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Full Length Research Paper

Modelling dry matter allocation within *Alnus nepalensis* D. Don trees in Nepal

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The models describing dry matter partitioning and allocation to various components within the individual trees would be important inputs for process-based individual tree growth models and simulation systems. This study presents the allometric and quadratic models fitted to the ratios of biomass data of various components (leaf, branch, stem, and root) of the individual tree against diameter at breast height (dbh). Data from twenty-seven *Alnus nepalensis* trees in mid-hill region of Nepal were used to develop the models. The most attractive fit statistics were found with the model of ratio of stem to leaf biomass ($R^2 = 0.95$), and similarly the models with the ratios of leaf to branch, leaf to above-ground, and leaf to total-tree biomass explained more than 90% variations. The results also showed that leaf, branch, above-ground and tree-total biomass amounts rapidly increased with increasing dbh. The ratios of leaf to branch, leaf to above-ground, leaf to total-tree, crown to total-tree, and root to total-tree biomass rapidly decreased with increasing dbh in earlier stage and gradually levelled off in the later stage. The models can be used for estimation of biomass of components of the individual tree. These models may also be useful inputs for process-based individual tree growth models which have been gaining the popularity in forest science in recent years.

Key words: *Alnus nepalensis*, biomass model, biomass ratio, dry matter allocation, Nepal.

INTRODUCTION

Estimation of dry matter (biomass) of total-tree and component-tree would be important for both forest management and scientific forestry purpose. The individual tree-based growth models (empirical or process-based) require biomass of each individual tree component such as leaf, branch, stem, bark and root as inputs that can be estimated from dendrometric information (Bartelink, 1996; Battaglia and Sands, 1998; Cannell and Dewar, 1994; Henry et al., 2011; Sharma, 2011; Vanclay, 1994). With increasing value of wood, the interest in and use of biomass and economic valuation of trees based on their component parts have rapidly grown (Avery and Burkhart, 1994; Husch et al., 1982; Ter-Mikaelian and Korzukhin, 1997). The total-tree and component-tree biomass models are based on allometric relationship of biomass with tree dimension such as diameter at breast height (dbh) (Henry et al., 2011; Keith et al., 2000; Sharma, 2011; Ter-Mikaelian and Korzukhin, 1997; Zianis et al., 2005). The standing tree biomass, which is also considered as important measure of site productivity, can be estimated using previously established biomass models and biomass tables. Since standing tree biomass of certain tree species reflects a potential productivity of site, a sustainable harvest plan for that species can be formulated based on the model-predicted biomass. Also, information of the individual tree or stand biomass provides a fundamental basis to assessment of carbon dynamics such as carbon acquisition and allocation within a particular ecosystem (Jarvis and Laverenz, 1983; Meadows and Hodges, 2002).

Of all tree components, foliage (leaf and twig) plays a key role in tree growth, as it is the main site of radiation, interception and photosynthesis and therefore very important for growth of a tree and its parts (Mauseth, 2003). The foliage amount is affected by spatial distribution of branch biomass within a tree, and foliage amount is related to sapwood area, because a functional relationship exists between them (Jarvis and Laverenz, 1983). The photosynthetes formed in foliage are translocated to different components and deposited therein. The amounts of foliage and branches are also functionally related to sapwood area of stem of the tree (Maguire and Hann, 1987; Shinozaki et al., 1964). Sapwood in the tree stem acts as a pipe for transportation of water and minerals from the roots to foliages. The stem sapwood area is also proportional to foliage biomass and each unit of foliage requires a unit pipeline of sapwood to conduct water from the roots (Shinozaki et al., 1964). Although, contribution of foliage biomass to total-tree biomass was too small (approximately, 4%), foliage is solely responsible for most of the transpiration and respiration processes and carbon uptake in a tree (Makela, 1986). Tree foliage is also very sensitive to climatic change and silvicultural treatment. Quantification of tree foliage in terms of biomass would be important from the assessment of site productivity point of view (Parresol, 1999). Plant physiologists have long recognized the importance of leaf area index and stem sapwood area as factors affecting many tree and stand level processes and functions such as photosynthesis, gas exchange, conductance, stand productivity, and canopy dynamics (Meadows and Hodges, 2002). The investigations on the dry matter partitioning and allocation within the individual trees have been carried out for some plants (Cannell, 1985; Steinberg et al., 1990; Wilson, 1988; Barrett and Ash, 1992).

Alnus nepalensis is a broad-leaved species and widely distributed in south Asia in altitudes between 600 m and 3000 m, but in Nepal between 900 and 2700 m (Lamichhaney, 1995). It prefers moist and well-drained soils and does not require high soil fertility but prefers permeable soils (Orwa et al., 2009). *A. nepalensis* constitutes 2.9% of total standing volume in Nepal (DFRS, 1999). This is one of the fast growing tree species, and has shorter rotation and therefore community forestry program in Nepal has given a high priority to this species for plantation, especially on the abandoned or degraded land in mid hill region (Jackson, 1994; Lamichhaney, 1995). *A. nepalensis* is capable of fixing significant amounts of nitrogen (Sharma and Ambasht, 1984, 1988). It is a promising fuel wood tree species, and can also be used for fodder, timber, and tannins and dyes (Jackson, 1994; Lamichhaney, 1995). Many studies have been made for this species in Nepal (Lamichhaney, 1984, 1995; Napier and Robbins, 1989; Orwa et al., 2009; Sharma, 2003, 2011; Sharma and Ambasht, 1984, 1986, 1988, 1991; Sharma et al., 1998). However, to the knowledge of the author, no studies has been carried out so far on dry matter partitioning and allocation to various parts of the individual *A. nepalensis* trees. Therefore, this study aims at fulfilling this gap. The developed models would be useful for quantification of total-tree and component-tree biomasses, and assessment of carbon dynamics such as carbon acquisition and allocation within a tree.

MATERIALS AND METHODS

Sampling and measurements

This study was carried out in a part of mid-hill region (Parbat and Syanja districts) of Nepal, and approximate latitude and longitude of a centre of the study area is 28° 13’ N and 83° 42’ E, respectively. The study area was located between Pokhara and Baglung cities (Figure 1).

Nine different *A. nepalensis* stand sites at Niyali, Patle, Bhogsing, Pakhure, Chhahari, Lunkhu, Duktan, Ghantari, Ghante villages were identified for measurements and felling. The selected stands were of different sizes and represented wide ranges of altitude (1150 to 2250 m), slope (25 to 55%), aspects and soil nutrient levels (Sharma, 2003, 2011). The seven stands were naturally originated and two stands originated from plantation, and both types of stands had a history of some thinning or selective cuttings carried out by local people. But cultural treatments (pruning, irrigation, and fertilization), over-disturbances or any exploitation due to anthropogenic or other factors were not reported. Only twenty-seven *A. nepalensis* trees of varying size [dbh (4.5 to 45.2 cm) and total-height (5.8 to 33.5 m) were selected for felling. The selected trees were representative to all possible size, age, site productivity and stand conditions within the study area. The diseased, buttressed, malformed and top-broken trees were excluded from being sampled. Detailed sampling design, felling and measurement procedures have been reported in Sharma (2003). Tree felling and root excavation was carried out through October, November and first week of December. All components of each felled tree (leaf, branch, bark, and root) were separated and weighted in-situ immediately after felling and extraction of roots. All parts of tree weights were recorded to a precision of 0.01 kg. It was assumed that about 1 to 2% fine roots of few sample trees could not be accounted for due to the entangled to the roots of neighbours or trapped by big rocks.

Depending on the size of sample trees, a good representative sub-sample from each green component (leaf: 0.5 to 2 kg, branch: 1 to 3 kg, stem: 1 to 5 kg, bark: 1 to 2 kg, root: 1 to 3 kg) was carried to a properly ventilated shelter (open shade) for air-drying and kept until constant weight was obtained. The numbers of days for completion of air-drying varied from 10 to 14 days depending on types of tree components. All air-dried sub-samples were then subjected to oven-drying until constant weight was obtained. The details of air-drying and oven-drying for the samples are reported in Sharma (2003, 2011). The oven-drying processes completed at temperatures between 70 and 85°C depending on types of tree components. Requirements of temperature and period for drying might vary from tree part to part as drying depends largely on the amount of moisture content, fibre density and chemical constituents of plant tissues (Khanna and Chaturbedi, 1994). Dry weight of each component of a tree was then calculated using dry to green weight ratio estimated from the samples. Moisture content of each component was estimated using following formula:

$$\% \text{ Moisture} = (\text{green biomass} - \text{oven dry biomass})/ \text{oven-dry biomass}) \times 100 \qquad (1)$$

Model development

The scatted plots of ratio of oven-dry biomass of each tree component against dbh suggested a non-linear relationship. Such

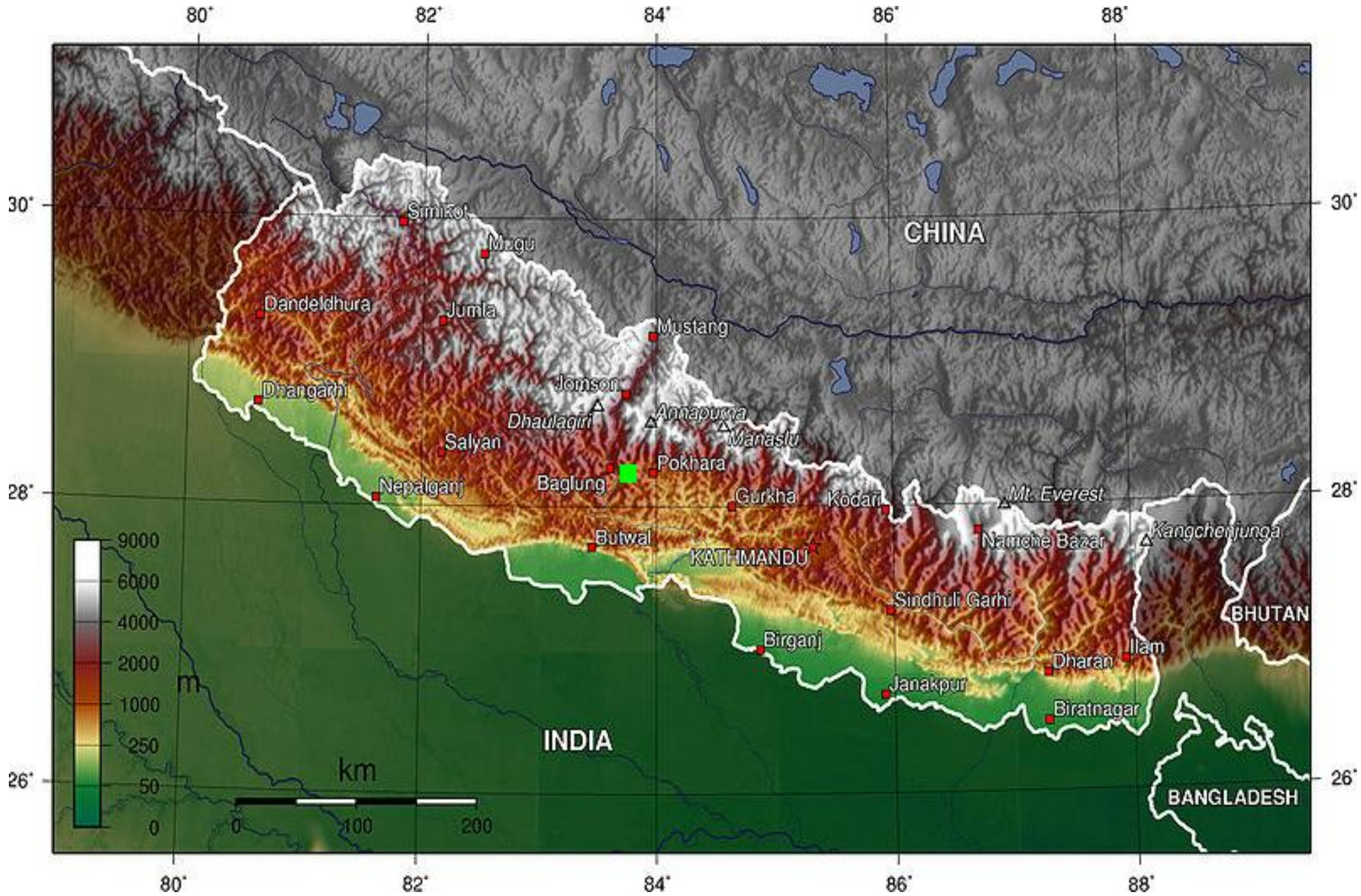

Figure 1. Approximate location of study area (a square filled with green colour). Source: wikimedia.org.

relationship was best described by an allometric function (Equation 2) except ratio of stem to branch biomass, which was best described by quadratic function (Equation 3).

$$R_i = b_1 D_i^{b_2} + \varepsilon_i \tag{2}$$

$$R_i = b_1 + b_2 D_i^2 + \varepsilon_i \tag{3}$$

Where R_i = biomass ratio for tree *i*, D_i = dbh of tree *i* (cm), b_1, b_2 = unknown parameters, and ε_i = unexplained variance, which is assumed to be independent and normally distributed with zero mean constant variance.

The model parameters were estimated using PROC NLIN in SAS (SAS Institute Inc., 2008). The fitted models were evaluated using coefficient of determination (R^2), root mean squared error (*RMSE*) and residual analysis (Ratkowsky, 1990; Montgomery et al., 2001). The graphs of model curves overlaid on the observed data were also examined to check whether models possess theoretical basis and biological logics. The model validation is an important part of modelling as validation increases the credibility and confidence about the developed models (Vanclay, 1994; Soares et al., 1995; Vanclay and Skovsgaard, 1997). But, validation by splitting data was not considered in this study because of few data. Resource limitation did not allow acquiring new independent data for validation.

RESULTS AND DISCUSSION

The estimates of moisture content in green condition and weight reduction in each component as a result of drying are presented in Table 1. The reduction of moisture content from air-dried sub-samples varied from component to component of the tree (leaf 14%, branch 15%, stem 21%, bark 17%, and root 24%). As a result of different fibre density, nature of foreign materials existed and chemical constituents of plant tissues such a large variation might have occurred (Khanna and Chaturbedi, 1994). When oven-drying the air-dried samples, the reduction of weight varied from 4 to 7%, which seems to be too small. The weight of stem and root reduced more substantially than that in other components. It is due to the fact that density of fibres in stems and roots are higher than in other components. Also more resistant chemical constitutes and foreign materials contained in stem and root tissues may lengthen the drying processes, but weight would substantially reduce after drying.

The observed ratio data of oven-dry biomass amounts were regressed against dbh using allometric function (Equation 2) and quadratic function (Equation 3). The

Table 1. Reduction of weight for different components of *Alnus nepalensis* trees.

Components	Reduction (%) with respect to in-situ green weight	
	Air-dry	**Oven-dry**
Leaf	53	57
Branch	50	54
Stem	44	51
Bark	46	50
Root	43	49

Table 2. Parameter estimates and fit statistics of models (Equations 2 and 3) fitted to data.

Biomass ratio (R_i)	Parameter estimates		Fit statistics	
	b_1	b_2	*RMSE*	R^2
Leaf to branch	1.5053	-0.6055	0.035	0.92
Leaf to above-ground	0.3866	-0.5661	0.008	0.93
Leaf to tree-total	0.2177	-0.4603	0.005	0.94
Below-ground to above-ground	0.8651	-0.3630	0.044	0.72
Below-ground to tree-total	0.4770	-0.2512	0.023	0.72
Crown to tree-total	0.5206	-0.1198	0.018	0.72
Bark to tree-total	0.0662	0.1631	0.009	0.62
Stem to leaf	1.3754	0.6259	0.724	0.95
Stem to branch	2.054	0.0003	0.158	0.43
Stem to crown	0.9518	0.2032	0.129	0.73
Stem to root	0.8561	0.3178	0.241	0.76
Stem to above-ground	0.5099	0.0730	0.017	0.73
Stem to tree-total	0.3195	0.1428	0.022	0.80

parameter estimates, fit statistics (for example, coefficient of determination, R^2) and model curves overlaid on the observed ratio data are presented in Table 2 and Figure 2, respectively. The parameter estimates are significant ($p < 0.05$). The most attractive fit statistics were found with model of ratio of stem to leaf biomass ($R^2 = 0.95$), and similarly, model with ratio of leaf to branch, leaf to above-ground, and leaf to total-tree biomass explained more than 90% variations. A ratio of stem to branch data fitted relatively poorly ($R^2 = 0.43$) and model with other ratio data options not presented in Table 2 showed non-significant parameter estimates ($p > 0.05$). Residual graphs of all models did not show systematic deviations confirming that the models described the data well.

Branch, above-ground and total-tree biomass decreased more rapidly with increasing dbh than the individual component biomass of leaf, crown and root. As a consequence, ratios of leaf to branch, leaf to above-ground, leaf to tree-total, crown to tree-total, crown to above-ground, below-ground to above-ground, below-ground to tree-total and root to tree-total biomass decreased rapidly with increasing dbh and at earlier stage and nearly levelled off in the later stage (Figure 2, first and second panels). The reason behind this might be that growth of the tree as whole and its components tend to stop when tree approaches to old age or when adequate growth resources are not available (Vanclay, 1994; Zeide, 1993). In general, when tree is young growth increases exponentially in all dimensions (height, diameter), and then gradually slows down to reach a constant and finally ceases to an old age. The ratios of stem to each of the components of the tree increased with increasing dbh (Figure 2, last two rows) as expected. Such increment is substantially higher with ratio of stem to leaf as stem needs larger amounts of photosynthetes for its healthy growth and development for ample physical strength required to support entire weight of crown (Cato et al., 2006; Dean and Long, 1986; Niklas, 1995; Niklas and Spatz, 2004; Khanna and Chaturbedi, 1994).

Generally, in younger age, ratio of below-ground to above-ground biomass is higher than in the later age (Smith and Smith, 2001). This indicates that most of the production (photosynthetes) goes to the root for its growth and development, and increase the strength required to perform supportive functions of the roots. Allocation of a large amount of photosynthetes to the roots enables tree to reach below-ground water and nutrients, and tree could survive on less fertile and harsh environment. Relatively higher ratio of below-ground to above-ground biomass in *A. nepalensis* tree (Figure 2,

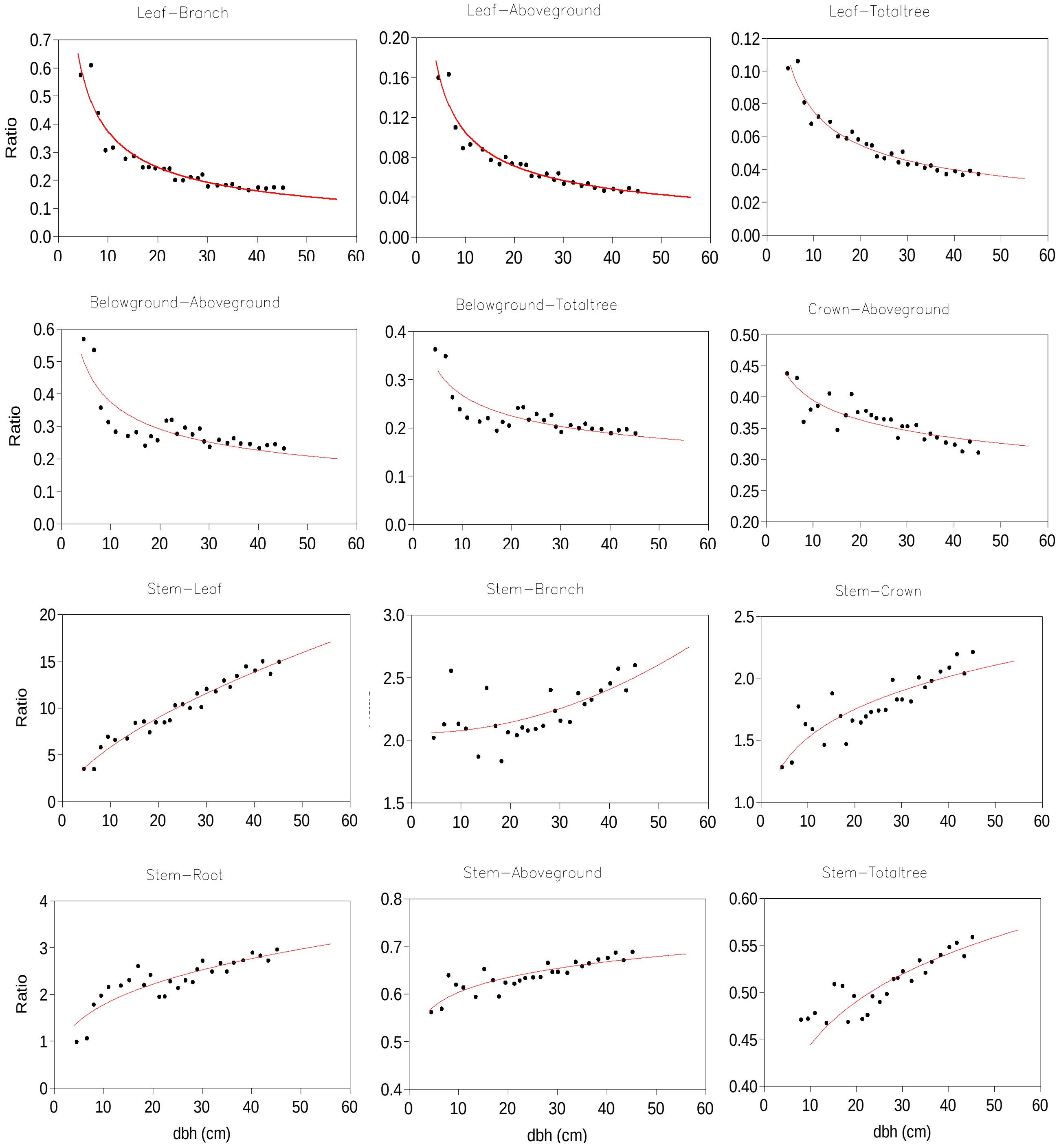

Figure 2. Model curves overlaid on the observed data.

first in second panel) also shows why this species in its earlier stage is able to grow on the degraded land. Decreasing ratio of leaf to branch biomass with increasing dbh (Figure 2, first in first panel) may also be a consequence of crown expansion mechanism (Smith and Long, 1989). Under the open-grown condition, when a tree matures and crown size increases, and biomass amounts of branch and foliage increases. As foliage biomass concentrates towards the end of branches to optimize solar radiation interception, relatively more branch biomass is needed to be strongly supportive to tree-foliage (Smith and Long, 1989; Fansworth and Niklas, 1995). Relatively, more branches can be expected in vigorous and deep-crowned trees than in shallow-crowned ones, resulting in a higher ratio of leaf to branch biomass in shallow-crowned trees.

The models presented in Table 2 may be useful to estimate biomass of various tree components (leaf, branch, root and crown) and total-tree biomass from stem biomass and easily measurable tree dimension such as dbh. Stem biomass can be easily estimated using stem volume equations and stem wood density or specific gravity. For all tree components except branch, a model predicts biomass fairly accurately. Estimated branch biomass would be relatively inaccurate as model fitted the stem-branch ratio data relatively poorly (Table 2). A ratio such as leaf to branch can be used to estimate branch biomass more accurately after leaf biomass is obtained with model of stem-leaf ratio. The developed models may be useful inputs for process-based individual tree growth models which are gaining the popularity in forest science today. The models may also be useful for estimation of biomass of each tree component or biomass of total tree including roots. The model's update through re-calibration and validation against new data from widest possible ranges of size, site quality and stand conditions across the country will be more useful.

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