branches; P and Mg in branches were 55% and 107% higher, respectively, than their initial content 90 days after establishment (Figure 4b,c).

For all components together, the amount of N, P, K, Ca, and Mg that potentially could be recycled from harvest residues to the soil 18 months following logging was 137.1, 4.7, 20.8, 94.5, and 2.2 kg ha^{-1}, respectively (Table 4). Most of N, P, K, and Mg, respectively 50%, 91%, 62% and 118% was released from decomposing leaves. The value for Mg was >100% because the other components immobilized Mg over the first 18 months. Bark could potentially contribute 61% of the Ca, 35% of N, and 25% of K (Table 4).

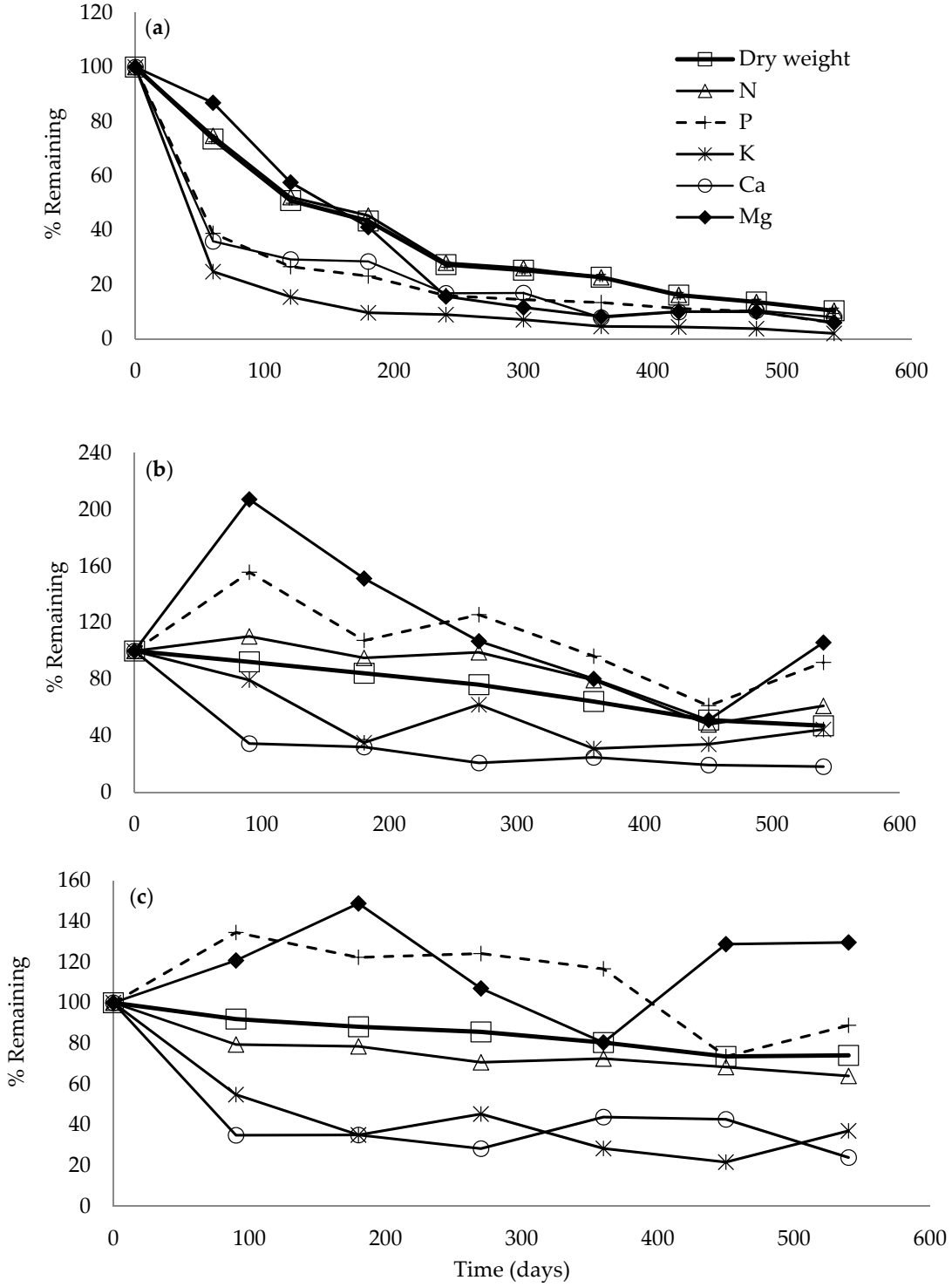

Figure 4. Loss of dry weight and release of nutrients during decomposition for 540 days for (**a**) leaves; (**b**) branches; and (**c**) bark of *A. mangium* in Northern Vietnam.

Table 4. Dry weight loss and nutrient release from different components of decomposing harvest residues 18 months following logging of a seven-year-old *A. mangium* plantation in Northern Vietnam. Standard errors are shown in parentheses (n = 5). DM is dry matter.

Components	Dry Weight Loss	Nutrient Release from Decomposing Harvest Residues (kg ha^{-1})				
	(t DM ha^{-1})	N	P	K	Ca	Mg
Leaves	2.3 (0.1)	68.1 (2.0)	4.3 (0.1)	12.8 (0.1)	12.6 (0.4)	2.6 (0.1)
Branches	3.5 (0.3)	20.9 (1.5)	0.2 (0.8)	2.7 (0.1)	23.7 (2.0)	−0.1 (0.0)
Bark	2.3 (0.1)	48.0 (2.8)	0.3 (0.0)	5.3 (0.2)	58.2 (1.5)	−0.4 (0.0)
Total residue with bark	8.1 (0.0)	137.1 (3.1)	4.7 (0.4)	20.8 (0.5)	94.5 (0.6)	2.2 (0.2)
Total residue without bark	5.8 (0.1)	89.0 (2.3)	4.4 (0.4)	15.6 (0.5)	36.3 (0.8)	2.6 (0.2)

4. Discussion

This study has shown that harvest residues retained on site in the form of bark, branches, and leaves of a seven-year-old *A. mangium* plantation accounted for two-thirds of the total initial dry weight and 24–64% of macro-nutrient contents of total residues that included litter and understory vegetation. The export of bark from the site would lead to the significant loss of some nutrients. Decomposition rates and nutrient release from the harvest residues were associated with the nutrient concentration (substrate quality) of each residue component. Despite the limited number of mesh bags used, this study clearly demonstrated large amounts of N, K, and Ca, but not P and Mg being released to the soil over the 1.5 year-study period. These results are now discussed in the context of the contribution of harvest residues to nutrient cycling in short-rotation plantations of acacia in the tropics, especially the role of bark residue.

Although the bark of the *A. mangium* represented just 15% of the total stand AGB, its export from the site would have reduced the total dry weight of all residues by one-third. The contribution of bark residue to this total dry weight was 41%, 31%, and 19% higher than that observed in *A. mangium* in Sumatra [21], *A. auriculiformis* in Southern Vietnam [1], and *E. dunnii* in Uruguay [17], respectively. Potentially the contribution of bark to total AGB in this study and at other sites in Vietnam (also 15%) [2] was proportionately higher than that observed in *A. mangium* in Sumatra (10%) [21,45], *A. auriculiformis*, and its hybrid (*A. mangium* × *A. auriculiformis*) in Vietnam (7–8%) [1,46] and *E. dunnii* in Uruguay (12%) [17]. For eucalypt and pine plantations, bark biomass generally accounts for 7–10% of total stand AGB [47–49]. Thus, retention of bark on site for *A. mangium* plantations tends to be more important in residue retention than for other species.

The bark component potentially conserved 30% of N, 18% of P, 14% of K, 41% of Ca, and 6% of the Mg content of all residues for recycling. For N, this was similar to that in *A. auriculiformis* in Southern Vietnam [1], but 20% and 50% greater than that in *A. mangium* in Indonesia [17,21] and *E. dunnii* in Uruguay [17,21], a difference that is attributable to the higher concentration of N in bark in the Vietnamese (1.5%) than Indonesian (1.1%) and Uruguayan (0.2%) studies. In contrast, K was between 22% and 56% lower than in these other studies [1,17,21] owing to its lower concentration (0.1% vs. 0.2−0.5%). This lower concentration may be associated with soil K being less available in this study than at the other acacia sites [1,21]. Concentration was also the factor that led to the nutrient content of only N (30%) and Ca (41%) approximately matching bark's one-third contribution to the dry weight of all residues. Hence, retention of the bark of *A. mangium* on site at harvesting conserves some nutrients better than others and was a relatively poor source of P, K, and Mg.

The patterns of mass loss during decomposition varied among components, with leaves decaying the fastest, consistent with previous reports for hardwood plantation species [16,17,20,41,50]. Among nutrients in decomposing material, the concentration of N is the most important factor determining the rate of decomposition in a given environment [29,30]. In this study, the decay constant (k) for leaves was 2.7 and 6.7 times higher and the N concentration 2.0 and 3.7 times higher than for branches and bark, respectively. The k of leaves and bark in this study were 50–65%

and 20–50% faster, respectively, than those observed in other studies of *Eucalyptus* plantations in Australia and Uruguay [41]; similarly, the *k* for branches was approximately 60% faster than for *Eucalyptus* species [16,17], and 66–96% faster than that observed for *Pinus radiata* D. Don plantations across New Zealand [51]. These higher *k* values are partly attributable to the higher N concentration in *A. mangium* harvest residues. In addition, higher temperatures and moisture contents in the tropical climate of Vietnam are factors that will cause faster rates of decomposition [52–54]. Thus, harvest residues from tropical acacia plantations release nutrients, especially N, more rapidly than other species.

During the first year of the study, net release of N was found from leaves and bark, while net immobilization of N occurred in branches. Net N release is influenced by the C/N ratio of the decomposing materials [17,29,30,55–57]. If C/N is >40, the net effect is N immobilization during decomposition [54]. In this study, the C/N ratio of branch residue was 65 [2]; therefore, the initial immobilization of its N was expected. N was subsequently mobilized owing to the oxidization of a C and N uptake, resulting in reduction of the C/N ratio during the decomposition process. Conversely, the C/N ratio of the leaf material was initially 17, and for bark it was 35 [2]. By comparison, in *E. dunnii*, the C/N ratios of leaf, branch, and bark were much higher at 36, 134, and 174, respectively [17] due to 13−47% lower N concentration in the eucalypt harvest residues. These lower C/N ratios in acacias than eucalypts were associated with a much faster release of N from *A. mangium* than *E.* hybrid (*E. urophylla* × *E. grandis*) harvest residues [34] and higher rates of N turnover in topsoil under *A. mangium* than *E. grandis* [58]. By the end of the 1.5-year study period, the total amount of N released from decomposing *A. mangium* harvest residues was 137 kg ha^{-1}, 35% of which released from bark. In contrast, bark made no net contribution to the release of N from harvest residues of *E. dunnii* and *E. globulus* for up to two years [16,17] and *E. grandis*, *E. globulus*, *E. dunnii,* and *Pinus taeda* L. for up to six months following harvest [59]. While the quantities of N taken up by *A. mangium* can be as much as 180 kg ha^{-1} yr^{-1} in the first two years of growth [21], *A. mangium* bark residue can potentially make an important contribution to this demand.

Over the 1.5 years of this study, harvest residues released only around 5 kg ha^{-1} of P. Other studies have found that a small amount of P at planting is sufficient to optimize growth of tropical plantation acacias [60,61], but this is in concentrated form near the seedling at planting, so the timing and rates of release of P from residues and its spatial distribution may not meet all of the demand for P early in the growth cycle. However, as the relative importance of the growth response to P declines with increasing stand age [21,61], the amount of P released from residues together with its release from other sources in the soil is likely to meet the demand later in the rotation.

High levels of immobilization of P but not N in the branches and bark during decomposition suggest that P was the more limiting to microbial decomposer activity of organic matter in this system. The addition of P fertilizer has been shown to increase microbial activity in *A. mangium* plantations [62,63]. Tropical plantation soils are characteristically low in soil P because of their high P-fixing capacity [21,25,64] and in this study, P in the topsoil (4.0 mg kg^{-1}) was very low, even for tropical plantation soils [65]. There was also a notable decline in soil available P in this study [66], that has also been found elsewhere in acacia plantations. Hence, the addition of P fertilizer may serve an added purpose—i.e., the promotion of decomposition and nutrient release from acacia harvest residues.

The release of K and Ca was very rapid, especially during the first three months of decomposition, and reflected the high K and Ca concentrations in the harvest residues. Such rapid release of K is commonly found in plantations across a range of environments [16,17,20,59] because K is highly mobile; hence its rapid leaching by rain soon after placement of the mesh bags in a number of related experiments [16,17,67,68]. The rapid release of Ca and decline in Ca concentration in harvest residues is linked to the rapid release rates of Ca oxalate [69,70], which accounts for 20–56% of total Ca in fresh plant tissues [69]. Over the study period, 20.8 and 94.5 kg ha^{-1} of K and Ca, respectively, were released from the residues, with bark contributing 25% of the K and 61% of the Ca, or potentially at least

one-quarter and >50% of the demand [21]. As growth responses to Ca and K fertilizers are uncommon in tropical acacia plantations grown with residue retention [1,71], the substantial contribution of residues to the K and Ca nutrient pools, the latter through bark, may explain this lack of response.

In contrast, the release of Mg was very slow, with net immobilization over the first few months, especially in the branch and bark components. The slow release of Mg is because it is dependent on cellular degradation in the residues [17,72]. In Ivory Coast, only 10% of initial Mg was released from decomposing litter of *A. mangium* and *A. auriculiformis* in a one-year study period [36]. In this study, <3 kg ha^{-1} was released, suggesting that *A. mangium* harvest residues may not meet the potential demand for Mg uptake by this species, which can be as much as 9 kg ha^{-1} year^{-1} over a similar period for an equivalent MAI [21].

5. Conclusions

Harvest residues played a crucial role in conserving nutrients for recycling in this *A. mangium* plantation, contributing 66% of the total dry biomass and 24–64% of macronutrients, of all residues, including litter and understory vegetation. Bark removal would have reduced the quantity of all residues by one-third, and a similar proportion of the Ca and N contents. Based on the amounts of nutrients recycled in 1.5 years of the study, we suggest that recycling of N, Ca, and K, but not P and Mg, were potentially able to meet a significant part of the nutrient demand in the next rotation. While slow release should have promoted capture of the nutrients by growing trees in the next rotation, the amount of N and K lost by leaching and P to the high-fixing tropical soil remains unknown. In addition, a high quantity of N, but not P, released may have caused a nutrient imbalance in the soils. As P supply is crucial to the growth of these acacias, the addition of P fertilizer at planting is recommended, both to boost immediate supply and to potentially enhance decomposition rates of the harvest residues.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/9/9/577/s1, Figure S1: The allometric relationships between dry biomass of stand components and tree diameter (DBH, cm). DM is dry matter. N = 30. Table S1: Nutrient releases (%) from leaf component over the 540-day period, nutrient release constant (k, year^{-1}), regression coefficient (R^2) and root mean squared error ($RMSE$) and haft-life ($t_{0.5}$, year) of nutrient degradation of *A. mangium* harvest residues in Northern Vietnam. N = 10 collection times.

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