

## Article

# Rubber Tree (*Hevea brasiliensis*) Biomass, Nutrient Content, and Heating Values in Southern Thailand

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Received: 24 June 2019; Accepted: 25 July 2019; Published: 28 July 2019



**Abstract:** Rubber trees (*Hevea brasiliensis* (Willd.) Muell.Arg.) are cultivated for latex production, but they also produce timber for industry, and logging residues can be used for power generation. In this study, we determined the biomass of above- and below-ground tree compartments (leaves, branches <3 cm in diameter, branches 3–5 cm in diameter, stumps and roots) of 20-, 25-, and 30-year-old rubber tree plantations in Songkhla province, southern Thailand, at the clear-cutting stage. We also studied the nutrient content and heating value of the compartments. The total dry mass (including leaves, branches, stems and stumps and roots) of the mature rubber wood stands was 157–289 Mg ha<sup>−1</sup>. The residual harvestable dry mass without leaves (39–68 Mg ha<sup>−1</sup>, branches <5 cm in diameter, stumps and roots) comprised 25% of the total dry mass. Nutrient concentrations were highest in the leaves, followed by small branches. In most cases, the stems and larger branches had similar concentrations. One ton of rubber tree biomass (leaves and stumps and roots included) contained an average of 2.4 kg N, 0.2 kg P, 3.4 kg K, and 4.8 kg Ca. Depending on the biomass of the stands, the rubber trees had 380–700 kg, 36–64 kg, 530–980 kg, and 750–1360 kg of bound N, P, K, and Ca per hectare, respectively. The effective heating value of the stumps and roots was the lowest (17.65 MJ kg<sup>−1</sup>). Stems and branches were similar (18.37–18.58 MJ kg<sup>−1</sup>), and leaves were the highest (20.34 MJ kg<sup>−1</sup>). The unharvested residual biomass in southern Thailand is a potential fuel source for power generation.

**Keywords:** stand biomass; tree compartments; carbon sequestration; ash content; heating value

## 1. Introduction

The rubber tree (*Hevea brasiliensis* (Willd.) Muell.Arg.) is cultivated for latex production in all tropical zones on over 10 million hectares [1]. Asia accounts for 97% of the world's natural rubber supply [2], and Thailand, Indonesia, and Malaysia are currently the world's largest natural rubber producers [3]. The economic lifetime of rubber trees is 20–30 years [4–7]. In Thailand, from 90,000 to 120,000 hectares of mature rubber plantations are clear-cut annually for replanting. The majority (68%) of the plantations are in the south of the country [8]. Rubber production has a strong impact on the rural economy and the alleviation of rural poverty, because producers are mainly small holders who represent more than 85% of the total area where rubber is produced in Thailand [8], and some 6 million people are involved in rubber plantation activities [5]. Smallholder rubber production is a viable and effective proposition for raising households and communities out of poverty, especially in Thailand [2].

The wood of rubber trees is a good raw material for the wood products manufacturing industry (e.g., sawn timber, plywood, particle board, furniture). Larger branches can be used for charcoal production. However, small branches and stumps and roots are not generally used, and in Thailand they are often burned to prepare sites for replanting. Especially large-scale rubber farmers owning more than 9.6 ha of rubber trees tend to burn rubber tree stumps and branch residues onsite before replanting [7]. The need to reduce greenhouse gas emissions and the dependency on fossil fuels is

increasing the value of renewable energy obtained from forests. The supply of rubber wood residue and stumps would be quite secure in the long term due to the rubber industry. Most of the utilization of rubber wood residual (crown and stumps and roots) biomass in Thailand would be for electricity generation [4]. In addition, the use of other conversion technologies, such as pyrolysis and gasification, could be used to generate energy from rubber tree residues. In Malaysia, the utilization of rubber wood biomass in energy generation is limited compared to other available residual biomasses, such as oil palm, rice and cocoa husks, and sugarcane stalks [3]. A steady supply of rubber wood logging residues in the long-term due to a thriving rubber industry would enable the planning of investments. However, to plan the use of residual biomass from rubber tree plantations, estimates on their quality and harvestable volume are needed.

The properties of biomass feedstock can be determined in a number of ways depending on the end use. Fuel wood properties can be described in terms of proximate and ultimate analysis, bulk density, heating value, composition, and tree species [9]. The calorific or higher heating value ( $qp(gross)$ ) can be determined with a bomb calorimeter, and the effective heating value can be derived from it. The effective or lower heating value of an oven dry biomass ( $qp(net)$ ) indicates the energy available in free combustion of oven dry biomass and is calculated as the calorific heating value minus the heat released by the condensation water that is created during combustion. The energy yield as measured by the heating value is one of the most important quality characteristics in energy generation. The heating value is affected by factors such as species, tree compartment (stem, branches, roots), and tree component (wood, bark, foliage) and the size of trees [10]. Knowledge of the heating values of different rubber wood compartments and the energy content of the whole rubber wood stand would thus provide guidelines for the further development of industry. A high ash content can reduce the heating value of biomasses [11]. In addition, high amounts of ash can also contribute to clogging of the ash handling mechanisms in conversion plants and can increase maintenance costs [12].

Information on the nutrient contents of rubber wood compartments, especially at the clear-cut stage, is needed to assess the amount of nutrients bound in the biomass as well as the nutrient depletion from the site. Additionally, high concentrations of alkali metals in a biomass can cause corrosion and agglomeration during combustion [13]. Large amounts of biomass harvested can result in large quantities of nutrients being removed from the site and could reduce the nutrient capital of the soil in short rotation plantations [14]. If the utilization of branches and stumps for bioenergy is increased, this would increase nutrient loss from the site and increase the need for fertilization. However, rubber tree plantations are already fertilized for higher yields of latex [15–17].

The main objective of this study was to calculate the stand level harvestable biomass of leaves, branches, stems, and stumps and calculate the amount of carbon and nutrients bound in these compartments. A second objective was to evaluate the heating value of rubber wood and its compartments.

## 2. Materials and Methods

### 2.1. Study Area

The study was carried out in rubber tree plantations in Songkhla Province in southern Thailand, close to Hat Yai (6°54' N, 100°19' E). The rubber tree plantations cover 1.8 million ha in southern Thailand [6], and in Songkhla Province they cover almost 300,000 ha [4]. The climate in the region is described as tropical monsoon (AM) in the Köppen–Geiger climate classification system. The temperature in Songkhla varies between 22 and 35 °C depending on the season, and average total annual precipitation is 1720 mm (Thai Meteorological Department). Most precipitation occurs in October–December. The soil type is clayey-skeletal and kaolinic with low levels of phosphorus and potassium, and it was assessed as nonfertile soil based on the Land Development Department's classification.

The diameter distribution (diameter at breast height, DBH) of three rubber wood stands (clone RRIM 600) was measured. Clone RRIM 600 is the most common clone used in Thailand, covering over 80% of the plantation area. In stand A (20 years of age), rubber production was ongoing; stand

B (25 years of age) was just being clear-cut; and in stand C (30 years of age), rubber production had already ended, but the plantation had not been renewed. The density of stands A and B was 357 trees ha<sup>-1</sup>, and that of stand C was 410 trees ha<sup>-1</sup>. The rubber trees were planted in rows, and when measuring the trees, the width of the rows was measured. In each stand, trees from several rows were measured, covering altogether 1484 m<sup>2</sup> in stand A, 1456 m<sup>2</sup> in stand B, and 880 m<sup>2</sup> in stand C. The dry biomass of the tree compartments was calculated with biomass equations based on the diameter at breast height developed from the same area for trees at the clear-cutting stage [18].

Altogether, 18 trees of different sizes (10–30 cm in DBH) were sampled from stand B, as described by Hytönen et al. [18]. After the trees were felled in the beginning of September, the leaves with their petioles were separated from the trees, as were thin branches (<3 cm in diameter) and thick branches (3–5 cm in diameter), stems (>5 cm in diameter), and stumps with roots cleaned from soil. Three sample discs (thickness 5–8 cm) were cut with a chainsaw from the butt, middle, and top sections of sample trees, as was a disc from the stump and roots. The samples were placed in sealed plastic bags and stored in the field in cold boxes filled with ice. The laboratory samples belonging to the same compartment were united and then divided into three samples. The number and mean diameter of roots >2 cm that were broken and left in the ground for each stump were determined. On average, nine roots (standard deviation (SD) = 4.8) >2 cm had broken in each stump. The mean diameter of the broken roots was 4.2 cm (SD = 0.8 cm).

## 2.2. Laboratory Analyses

In the laboratory, the samples were dried at 105 °C to a constant weight. The calorific heating value ( $qp_{gross}$ ) of the dry matter was determined with a calorimeter (IKA C5000, IKA-Werke GmbH & Co., Staufen, Germany). Prior to the analysis of the heating value, the dried and milled (Retsch SM-1 mill, Retsch, Haan, Germany) samples were pelletized. In order to calculate the effective (lower, net calorific value on a dry basis) heating value ( $qp_{net}$ ), it is necessary to know the hydrogen content of the compartments, since the heat of the condensation of water vapor created during combustion has to be taken into account. The hydrogen concentrations measured for the studied compartments were used. The following equation was used in the calculation [19,20]:

$$qp_{net} = qp_{gross} - 2.45 \cdot 0.09 H_2 \quad (1)$$

where  $qp_{net}$  is the effective heating value (kJ kg<sup>-1</sup>),  $qp_{gross}$  is the calorific heating value (kJ kg<sup>-1</sup>), 2.45 MJ kg<sup>-1</sup> is the latent heat of vaporization of water at 20 °C, 0.09 is the factor expressing one part of hydrogen and eight parts of oxygen for nine parts of water, and  $H_2$  is the hydrogen content of the dry biomass.

The ash content of the samples was analyzed by dry-ashing the samples for 8 h at 550 °C in a muffle furnace. The C, H, and N concentrations were analyzed with a CHN-analyzer, and the total nutrient concentrations (P, K, Ca, Mg, Cd, Cu, Mn, S, Zn) were analyzed using inductively coupled plasma atomic emission spectrometry (ICP-OES) at the laboratory of Ahma Environment LTD.

## 2.3. Statistical Analysis

Differences in ash, hydrogen, and nutrient concentrations in the compartments were tested with an analysis of variance. An arcsine transformation was carried out prior to analysis for those variables that were expressed as a percentage. Tukey's test at a significance level of 0.05% was used to study differences between the compartments.

## 3. Results

### 3.1. The Biomass of Rubberwood Compartments

The total dry mass (including leaves, stumps, and roots) of the mature rubber wood stands was 157 Mg ha<sup>-1</sup> in the 20-year-old stand and 289 Mg ha<sup>-1</sup> in the 30-year-old stand (Table 1). Most of

the total dry biomass (74%–76%) was in stems (Table 1). The stumps and roots had 23–40 Mg ha<sup>−1</sup> dry mass depending on the stand age. The stumps and roots contained 14%–15% of the dry mass. The branch dry mass was 17 Mg ha<sup>−1</sup> in the 20-year-old stand and 29 Mg ha<sup>−1</sup> in the oldest stand. Both branch sizes (smaller than 3 cm, and 3–5 cm in diameter) contained 5%–6% of the total biomass, and the leaves contained only 1%. The share of the residual biomass without leaves in the three mature rubber tree stands was 25%. The residual harvestable biomass (branches <5 cm in diameter, stumps and roots) was 39 Mg ha<sup>−1</sup> in the 20-year-old stand and 68 Mg ha<sup>−1</sup> in the older stand.

**Table 1.** Dry mass of leaves, branches, stems, and stumps and roots in rubber tree plantations that were 20, 25, and 30 years of age. The top number in each cell is the biomass, and the lower number in parentheses is the percentage of total biomass. DBH: diameter at breast height, H = height.

Stand (Age)	Mean DBH, cm	Mean H, m	Biomass, Mg ha <sup>−1</sup>						Total
			Leaves	Branches <3 cm	Branches 3–5 cm	Branches <5 cm	Stems	Stumps and Roots	
A (20)	23.7	19.8	1.97 (1.3)	8.92 (5.6)	7.53 (4.8)	16.45 (10.5)	115.98 (73.8)	22.72 (14.5)	157.12 (100.0)
B (25)	24.6	20.1	2.14 (1.2)	9.70 (5.5)	8.17 (4.8)	17.87 (10.5)	126.98 (74.0)	24.67 (14.4)	171.67 (100.0)
C (30)	28.4	20.9	3.47 (1.2)	15.82 (5.5)	12.96 (4.5)	28.78 (10.0)	217.39 (75.1)	39.72 (13.7)	289.35 (100.0)

### 3.2. Ash, Carbon, Hydrogen, and Nutrient Concentrations

The ash and nutrient concentrations in the rubber tree biomass differed significantly according to the compartments, with the exception of Cd (Table 2). Leaves had the highest concentrations, and small branches had the second highest concentrations. In most cases, the nutrient concentrations in stems and larger branches did not differ. The stumps and roots had similar concentrations to stems with the exception of Ca, which was higher in the stumps and roots.

For the hydrogen content, which was required for calculating the effective heating value, there were small differences between compartments. Leaves had a higher hydrogen content than woody compartments. The leaves had the highest carbon concentration and the stumps and roots the lowest.

**Table 2.** Ash, H, C, and nutrient contents of rubberwood compartments. *F*-values and their significance (*p*). Means marked with the same letters within a row do not differ from each other at a significance level of *p* < 0.05 according to Tukey's test.

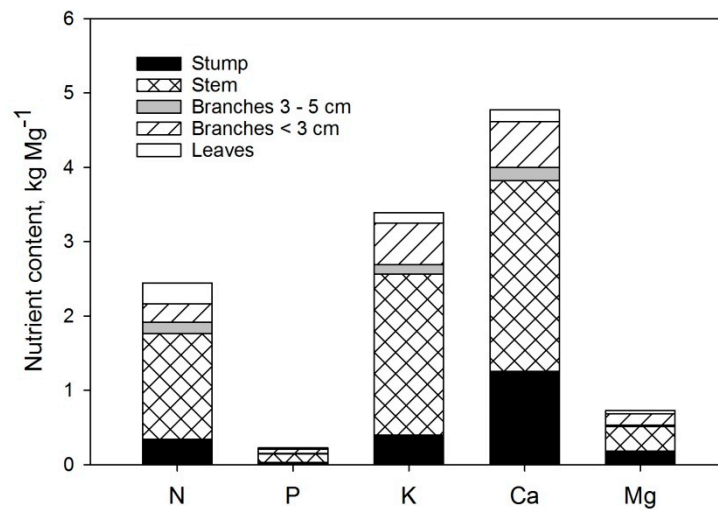
	Compartment					<i>F</i>	<i>p</i>
	Leaves	Branches <3 cm	Branches 3–5 cm	Stem	Stump and Roots		
Ash, %	6.7 d	3.0c	2.2 b	1.6 a	3.3 c	137.708	<0.001
H, %	6.3 b	5.9 a	5.9 a	5.9 a	5.8 a	60.083	<0.001
C, %	52.3 c	50.3 b	50.2 b	49.8 b	48.9 a	82.348	<0.001
N, g kg <sup>−1</sup>	22.6 d	4.4 c	2.1 b	1.9 a	2.3 ab	2219.357	<0.001
P, g kg <sup>−1</sup>	1.3 b	1.0 b	0.2 a	0.2 a	0.2 a	13.821	<0.001
K, g kg <sup>−1</sup>	11.6 b	9.9 b	2.6 a	3.0 a	2.7 a	18.315	<0.001
Ca, g kg <sup>−1</sup>	12.4 b	10.0 b	3.6 a	3.5 a	8.4 b	17.522	<0.001
Mg, g kg <sup>−1</sup>	3.5 c	2.7 bc	0.4 a	0.5 a	1.2 ab	9.204	0.002
Cd, mg kg <sup>−1</sup>	0.3 a	0.4 a	0.3 a	0.3 a	0.6 a	2.252	0.136
Cu, mg kg <sup>−1</sup>	11.7 b	9.9 b	2.6 a	2.5 a	bdl	15.984	0.001
Mn, mg kg <sup>−1</sup>	743.3 b	533.3 b	74.3 a	68.7 a	84.0 a	13.019	0.001
S, mg kg <sup>−1</sup>	2510 b	1983 b	397 a	373 a	387 a	14.647	0.001
Zn, mg kg <sup>−1</sup>	35.0 c	28.7 bc	8.6 a	10.1 a	16.0 ab	12.526	0.001

bdl = below detection limit.

### 3.3. Nutrients and Carbon Bound in Stands and the Unit Amount of Biomass

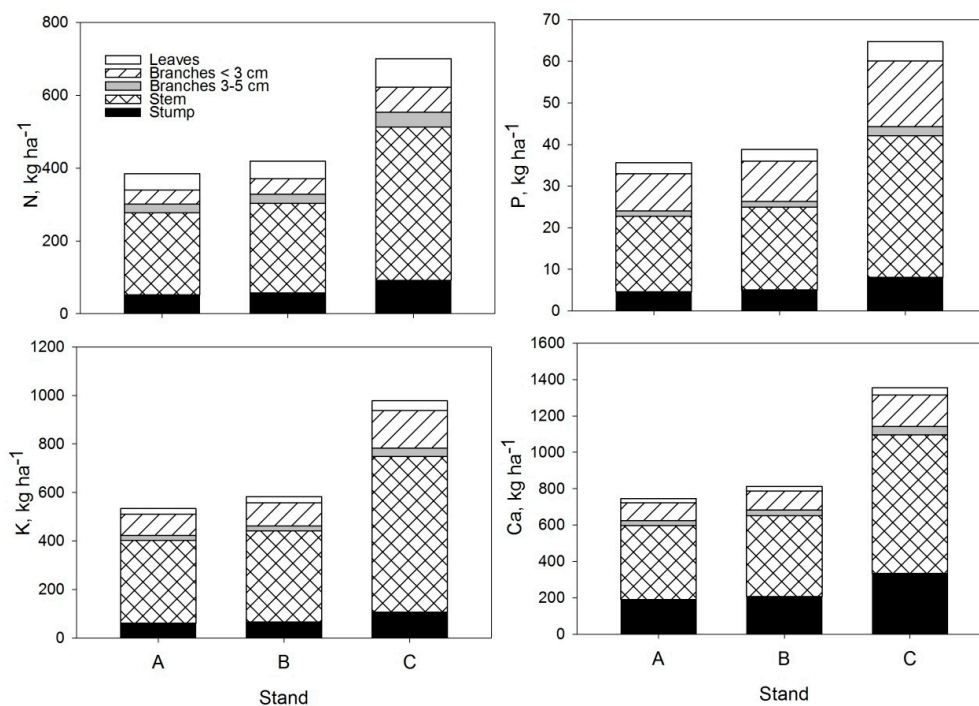
The nutrient content (kg Mg<sup>−1</sup>) of leafless rubber tree biomass (Figure 1) was calculated based on the nutrient concentration (Table 2) and biomass of the tree compartments (Table 1). One ton of rubber

tree biomass in the stands contained on average 2.4 kg N, 0.2 kg P, 3.4 kg K, 4.8 kg Ca, and 0.7 kg Mg. Most of the nutrients were located in the stems. Even though the nutrient concentrations in the leaves were high compared to the stems, their share of the total biomass was only 1%.



**Figure 1.** The content of N, P, K, Ca, and Mg bound in rubber tree biomass, by compartments, in plantations in southern Thailand.

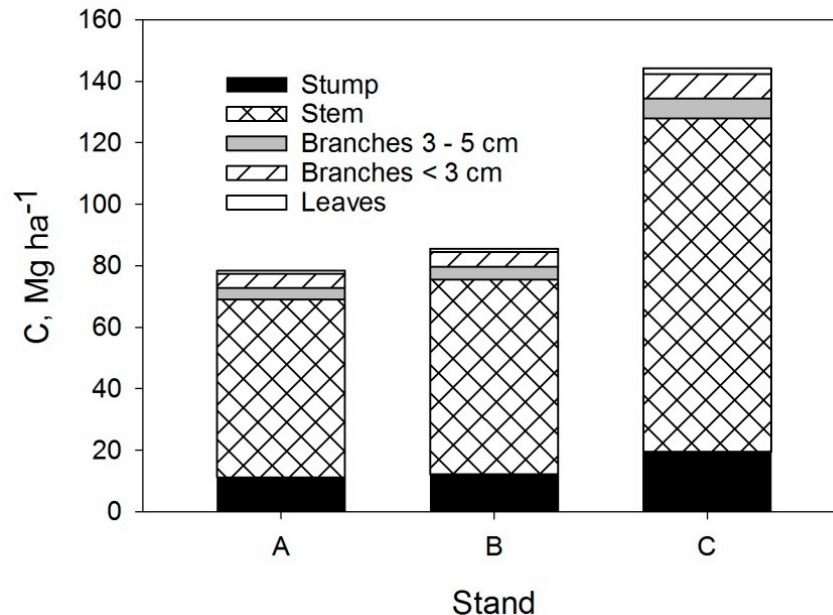
The amount of nutrients bound in rubber tree plantations increased with stand biomass (Figure 2). Stands A and B had 380–420 kg ha<sup>-1</sup> of bound N, and the overmature stand had 700 kg ha<sup>-1</sup>. The amount of P was smaller (36–64 kg ha<sup>-1</sup>). Rubber trees had more bound K (530–980 kg ha<sup>-1</sup>) than N in their biomass, and the amount of Ca was even higher (750–1360 kg ha<sup>-1</sup>). The amounts of Mn (17–31 kg ha<sup>-1</sup>), Zn (2.0–3.5 kg ha<sup>-1</sup>), and Cd (60–110 g ha<sup>-1</sup>) bound in the rubber tree biomass were smaller. The residual harvestable biomass (branches <5 cm in diameter, stumps and roots) contained 30% of N, 41% of P, 31% of K, and 43% of Ca in the total stand nutrient pool.



**Figure 2.** The quantity of N, P, K, and Ca bound in different compartments of rubber tree plantations that were 20 years (Stand A), 25 years (Stand B), and 30 years (Stand C) of age in southern Thailand.



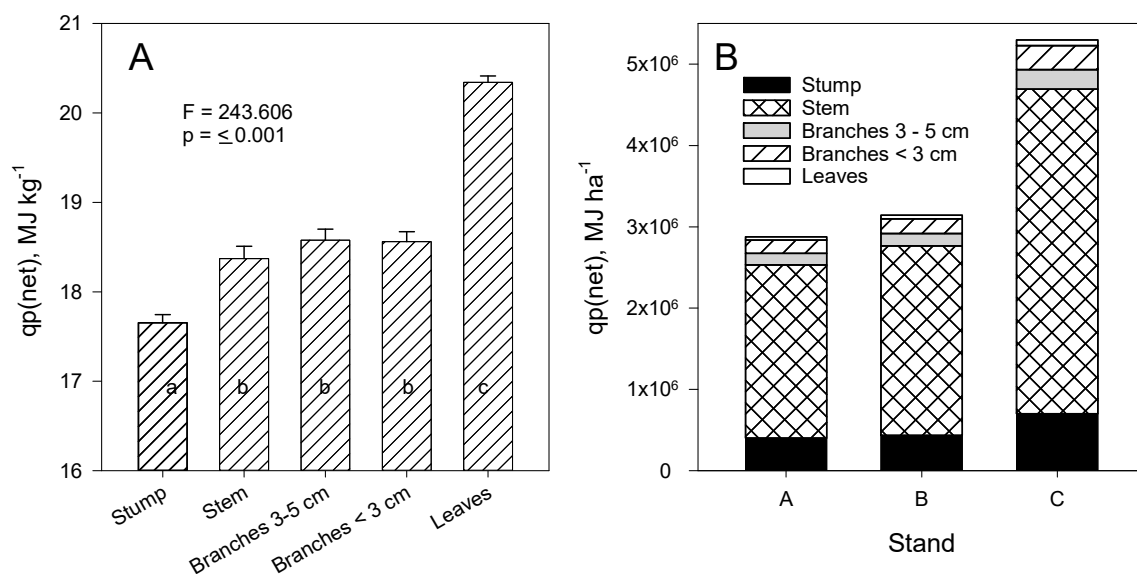
The stands had bound 78–144 tons of C ha<sup>-1</sup> (Figure 3) in their biomass. The stems had 74%–75% of the bound carbon. The stumps and roots were the second largest carbon store (14%), followed by the branches (11%–15%). The leaves contained only 1% of the total carbon bound in the complete tree biomass.



**Figure 3.** The amount of carbon (C) bound in different compartments of rubber tree plantations that were 20 years (stand A), 25 years (stand B), and 30 years (stand C) of age.

### 3.4. The Heating Value of Rubberwood Compartments and Stands

The effective heating value of the stumps and roots was the lowest (17.653 MJ kg<sup>-1</sup>), and that of the leaves was the highest (20.343 MJ kg<sup>-1</sup>). The effective heating values of the stems and branches did not differ (18.370–18.577 MJ kg<sup>-1</sup>) (Figure 4A).



**Figure 4.** The effective heating value of the oven dry biomass ( $qp(net)$ ) of rubber wood compartments (A) and the energy content of rubber tree plantations that were 20 years Stand A), 25 years (Stand B), and 30 years (Stand C) of age (B). Means marked with the same character do not differ from each other according to Tukey's test at significance level of  $p < 0.05$ .

Stand C, with the highest biomass stocking, had the highest energy content (total effective heating value) on a dry weight basis per hectare (Figure 4B). The stems contributed the most to the energy content (74%–75%), and the share of stumps and roots was 13%–14%. The branches had 10%–11% of the total stand energy content. The share of the leaves was only 1.3%–1.4% of the total stand biomass. Stumps and roots and branches contributed 23%–25% of the energy content of the stand. If the leaves were included, the share of residual biomass was 25% of the total stand energy content. The total energy contents in stands A, B, and C were 288, 315, and 530 GJ ha<sup>-1</sup>, respectively, reflecting the magnitude of stand biomass.

#### 4. Discussion

The biomass of rubber tree plantations increases with the age of the trees. We studied plantations at the end of the latex production cycle that were to be clear-cut and replanted. Generally, the rotation length is 25 years, but if the plantation is for some reason not regenerated in time but left to grow for a few more years, the stand biomass increases considerably, as it did in this study in the 30-year-old plantation where latex collection had ceased.

The biomass of the plantations depends on many factors, including the planting density, management strategies, and age. In Thailand, the planting density and rotation length are generally similar to our study. The total dry mass in the studied 20-year-old stand (157 Mg ha<sup>-1</sup>) was higher than what Saengruksong et al. [21] measured (141 Mg ha<sup>-1</sup>) in a similar aged plantation in northeastern Thailand. The clearly higher biomass in the 30-year-old stand (289 Mg ha<sup>-1</sup>) shows that letting trees grow older would increase the biomass considerably. Leaves constituted only 1% of the biomass, which was less than in the 4–25-year-old rubber plantations in Thailand (3%–4%) [7,21]. Due to the sampling time in this study, the leaf mass was probably not at its maximum. Thus the amount of leaves in this study was lower (2.0–3.5 Mg ha<sup>-1</sup>) than in the stands measured by Saengruksong et al. [21] (4.1 Mg ha<sup>-1</sup>).

Stumps and roots could be an attractive feedstock for power generation in rural communities. Their amount increases with an increase of the stand age. The share of stumps and roots of the total biomass (14%–15%) was within the range reported in other studies (12%–20%) [7,21,22]. Their dry mass (24 Mg ha<sup>-1</sup>) in a 20-year-old stand was similar to that measured (24.3 Mg ha<sup>-1</sup>) by Saengruksong et al. [21]. The residual harvestable dry mass without leaves (branches <5 cm in diameter, stumps and roots) was 39 Mg ha<sup>-1</sup> in the 20-year-old stand and constituted 25% of the total biomass. The approximately 12,000 ha of rubber tree plantations that are clear-cut annually in Songkhla province (assuming that 4% are cut down annually) would thus annually produce approximately 470–510 Gg of residual dry biomass using rotation lengths of 20–25 years.

Carbon stocks depend on biomass and its C content. There were small differences in the C content of the compartments, with leaves having the highest C content (52.3%), as reported by Wauters et al. [23] (50.2%–50.8%). The total C content of the trees was 49.8%, which was close to the IPCC default value of 0.5 [24]. Quite variable C contents have been used when converting rubber wood biomass to carbon. Wauters et al. [23] reported stems and branches with a slightly lower C content (47.8%–49.5%) than in this study (49.8%–50.2%). Considerably lower C concentration values have been reported for rubber tree compartments by Chantuma et al. [6], Maggiatto et al. [25], and Munasingh et al. [26]. However, much higher values have also been presented (55%–58% for stems, roots, and leaves) [21].

Carbon sequestration figures in the range of this study for mature rubber tree stands have been presented in previous studies. The total carbon pools in the 20-year-old (78 Mg C ha<sup>-1</sup>) and 25-year-old stands (86 Mg C ha<sup>-1</sup>) were similar to stands of a similar age in northern Thailand [6,21], but were lower than what Petsri et al. [7] reported in their 25-year-old stand (110 Mg C ha<sup>-1</sup>). A considerably lower carbon sequestration figure than in this study was reported by Cheng et al. [27], who reported 91 Mg C ha<sup>-1</sup> in a 30-year-old plantation in Hainan, China. Besides carbon bound in the biomass, 14–33 Mg C ha<sup>-1</sup> was transported from the sites in latex during a 20-year rotation [28].

The ash content varies according to the tree species, tree age, and tree compartments. The differences in the ash content in tree compartments, except for stumps and roots, probably reflected the share of bark in the different compartments, because wood generally had a lower ash content than bark. The ash content of leaves was the highest, almost 7%. The ash content of the above-ground leafless biomass of rubber wood was 1.8%. The ash content of mature rubber trees is quite high, but is comparable to boreal aspen (*Populus tremula* L.) [19,20]. This also holds true for short-rotation willows (*Salix* spp.) grown in Europe and North America, which have an ash content of 1.8%–1.9% [29,30]. Unfortunately, high amounts of ash in feedstock can reduce the heating value and cause the clogging of bed sand and the malfunction of ash-handling mechanisms in power plants, leading to higher cleaning and maintenance requirements for boilers [11,12].

The foliar N, P, Ca, and Mg concentrations of the 20-year-old trees in this study were lower than those measured in previous studies [15,31–33]. The inclusion of leaf stalks in the foliar biomass probably accounted for the lower nutrient concentrations in this study. Additionally, annual fertilization may have been stopped before clear-cutting, since fertilizer application even in productive mature plantations is sometimes neglected [33]. It is probable that even short storage at the site would mean that the leaves were mostly shed: Nutrient-rich leaves may have been left onsite, and a leafless biomass was harvested. Additionally, a considerable amount of nutrients in the senescent leaves were re-translocated [34], and nutrients in the litterfall were recycled [31].

The nutrient removal in the harvesting of leafless biomass (stems, branches, stumps and roots) in the 20-year-old stands would be 750 kg N ha<sup>−1</sup>, 35 kg P ha<sup>−1</sup>, 530 kg K ha<sup>−1</sup>, and 750 kg Ca ha<sup>−1</sup>. However, in rubberwood plantations, nutrients are also transported from the site in latex. The nutrient transport in a Brazilian 13-year-old rubber wood stand in latex (1700 kg ha<sup>−1</sup>) was 4.9, 1.9, 5.0, 1.4, and 0.4 kg ha<sup>−1</sup> per cropping season for N, P, K, Ca, and Mg, respectively [31].

Fertilization, especially with N and P, is an important management tool in the cultivation of rubber trees [5,35]. According to farmer interviews, 99% of mature rubber plantations in Thailand are fertilized with either chemical or organic fertilizers or both, with average rates of chemical fertilizers being 105/53/92 kg ha<sup>−1</sup> of N/P/K, which is consistent with national recommendations [15]. Lower fertilizer rates are recommended in India depending on the soil status, ranging from 30–45 kg of N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O [36]. Since in Thailand two-thirds of plantations have intensive or very intensive fertilization practices [15], the risk of depletion of primary nutrients in the growing sites even when trees are harvested with their roots and branches is lower than in normal forestry.

Alkali metals (K, Na), alkaline earth metals (Ca, Mg), and transition metals (Mn) can cause the agglomeration of bed sand in circulating fluidized bed boilers [13]. They may also cause clogging in boiler grates in more conventional boilers. Rubber tree leaves and small branches have concentrations of Na, K, Ca, and Mg 3 to 4 times higher than stems, but in the case of Mn, the difference is 10-fold. A detailed study is needed to determine if the observed concentrations would be harmful to boilers. However, these figures for rubber tree leaves and branches are much higher than those that have been found for boreal conifers, which are considered to be a somewhat problematic fuel for circulating bed boilers [37].

Changes in the amounts of bark and wood proportions often have a significant effect on the wood properties and nutrient contents of trees. The size of residue components of rubber trees is so high that it justifies an interest in their recovery for power generation. The heating values per kilogram of the dry matter in the branches were comparable to those in the stems. Leaves had the highest heating values. However, should they be included in the harvested volume, they would make only a very small contribution to energy yield. Furthermore, it would be better if leaves remained onsite to provide the next tree generation with a potential nutrient flux. This could be carried out by letting the residual mass dry on the site utilizing transpiration drying. This would provide the double benefit of shedding leaves on the site and drying the residual mass for further utilization. Stumps and roots alone account for some 15% of total tree biomass. Even if the heating value is lower in comparison to other compartments, the total energy content per hectare is attractive from a utilization point of view.



## 5. Conclusions

Considerable amounts of biomass in unharvested residual biomass in southern Thailand are a potentially valuable resource in power generation. Due to the thriving rubber industry, the supply would be secure. What remains to be studied is the productivity and cost of the recovery of the residual biomass if industrial-scale recovery from thousands of rubber tree hectares is planned. Even though considerable amounts of nutrients are exported from the site, fertilization of the plantations probably maintains the supply of the primary nutrients.

The alkali metal, alkaline earth metal, and transition metal contents were high in the residual branch and leaf compartments. As these may cause a power plant maintenance challenge with increased running costs, the effects of their use should be studied before launching a large-scale campaign to harvest leaves and branches.

The heating values of biomass compartments showed that the rubber trees fell into the general range of lignocellulosic feedstock. Even if leaves had a significantly higher heating value than the other compartments, they accounted only for a small percentage of the fresh biomass. As such, they should be left onsite to enhance nutrients for the next tree generation. More importantly, reducing the moisture content through natural onsite drying would increase the harvestable energy content, lower recovery costs, and improve combustion efficiency. As an appropriate recovery method for residual rubber tree biomass does not exist yet, future studies on the issue should be designed to include drying experiments both onsite and on landings.

**Author Contributions:** J.H., J.N., N.K., and T.K. designed the study. N.K. and T.K. selected the study site and organized field work. N.K. managed project administration. J.H. wrote the preliminary manuscript, which was finalized by all authors.

**Acknowledgments:** The study would not have been possible without the participation of the students of Kasetsart University's Department of Forest Engineering in the fieldwork. Tero Takalo helped with the measurements and Seppo Vihanta with the calculations. The support of the Royal Thai Embassy in Finland and the Säätiöiden Post Doc pool are gratefully acknowledged.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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