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BIOMASS EQUATIONS FOR RUBBER TREE (*HEVEA BRASILIENSIS*) COMPONENTS IN SOUTHERN THAILAND

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The rubber tree (*Hevea brasiliensis*) is cultivated for latex production, but its timber is used in industry and its logging residues can be used for power generation. The reliable estimation of biomass is basis for operational calculations. In this study, allometric biomass equations for fresh and dry biomass of the above- and belowground non industrial tree components of mature rubber tree (leaves, branches < 3 cm in diameter, branches 3–5 cm in diameter, stumps with roots, stem) at the clear-cutting phase were developed. The models were based on 18 sample trees of clone 600 harvested in Songkhla province, southern Thailand. Diameter at breast height (DBH), height (H) and their combination (DBH^2*H) were tested as independent variables. In the models, easily measurable DBH gave a considerably higher coefficient of determination than H. Combining both DBH and H in the models did not improve the equations. The equations provided logical biomass predictions and they had high coefficient of determination. Fresh mass equations can be used in predicting the value of trees in local markets and dry mass equations for estimating the amount of residual biomass in mature rubber tree plantations in southern Thailand.

Keywords: Tree biomass, biomass equations, dry mass, fresh mass, branch mass, stump mass

INTRODUCTION

Rubber tree (*Hevea brasiliensis*) is cultivated for latex production in all tropical zones on a total land area of about 9,675,000 ha. Thailand is currently the world's largest natural rubber producer (Jawjit et al. 2015) and most of the concentrated latex produced in Thailand is exported. The economic lifetime of a rubber tree is 25–30 years and about 3–4% of the rubber tree growing area is cut down for replanting annually (Krukanont & Prasertsan 2004, Chantuma et al. 2012). Thus, 90,000–120,000 ha of mature rubber plantations are clear-cut annually. The majority (68%) of the plantations are in the south of the country (Chantuma et al. 2012). Rubber production has a strong impact on the rural economy and alleviation of rural poverty since rubber producers are mainly smallholdings which represent more than 85% of the total rubber area in Thailand (Chantuma et al. 2011). In Thailand, smallholder rubber production has been successful in moving households and communities out of poverty (Fox & Castella 2013).

In addition to latex production, rubberwood is also a good source of raw material for sawmill and factories producing plywood product such as furniture and kitchenware. Larger-size branches (> 5 cm in diameter) are used for charcoal production but rubberwood logging residues are generally not utilised. In Thailand the residues are usually burned before preparing the site for replanting. Residual rubber tree biomass can be used to generate electricity in rural areas (Krukanont & Prasertsan 2004). The utilisation of this resource for generation of energy could provide small and steady additional income to rural farmers. Supply of rubberwood logging residues would be secure in the long term due to the thriving rubber industry. In addition to small branches left at the site, sawmill waste (sawdust, wood off-cuts) can also be utilised for energy (Krukanont & Prasertsan 2004).

When grown on non-forested land, rubber trees could also act as carbon sink by sequestering carbon in biomass and indirectly in soils. Carbon sequestration in biomass and carbon stock changes in soil during the lifecycle of rubber tree plantations have been studied widely (e.g. Blécourt de et al. 2013, Petsri et al. 2013, Satakhun et al. 2013, Blagodatsky et al. 2016). In these studies carbon bound in biomass has been determined with direct carbon models relating diameter to tree carbon content, or biomass has been first estimated with biomass models and dry mass of trees was then converted to carbon content of the trees. These studies did not separate tree components and were developed to be used for a wide range of tree sizes ranging from 1-year-old trees to mature trees. Petsri et al. (2013) used biomass data in the relationship of rubber tree diameter at breast height (DBH) with dry weight of stem plus branches, leaves and roots. Their model did not separate stem and braches and thus could be used for determining crown biomass.

The most common method for estimating tree biomass is using regression analysis and allometric biomass models. Equations are developed by weighing entire trees or their components and relating weight to easily measurable dimensions, such as DBH and height (H). Several studies presenting biomass models of rubber trees have been published. However, studies concentrating on trees at clear-cutting age and size are scarce. Most studies have used sample trees ranging from very small and young trees to trees at clear-cutting and regeneration age (e.g. Yang et al. 2005, Saengruksawong et al. 2012). The models did not report the different biomass components, especially branches and stumps, which are both important when considering residual use of biomass. On the contrary, biomass models for total aboveground dry mass of rubber trees have been widely published although diameter (or girth) was measured at different heights. Using equations based on different heights of measured diameter can result in considerable differences in biomass of trees having the same diameter but measured at different heights (Sone et al. 2014). Due to this, the equations cannot be compared with equations using DBH measured at 1.3 m aboveground (Rojo-Martínez et al. 2005, Maggiotto et al. 2014).

Reliable estimation of biomass on a given area is the basis for all productivity and operational calculations. There is lack of equations for determining residual (crown and stumps) biomass in stands at the clear-cut phase. There is a need to improve the estimation of rubber tree crown biomass, since the interest in the utilisation of this resource for energy or other purposes is currently increasing. Since in southern Thailand rubberwood is generally sold fresh in the field, models for estimation of fresh mass of trees are also needed.

The main aim of this study was to construct fresh and dry mass biomass functions for mature stands at clear-cutting age. Development of biomass equations requires biomass data on stem, crown and stump–root system of sample tree. Direct measurement of tree biomass is often not feasible in practice. Therefore, the biomass estimates use regression models based on easily measurable tree variables.

MATERIALS AND METHODS

The study was carried out in Songkhla Province in southern Thailand. The rubberwood plantation used in the study was located close to Hat Yai (6° 54' N, 100° 19' E). In southern Thailand rubber tree plantations cover 1.8 million ha (Chantuma et al. 2012), of which 300,000 ha is in Songkhla province (Krukanont & Prasertsan 2004). The region experiences a tropical monsoon climate. The temperature at Songkhla varies between 22 and 35 °C depending on the season and total annual precipitation is 1720 mm, most of which falls in October till December.

Altogether 18 trees (clone 600) from a rubber tree plantation planted in 1991 were sampled in the beginning of September 2016. Stand density at the time of sampling was 357 trees ha^{-1}. The stand was no longer tapped. Only normal living trees without defects (broken tops, cracks) growing inside the plantation (no border trees sampled) and covering the whole diameter range (DBH 10–30 cm) in the plantation were sampled. The sampled trees were numbered and marked at ground level and at 1.3 m.

Before cutting the trees, their DBH and diameters at stump height were measured at two opposite directions with a precision of 1 mm. Trees were felled using an excavator by digging out the soil around the tree and pushing it to the ground. Tree height, measured using measuring tape after felling, was the length from the stump to the top of the tree. Branches and tops of stems were marked with different colours indicating diameters of 3 and 5 cm. All leaves, including petioles, were separated from the trees and weighed. Branches were divided into thin (< 3 cm in diameter) branches that were left at site unutilised and thick branches (3–5 cm in diameter) that were used for charcoal production. Fresh weights of these tree components were weighed using a scale to a precision of 1 g. Stem (tree parts > 5 cm in diameter) as well as stump and roots (soil removed) were measured using a scale mounted in an excavator boom with a precision of 100 g. Root diameters over 2 cm that were broken during excavation were tallied for diameter. Components from each tree were sampled for determination of moisture content. All leaves, and thin and thick branches of a sample tree were piled and a representative sample of around 500 g was taken from each component, weighed immediately in the field, placed in sealed plastic bags and stored in the field in boxes filled with ice. Three discs were cut from the stem using a chainsaw from the top, middle and lower sections and one disc was taken from the stump. The moisture samples were dried at 80 °C in the laboratory at Kasetsart University. Moisture contents of all samples were calculated. Based on the moisture content, dry weights of all measured components of all trees were calculated. The form of allometric biomass equation used was

$$Y_i = a\, X_i^b e_i \qquad (1)$$

where Y_i = weight of the i^{th} sample tree, a and b = model intercept and slope respectively, e_i = random error associated with estimating the weight of the i^{th} sample tree, X = independent variable and i = any one of the sample tree. DBH is the most commonly used parameter because it can be easily measured in the field with great precision. In this study, we tested height and the incorporation of height into the equation together with DBH as DBH^2*H. The models were fitted to data using ordinary least squares regression analysis after logarithmic transformation to linear form ln(Y) = ln(a + b) × ln(X). The slight systematic bias introduced by this log-transformation was corrected with the correction factor proposed by Meyer (1941), i.e. correction with $s_e^2/2$, where s = residual of the equation. Differences in moisture content of the components were tested with analysis of variance. An arcsine transformation was carried out prior to analysis for variables expressed as percentages.

RESULTS

Moisture content

Moisture content was lowest in stems and stumps (each 43%) and increased with decreasing size of the components (Figure 1). Moisture contents of thin and thick branches were 8 and 3% higher respectively than the stems and stumps. Leaves had the highest moisture content

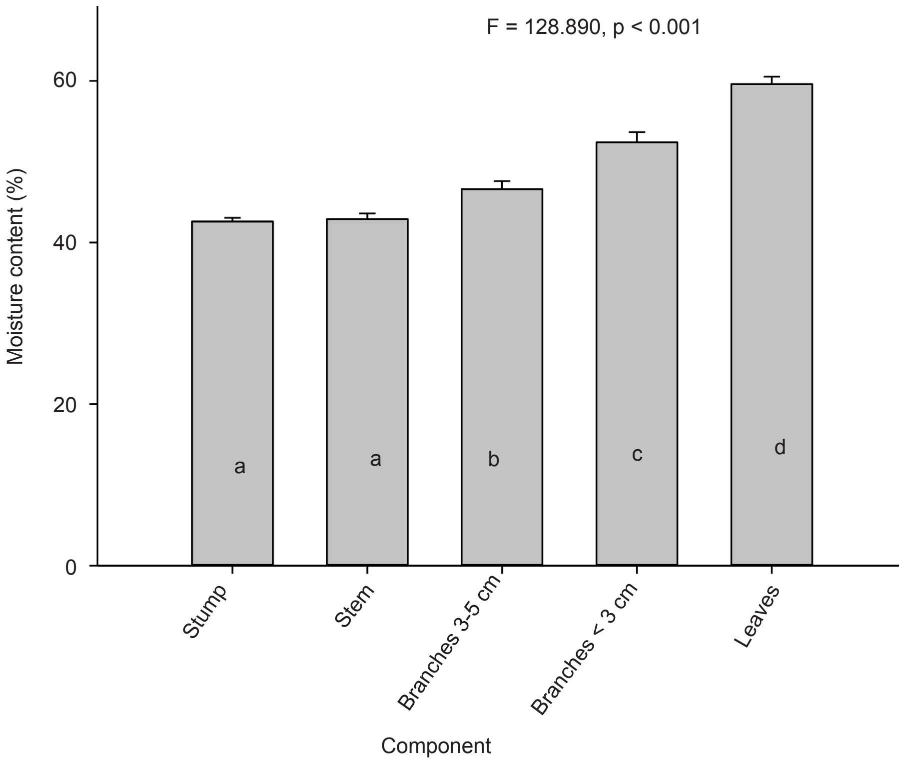

Figure 1 Moisture content of rubber tree biomass components; bars show standard error

(60%). Differences in moisture contents of the components were significant. DBH did not correlate significantly with moisture content even though stem moisture content correlated almost significantly ($r = -0.437$, $p = 0.070$) with diameter, indicating that bigger trees have lower moisture content than smaller trees. Moisture content of leaves correlated significantly and positively with moisture contents of stems ($r = 0.540$, $p = 0.021$), thick branches ($r = 0.799$, $p < 0.001$) and thin branches ($r = 0.715$, $p = 0.001$).

Fresh and dry mass equations

In the biomass models DBH as independent variable gave a much higher coefficient of determination and smaller coefficient of variation than H (Tables 1 and 2). Incorporating H into the model (DBH^2*H) did not increase the prediction. Thus, DBH was, in all cases, the best predictor of rubberwood biomass. The stem models had the highest coefficient of determination (98%) both for dry and fresh mass (Figure 2, Tables 1

Table 1 Equations for fresh mass of rubberwood

Component	DBH					H					DBH^2*H				
	a	b	r^2 (%)	V (%)	SE	a	b	r^2 (%)	V (%)	SE	a	b	r^2 (%)	V (%)	SE
Leaves	0.00691	2.378	66.3	62.9	0.577	0.00010	3.886	43.2	86.8	0.749	0.001897	0.943	63.1	66.4	0.605
Branches < 3 cm	0.01400	2.588	84.7	38.9	0.375	0.00007	4.474	61.7	64.9	0.593	0.003124	1.036	82.1	42.3	0.406
Branches 3–5 cm	0.02023	2.383	80.4	41.8	0.401	0.00032	3.858	51.4	70.0	0.631	0.005615	0.943	76.2	46.4	0.442
Stem	0.07939	2.790	98.1	13.4	0.133	0.00007	5.239	84.4	39.3	0.379	0.012910	1.133	97.9	13.8	0.138
Stump	0.04258	2.469	88.6	30.9	0.302	0.00021	4.328	66.4	55.5	0.518	0.009940	0.991	86.3	34.0	0.331
Branches < 5 cm	0.03536	2.469	87.4	32.7	0.319	0.00029	4.165	60.7	61.2	0.564	0.008788	0.984	84.0	37.2	0.360
Leafless aboveground	0.11329	2.713	98.3	12.0	0.120	0.00016	5.088	81.8	41.4	0.398	0.020784	1.099	97.6	14.5	0.145

Models have the form $Y = aX^be$ where Y = mass (kg), X = DBH, H or DBH^2*H (DBH in cm, H in m), a and b = constants, r^2 = coefficient of determination, V = coefficient of variation, SE = standard error, DBH = diameter at breast height, H = height

Table 2 Equations for dry mass of rubberwood

Component	DBH					H					DBH^2*H				
	a	b	r^2 (%)	V (%)	SE	a	b	r^2 (%)	V (%)	SE	a	b	r^2 (%)	V (%)	SE
Leaves	0.00193	2.499	69.1	61.8	0.569	0.00002	4.191	47.5	85.7	0.742	0.00048	0.995	66.3	65.1	0.594
Branches < 3 cm	0.00738	2.551	84.7	38.2	0.369	0.00003	4.483	63.9	61.6	0.568	0.00164	1.024	82.6	41.0	0.394
Branches 3–5 cm	0.01074	2.382	81.7	39.9	0.384	0.00003	3.942	54.6	66.5	0.605	0.00289	0.946	78.0	44.1	0.421
Stem	0.03510	2.863	97.8	14.5	0.145	0.00002	5.420	85.6	38.8	0.374	0.00556	1.165	98.0	14.0	0.139
Stump	0.02440	2.470	87.9	32.0	0.313	0.00012	4.337	66.1	56.0	0.522	0.00568	0.991	85.7	35.0	0.340
Branches < 5 cm	0.01854	2.451	87.6	32.2	0.314	0.00012	4.212	63.2	58.4	0.541	0.00452	0.980	84.8	35.9	0.348
Leafless aboveground	0.05155	2.783	98.1	13.4	0.134	0.00005	5.195	83.4	40.5	0.390	0.00885	1.129	97.7	14.6	0.145

Models have the form $Y = aX^be$ where Y = mass (kg), X = DBH, H or DBH^2*H (DBH in cm, H in m), a and b = constants, r^2 = coefficient of determination, V = coefficient of variation, SE = standard error, DBH = diameter at breast height, H = height

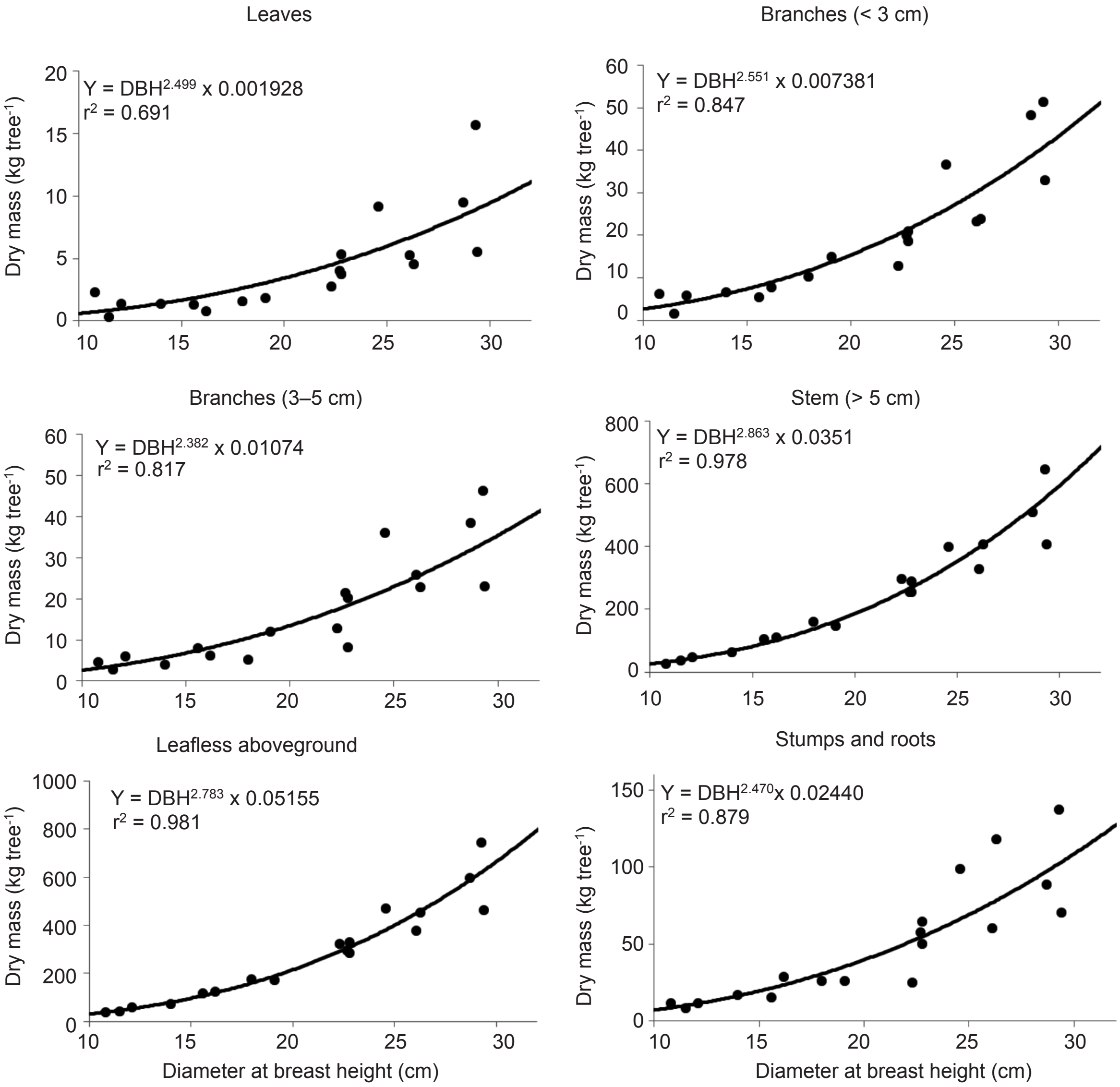

Figure 2 Dry mass equations for rubberwood tree components; Y = mass (kg) and r^2 = coefficient of determination

and 2). Mass equations for stump and branches < 5 cm also had high coefficient of determination (84–86%). The coefficient of the equations decreased with decreasing size of the component. Leaf mass had the lowest coefficient of determination, i.e. 63–66%.

All leaves and branches were collected and measured precisely, but due to mechanical felling of the trees, some roots broke in the process and were left in the soil. The number and mean diameter of roots > 2 cm that were broken and left in the ground for each stump were determined. On the average nine roots (standard deviation (SD) = 4.8) > 2 cm had broken in each stump. Mean diameter of the broken roots was 4.2 cm (SD = 0.8 cm) (Figure 2).

The additivity of the biomass models was compared by calculating predictions for each diameter with different component equations (branches < 3 cm, branches 3–5 cm and stems) and comparing these values with values obtained with the equation for leafless aboveground biomass (Figure 3). The estimates were close to each other with maximum difference being 2%, showing that the additivity of the component equations was good. Within the sample trees, the two estimating methods gave very similar results.

DISCUSSION

The estimation of stem volume and tree biomass is needed for both sustainable planning of forest resources and for studies of energy and

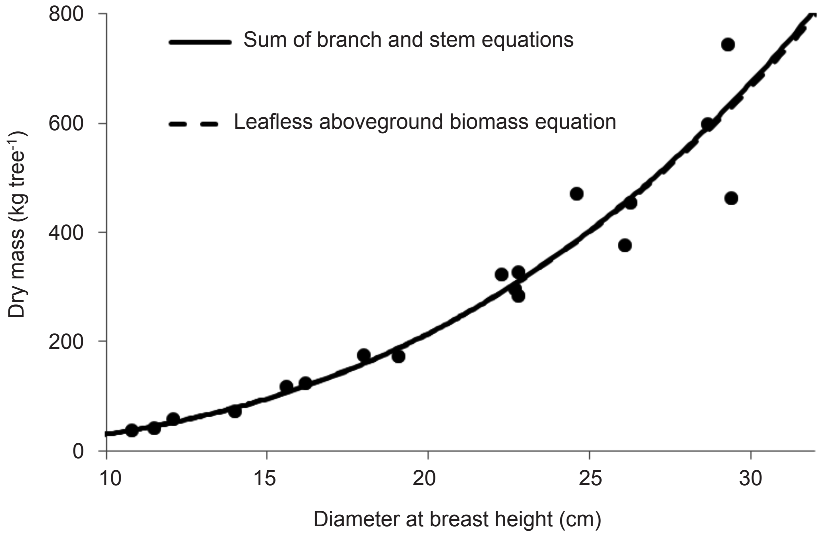

Figure 3 Comparison of predictions of leafless aboveground biomass by summed values of component equations (branches < 3 cm, branches 3–5 cm and stems) with equations for leafless aboveground biomass

nutrient flows in ecosystems. In this investigation allometric biomass equations for rubber tree components were derived in the form of power functions. Such allometric models are widely used in studies of tree biomass, including in vast majority of European studies. Regression techniques have been widely used in biomass studies (Crow & Schlaegel 1988). Generally the dry weights of destructively harvested sample trees and their components are related by regression equations to a readily measurable dimension or combination of dimensions. The dimensions most frequently used in regression analysis and describing the allometric structure of trees include tree height and diameter (Zianis et al. 2005).

Tree biomass is primarily a function of DBH and it is relatively insensitive to tree height (Payandeh 1981). Most published European biomass equations are based on DBH (Zianis et al. 2005). In rubber tree stands measurement of height can be difficult due to closed canopies. Also, the variation in height in mature stands within a large diameter range is small. In this study, height was measured accurately after felling the trees. Despite this, H as independent variable in the models gave much lower coefficient of determination that DBH. Even when DBH and H were integrated as independent variables (DBH^2*H) in the models the coefficient of determination was slightly lower than with DBH alone. For tree species in moist tropical forest of west Africa incorporating H to DBH in allometric models did not improve the regression precision (Djomo et al. 2010). According to this study, height was a poor predictor of rubberwood biomass. On the contrary, DBH described best the allometric relationship and was also easier to be measured than tree height. Height and other parts such as crown length and volume are not easy to measure in the field. To avoid defects and scars from rubber tapping, diameter has been measured in some studies at heights of 1.2, 1.5 and 1.7 m. Tapping height depends on the age of trees and, in old trees, it can be over 1.7 m. Thus, we used DBH (1.3 m), which is used in forestry as a standard. To increase reliability, the diameter was measured from two opposite directions and a mean was calculated.

Living trees acquire moisture through water intake from the soil. Moisture content varies from one tree part to another. Since moisture content of live trees varies with season, the sampling date, in addition to moisture content, could affect the fresh mass of leaves. Moisture content was similar in stems and stumps and moisture content increased when moving to smaller branches and leaves. However, moisture content of all components reported by Maggiotto et al. 2014 for a study done in Brazil was 4–5% units higher than in this study.

Rainy season in southern Thailand usually begins in early September, the time during which this study was conducted. Rubber trees shed their leaves and renew them every year. In southern Thailand the defoliation generally starts in February. Defoliation and development of new leaves can be somewhat interspersed in time. In clonal plantations the timing of defoliation was probably quite uniform. Some trees may remain completely defoliated for days, whereas others form new leaves before all the old leaves have dropped (Rojo-Martínez et al. 2005). Dry mass of leaves in this study increased with increasing stem diameter. This is in contrast with the results of Rojo-Martínez et al. (2005) who found the leaf mass of trees in the range of 15–40 cm DBH to be quite stable (11–15 kg leaves tree^{-1}) and the 15-cm diameter trees even had more leaves than trees with greater DBH. In the present study, similar to Rahaman and Sivakgumaran (2001), the same amount of leaves was reached only when trees were 30 cm in DBH. The proportion of leaves in total biomass in this study dropped from 1.7% in small trees (8 cm DBH) to 1.2% in large trees (30 cm) (Table 3). Chantuma et al. (2012) reported the proportion of leaves in 25-year-old trees to be 1.4%.

The main aim of the present study was to determine equations for biomass components not currently used commercially. Stems and branch components > 5 cm in diameter are currently widely used. Thus, we concentrated on smaller branches and stumps. The recovery of branches was 100%, but for stump there were broken roots, decreasing the recovery of stump and root mass. Soil was removed from stumps before weighing, but in some cases small amounts of soil remained. Trees were felled using excavator that dug the soil around the tree and pushed the tree to the ground. For the purposes of utilisation, the amount of recovered stump and root biomass was satisfactory.

Biomass of all components increased with increasing tree size. However, the proportion of branches < 5 cm in diameter decreased with increasing tree diameter. In trees with 10 cm DBH, branches accounted for 24% of total biomass, When DBH increased to 20 and 30 cm, only 11 and 10% respectively of dry mass consisted of branches. Trees 10 cm in DBH had 5 kg branches (< 5 cm in diameter), and trees with 20 and 30 cm DBH had 29 and 77 kg branches respectively (Table 3).

Dry mass of stumps increased from 7 kg tree^{-1} for trees with DBH of 10 cm to 40 and 109 kg tree^{-1} for the 20 and 30 cm DBH trees respectively. Stumps and roots comprised 19% of the biomass in 10 cm trees and this value decreased to 16 and 14% in trees having 20 and 30 cm DBH. This concurred with the model by Blagodatsky et al. (2016) which showed that 35-year-old rubber tree stands had 14% of their biomass belowground (Table 3).

Table 3 Fresh and dry mass of rubber tree components in trees of different sizes

DBH (cm)	Fresh mass tree^{-1}					Dry mass tree^{-1}				
	Leaves	Branches < 3 cm	Branches 3–5 cm	Stem	Stump	Leaves	Branches < 3 cm	Branches 3–5 cm	Stem	Stump
8	1	3	3	26	7	0	1	2	14	4
10	2	5	5	49	13	1	3	3	26	7
12	3	9	8	81	20	1	4	4	43	11
14	4	13	11	125	29	1	6	6	67	17
16	5	18	15	182	40	2	9	8	98	23
18	7	25	20	252	54	3	12	10	138	31
20	9	33	25	339	69	3	15	13	186	40
22	11	42	32	442	88	4	20	17	245	50
24	13	52	39	563	109	5	24	21	314	63
26	16	64	48	704	133	7	30	25	395	76
28	19	78	57	866	159	8	36	30	488	92
30	22	93	67	1049	189	9	43	35	595	109
32	26	110	78	1256	222	11	51	41	715	127
34	30	129	90	1488	257	13	60	48	851	148
36	35	149	103	1745	296	15	69	55	1002	170

DBH = diameter at breast height

Comparison of the present equations with those published earlier was difficult due to differences in the measuring height of diameter ranging from 0.2 to 1.7 m. In most cases the equations were based on trees having an age variation from 1 year old to mature trees. The aim for model development has been to study carbon sequestration in an age series of plantations. Our aim was to study stands where tapping had ended and the stands were to be clear-cut.

A desired feature of equations for tree components is that the sum of predictions for the individual tree component equals the prediction for the whole tree. A common problem in biomass equations is poor additivity of the mass obtained using dry mass equations for the different components of a sampled tree. When dry mass equations for the different components are calculated independently, and when the sampling errors of the different components differ, the result may be a group of regression equations behaving irrationally with respect to each other (Cunia & Briggs 1984). Missing data for some components can hinder additivity. Several procedures for solving the problem have been presented (Cunia & Briggs 1984). To increase additivity in the present study, there were no missing data in the sample tree component biomass and the same independent variables were used in the dry mass models of different components. The additivity of the presented equations was good.

The present biomass equations can be used to estimate biomass of rubber tree plantations at clear-cut age when latex tapping is finished. However, one should be cautious when applying these equations for other clones and areas. Increasing the number of biomass model trees from other areas would be needed to establish generalised biomass equations. Equations for residual biomass can be used for estimating the amount of biomass available from rubber tree plantations for power plants in southern Thailand. The biomass equations can be applied directly to tree level inventory data, when the measured dimension of trees is DBH. Since the selling of rubber trees is currently based of fresh weight, often visually estimated, the presented fresh mass equations offer a more precise way to estimate weights of the rubber tree and its components. However, more information on the changes in moisture content during the year would be needed in order to make season-specific fresh mass equations. The influence of rubber tree clone on the relationship between stem diameter and biomass or volume is not well-known and contrasting results have been obtained (Khun et al. 2008, Blagodatsky et al. 2016).

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