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AN OVERVIEW OF ALLOMETRIC EQUATIONS USED FOR BIOMASS ESTIMATION IN NEPAL

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ABSTRACT

Estimation of biomass is an important tool in the management of different types of natural forests and plantations in Nepal. It is essential to estimate growing stock (biomass) in a particular area for better management of government-managed forest, private forest and community forests through the use of reliable allometric equations. The importance in producing allometric equations for biomass estimation of tree components for fuel wood and fodder has increased due to assessment of forest carbon in recent years in Nepal. The existing tree-wise allometric equations developed for predicting biomass of tree components are for a fewer number of species. Very few organisations have been involved in biomass studies. Mostly, the equation Ln (W) = a + b Ln DBH (W refers to green or oven-dry weight of tree components in kg and DBH refers to over bark diameter at breast height in cm measured at 1.3m or 1.37 m) has been used for estimation of above-ground biomass for 46 tree and NTFP species in the Terai, Siwalik and Mid-hills of Nepal. The biomass studies have been carried out for three mixed species in the Mid-hills and two mixed species in the Terai. The equation, Ln (W) = a+b Ln (D^2L) has been developed for estimation of foliage, branch and culms of four bamboo species (*Bambusa nutans* sub sp. *nutans*, *B. nutans* sub sp. *cupulata, B. tulda* and *Dendrocalamus hookeri*) in the Terai region of Nepal. These equations for biomass prediction are available for predicting the above-ground tree components (stem, branch, and foliage in most cases) and only for some of the major tree species. There are no equations or models for predicting the below-ground-components of tree biomass (stump and root) in Nepal. The existing allometric equations for estimation of biomass have been developed from a narrow geographical area and small-sized trees in most cases, which has caused the limited use of such equations. Gaps and shortcomings related to developed allometric equations are discussed. Sound government plan and support, amendment in existing rules and regulations, strong coordination among the institutions (government, non-government and private), and use of standard manuals are some of the major future priorities to carry out above-ground and below-ground biomasses in Nepal.

Key words: Allometric equation, Biomass estimation, Application, Terai, Mid-hills, Nepal.

Introduction

The forests supply fuel wood, fodder, poles, timber and many other products to meet the requirement of rural communities since long time. They also provide essential raw materials for national development and help to maintain a sound environment (TISC, 2000). To meet the needs of communities for fuel wood, fodder and litter from the community forests on an annual basis it is necessary to assess quantity of fuel wood and fodder available from these community forests. The demand of fuel wood, fodder and litter has increased significantly due to increasing numbers of forest user groups (FUGs) in the country. In this context, development of allometric equations of different tree and NTFP species are necessary to quantify growing stock (biomass) in a particular area for better management of community forests (>18000 CFUGs) including government-managed and private forests.

There is an obvious need to manage the forests to ensure the sustainable production of the forests to meet the needs of local people according to the management objectives. Planned management requires a data base on growth and yield to determine the utilization schedules (Applegate *et al.*, 1988a). Forest inventory usually tries to estimate the volume or biomass of stem, branches and foliage, but not stump and roots (below ground biomass). This is because stumps and roots are difficult to measure, and they are not often utilized (Pukkala *et al.*, 1990). In future, there is an urgent need of testing the sampling methods developed elsewhere for estimation of branch, foliage biomass and below ground biomass (roots and stump) of different tree species in Nepal. This paper attempts to find out the present status of biomass studies in Nepal, and identifies the gaps and shortcomings.

Very few organizations and projects have been involved in biomass studies in Nepal since 1980s. The Department of Forest Research and Survey (earlier known as Forest Research and Survey Centre) is the main

Critical review of allometric equations developed for biomass estimation in Nepal, its gaps and limitations assists a great deal to the research organizations and individual researchers for effective planning to prioritize and carry out further research.

government organization to carry out biomass studies to develop allometric equations in the country through its biometry section. The Nepal- Australia Forestry Project (NAFP) and Forest Resource Information System Project (FRISP) had carried out biomass studies and developed allometric equations for a number of tree species in the mid-hills. Similarly, the Institute of Forestry and Oxford Forestry Institute have been involved in biomass studies.

Types of allometric equations

Based on the available published and unpublished reports, twenty-three different types of allometric equations have been reported for 50 tree and NTFP species (Appendix 1). In general, the logarithmic transformed model, Ln W=a'+b Ln DBH, was found to be developed for biomass estimation of stem wood, branch wood, foliage, and above-ground wood (green and oven-dry). The tree components used for developing equations differed greatly depending on the purpose of the studies. Joshi (1985) has developed many equations for branch (branch wood plus foliage), branch wood, foliage, stem wood, bark (bole, whorl, crown, branch), whorl (whorl wood plus foliage), whorl wood, whorl foliage, crown (crown wood plus foliage), crown wood, crown foliage, total above-ground (tree) of *Pinus roxburghii* (Appendix 1). The three species, *Cinnamomum tamala*, *Shorea robusta* and *P. roxburghii* have allometric equations for bark. The equation, Ln (W) = a+b Ln (D^2L) has been developed for estimation of foliage, branch and culms of four bamboo species (*Bambusa nutans* subsp. *nutans*, *Bambusa nutans* subsp. *cupulata, Bambusa tulda* and *Dendrocalamus hookeri*) in the Terai region of Nepal (Appendix 1).

Species used in allometric equations by physiographic region

Fifty species (tree, NTFP including four bamboo species) have been used for producing a number of allometric equations. Joshi (1985) has developed many allometric equations for *P. roxburghii* in the Inner Terai (Siwalik). Raeside (1986) has prepared biomass and volume models for *Pinus wallichiana* in the mid-hills and Hawkins (1987) has developed biomass and volume models for *Eucalyptus camaldulensis, Dalbergia sissoo, Acacia auriculiformis*, and *Cassia siamea* in the Central BhabarTerai of Nepal.A number of allometric equations have been developed for 22 tree species (Thompson *et al.*, 1988) in a single study; the major tree species are *Alnus nepalensis*, *P. roxburghii*, *P. wallichiana* and *Schima wallichii*. Similarly, Tamrakar (1999) has developed models for four individual tree species and three mixed tree species in a single study (Appendices 1 and 2). The major species in his study are *Quercus* spp., *Castanopsis* spp. and *S. wallichii*. Acharya *et al*. (2003) have developed two models for mixed tree species for eastern and western Terai (Appendix 2).

Allometric equations have been developed for twelve tree species and four bamboo species in the Terai region of Nepal. The most used species for biomass studies are *S. robusta* (3) and *E. camaldulensis* (3). Five exotic species, *A.auriculiformis*, *C. siamea*, *E. camaldulensis*, *E. tereticornis* and *Tectona grandis*, have also been used in developing equations. The biomass studies on three tree species, *Ficus semicordata*, *B. variegata*, and *P. roxburghii,* have been carried out in the Siwalik (Table 1).

The biomass studies of 33 individual trees and one NTFP species have been conducted in the mid-hills of Nepal. *P. roxburghii* has been studied mostly (four times) in this zone. It is followed by other tree species, *Alnus nepalensis* (2), *Castanopsis indica* (2), *Castanopsis tribuloides* (2), *F. semicordata* (2) and *S. wallichii* (2). Only one exotic species, *Pinus patula*, has been used in biomass study to develop allometric equations (Table 1) in this region.

The biomass studies of two NTFP species, *Daphne bholua* and *Daphne payracea*, have been carried out in high mountains. These two species are very useful for making quality paper.

Use of predictor variables in biomass studies

In most cases, diameter at breast height, DBH (cm), has been used as a predictor variable in allometric equations. In few cases, diameter at 30 cm for *Cassia siamea*, diameter at 50 cm for *B. variegata*, crown diameter and height for *F. semicordata*; crown diameter (m) for estimating oven dry pole of *Leucaena leucocephala*, have been used as predictor variables.

Joshi (1985) has used few predictor variables for estimation of tree components of *P. roxburghii*, which are: basal diameter (cm) for estimation of branch (foliage plus branch wood), branch wood, branch bark, and foliage; mean branch length (m) in a whorl and number of branches in a whorl for estimation of whorl (foliage plus wood), whorl wood, whorl bark, and whorl foliage; diameter at breast height (cm), reciprocal of the height to the crown base and crown base diameter (cm) for estimation of total crown, crown wood, crown bark, and crown foliage; diameter at breast height (cm), total height (m) for tree, stem bole, bole wood, and bole bark (Appendix 1).

Many researchers have given the reasons for using DBH only as a predictor variable for biomass estimation of tree components. Some researchers agree that allometric equations used for producing single-tree biomass tables to predict the weight of an individual tree from its diameter are reliable for undamaged trees of a number of species of Nepal (Applegate *et al*., 1985; Joshi, 1985; Raeside, 1986; Hawkins, 1987). Although, the allometric equations developed from a single predictor variable, DBH can be applied only at the local level.

According to Thompson (1990), single-tree biomass tables developed from allometric equations are useful in circumstances where a population, shows a relationship, which is precise and constant over time, between the component weights of interest and an easily measured variable such as diameter. Thapa (1992) states the advantage in producing allometric equations using DBH as a predictor variable, as DBH can be measured easily with less error than height and increases the utility of biomass tables to the forestry sector. However, the advantage of using DBH lies in the fact that if the relationship (weight and dbh) is valid for a sufficiently large plantation area and if it does not change over a period of time, then the allometric equations used in developing biomass tables can be used in subsequent inventories. Again, this relationship breaks down if the tree has been lopped or pruned, which require a new set of allometric equations to develop tables (Thompson, 1990). Hawkins (1987) used DBH and height as predictor variables for biomass estimation of some species in the Central / Bhabar Terai of Nepal. He tested and rejected the measurement of total height due to time consuming and due to large errors in measurement. The inclusion of height provided only a small increase in the precision of regressions while the time required was three times more for the field inventory. Tree height as a component of the independent variable only increased the regression coefficients by between 2 to 5 %, and they excluded it in the analysis in consideration of the time and effort in measuring tree height in the field. For practical reasons and simplicity of measurement in the field, DBH is the preferred predictor variable for estimation of biomass of tree components (Applegate *et al*., 1988 b). Tandan *et al*. (1988) also agree on that an additional variable of height is not necessary as a predictor variable in consideration of the cost, provided equally efficient prediction models are available with DBH alone. However, Pukkala *et al.* (1990) suggest that DBH as a predictor variable can be used for producing allometric equations for estimation of biomass of tree components at the local level, whereas two predictor variables (e. g., DBH and height) can be used to produce standard allometric equations for estimation of biomass of tree components in a wider area.

Allometric equations by green and oven dry weights

In general, allometric equations are produced for oven-dry weights rather than fresh weight, since the latter will vary due to differing moisture content within a tree, between trees of one species, with length of time after cutting and with sites and seasons. Thus, true comparisons related to biomass of plant material cannot be made from the fresh weights. Further, the use of oven-dry weight provides a standard reference by which different measurements can be compared. Also, further

Table 1 : Species used in developing allometric equations by physiographic region

Region	Species
Terai/Bhabar-Terai (12 tree species; four bamboo species)	Tree species: *Acacia auriculiformis* (2), *Acacia catechu, Cassia siamea, Dalbergia sissoo* (2), *Dalbergia latifolia*, *Shorea robusta* (3), *Tectona grandis*, *Eucalyptus camaldulensis* (3), *Eucalyptus tereticornis, Pterocarpus marsupium, Ficus semicordata , Bauhinia variegata* Bamboo species: *Bambusa nutans* subsp. *nutans, Bambusa nutans* subsp. *cupulata, Bambusa tulda* and *Dendrocalamus hookeri*
Siwalik or Churia Hills including Inner Terai (three tree species)	*Ficus semicordata, Bauhinia variegate* and *Pinus roxburghii*
Mid-hills (33 tree species; one NTFP species)	Tree species: *Alnus nepalensis* (2), *Pinus roxburghii* (4), *Pinus patula*, *Pinus wallichiana*, *Castanopsis indica* (2), *Castanopsis tribuloides* (2) *Bauhinia variegata, Casearia graveolens, Engelhardia spicata, Eugenia operculata, Eurya acuminate, Ficus lacor, Ficus neriifolia, Ficus semicordata* (2), *Fraxinus floribunda, Leucaena leucocephala, Litsea monopetala, Lyonia ovalifolia, Maesa macrophylla, Melastoma malabathricum, Myrica esculenta, Myrsine capitellata, Phyllanthus emblica, Pyrus pashia, Quercus floribunda, Quercus lanuginose, Quercus leucotricophora, Quercus glauca, Rhododendron arboreum, Rhus wallichi, Schima wallichii* (2), *Viburnum coriaceum, Wendlandia coriacea;* NTFP species: *Cinnamomum tamala*
High Mountain	NTFP species: *Daphne bholua* and *Daphne papyracea*

(Figures in parentheses indicate the frequency of species used in allometric equations.)

conversion to other units is usually only possible from dry-weight units, e.g. to energy for fuel, protein content for leaves (Thompson, 1990). Thus, there is no question of importance of oven dry weight equations, however, the green weight allometric equations of different components of a number of tree and NTFP species are larger in number than that of the oven-dry allometric equations in Nepal (Appendix 1).

Gaps and shortcomings

Destructive sampling is difficult due to the existing forest act and rules of government of Nepal. In the present state, biomass studies are dependent on the harvesting schedules of collaborative forest management systems implemented by the Department of Forests (DoF) in the Terai and community managed forests in different parts of the country. Leaf-shedding time of trees and harvesting times are to be the same in a number of tree species, which is an obstacle for a study on foliage biomass. The grant of money to carry out bio mass studies at the national level is also difficult to obtain.

A number of biomass studies (Joshi, 1985; Raeside, 1986; Hawkins, 1987) are based on small trees from a geographically restricted area, which means that the published allometric equations are of local importance only (Pukkala *et al.*, 1990). Standard biomass allometric equations to a great extent are missing in Nepal.

There are many other important tree and non timber forest product (NTFP) species in Nepal which have high value in biomass production for the use of local communities. However, there are very limited allometric equations for predicting the biomass of such species.

In Nepal, allometric equations are only available for estimating the above-ground components of tree biomass and only for some of the major tree species (Sharma and Pukkala, 1990; Laamanen *et al*., 1995; TISC, 2000; Acharya *et al*., 2003). There are no allometric equations available for predicting the below-ground-components of tree biomass, i.e. stump and root biomass, based on the data collected by tree species in Nepal (Eerikanen *et al.,* 2012). However, it is very much essential to estimate carbon stock in the forests of Nepal. Validations of the existing allometric equations are very few. It is necessary to know how safely the developed equations can be used in a certain locality for biomass estimation of single tree species, stand or forest types. Majority of the allometric equations are produced based on green weights of components of tree and NTFP species, which cannot be compared with biomass of the same tree and NTFP species in the same locality or other areas.

Future priorities

In the present scenario of carbon trade, both above and below-ground biomass studies are essential for different species and forest types in five physiographic regions of Nepal. It is an equally important to update the previous allometric equations produced for single tree species in different parts of the country. A strong coordination among the institutions (government, non-government and private), mechanism for availability of capable human resources, capacity enhancement and use of standard manuals are important considerations for biomass studies to be carried out throughout the country.

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Appendix 1: Information related to allometric equations for different tree species

SN	Scientific name	Physiographic region	Model	DBH or D_{15} range (cm)	Period	Equations (green-G, oven-dry-OD weight)	Equation for tree components	Source
Trees								
1	*Acacia auriculiformis*	Eastern Terai	Ln W = a'+b Ln DBH	4.1-18.5	1990s	G, OD	S, Br, S + Br	Thapa, 1992
2	*Acacia auriculiformis*	Central Bhabar-Terai	,, ,,	1.7-10.1	1980s	G, OD	S, Br, F, S + Br, total	Hawkins, Thomas, 1987
3	*Acacia catechu*	Eastern Terai	,, ,,	5.9-20.3	1990s	G, OD	S, Br, S+Br	Thapa, 1992
4	*Alnus nepalensis*	Mid-hills	,, ,,	2-51	1980s	G	S, Br, F	Thompson *et al.*, 1988
5	*Alnus nepalensis*	Mid-hills (five dev. regions)	,, ,,	3-22	1990s	G, OD	S, Br, F, S+Br, total	DoF, 1996
6	*Bauhinia variegata*	Terai, Inner Terai (Siwalik) and Mid-hills	Ln Y = a'+b Ln X , where. Y =foliage, total wood and total biomass in kg, X= diameter at 50 cm and breast height in cm; for each four site and all sites combined including on-farm trees	D_{50} = 2 -16 cm for experimental sites DBH (X)= 7.5 -22 cm for trees with >5 years (on-farm)	1990s	OD	F, wood (S+Br), total	Karki, 1994
7	*Casearia graveolens*	Mid-hills	Ln W = a'+b Ln DBH	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
8	*Cassia siamea$$*	Central Bhabar-Terai	,, ,,	4.4-14	1980s	G, OD	S+Br, total	Hawkins, 1987
9	*Castanopsis indica*	Mid-hills	,, ,,	2-10	1990s	G, OD	S, Br, F, S+Br, total	DoF, 1996
10	*Castanopsis indica*	Mid-hills	,, ,,	1-26	1990s	G	S, Br, F	Tamrakar , 1999
11	*Castanopsis tribuloides*	Mid-hills	,, ,,	2-17	1990s	G, OD	S, Br, F, S+Br, total	DoF, 1996
12	*Castanopsis tribuloides*	Mid-hills	,, ,,	1-26	1990s	G	S, Br, F	Tamrakar, 1999
13	*Dalbergia sissoo*	Central Terai	,, ,,	4.5-21.1	1980s	G, OD	S, Br, S+Br	Hawkins, 1987
14	*Dalbergia sissoo*	Eastern Terai	,, ,,	3.9-15.5	1990s	G, OD	S, Br, S+Br	Thapa, 1992
15	*Engelhardia spicata*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
16	*Eucalyptus camaldulensis*	Central Bhabar-Terai	,, ,,	2-13.6	1980s	G, OD	S, Br, F, S+Br, total	Hawkins,, 1987
17	*Eucalyptus camaldulensis*	Eastern Terai	,, ,,	4-18	1990s	G, OD	S, Br, S+Br	Thapa, 1992
18	*E. camaldulensis*	Central Terai	Ln Y = a'+b Ln X; Y=biomass of bole, branch and leaves, X=square of diameter at breast height x wood density	DBH=2 – 34 cm Height = 2 to 27 m	2011-	OD	S, Br, F	Mandal *et al.*, 2013
19	*Eucalyptus tereticornis*	Eastern Terai	Ln W = a'+b Ln DBH	2.2-19.1	1990s	G, OD	S, Br, S+Br	Thapa, 1999
20	*Eugenia operculata*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
21	*Eurya acuminata*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
22	*Ficus lacor*	Mid-hills	,, ,,	5-16	1990s	G, OD	S, Br, F, S+Br, total	DoF, 1996
23	*Ficus neriifolia*	Mid-hills	,, ,,	2-9	1990s	G, OD	S, Br, F, S+Br, total	DoF, 1996
24	*Ficus semicordata*	Mid-hills	,, ,,	3-14	1990s	G, OD	S, Br, F, S+Br, total	DoF, 1996
25	*Ficus semicordata*	Terai, Inner Terai (Siwalik) and Mid-hills	Ln Y = a'+b Ln X_1+Ln X_2; where Y= fodder, total wood and total biomass (kg), X_1=crown diameter in m, X_2 = height in m; model for region and each four site	Crown diameter= 0.5-6 m; Height = 2-13 m (experimental and on-farm trees); up to 5-years and beyond	1990s	OD	F, wood (S+Br), total	Karki, 1994
26	*Fraxinus floribunda*	Mid-hills	Ln W = a'+b Ln DBH	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988

27	*Leucaena leucocephala*	Mid-hills	Ln W = a+b Ln DBH; Ln W=a+b Ln (cd)	DBH: 6-11 cm Crown diameter (cd) = 3-5,2 m	1990s	OD	F, pole	Kiff and Amatya, 1994
28	*Litsea monopetala*	Mid-hills	Ln W = a'+b Ln DBH,	2-13	1990s	G, OD	S, Br, F, S+Br, total	DoF, 1996
29	*Lyonia ovalifolia*	Mid-hills	,, ,,	1-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
30	*Maesa macrophylla*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
31	*Melastoma malabathricum*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
32	*Myrica esculenta*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
33	*Myrsine capitellata*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
34	*Phyllanthus emblica*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
35	*Pinus patula*	Mid-hills	,, ,,	2-51	1980s	G	S, Br, F	Thompson, 1988
36	*Pinus roxburghii*	Mid-hills	,, ,,	2-51	1980s	G	S, Br, F	Thompson *et al.*, 1988
37	*Pinus roxburghii*	Mid-hills	,, ,,	3-11	1990s	G, OD	S, Br, F, S+Br, total	DoF, 1996
38	*Pinus roxburghii*	Mid-hills	Ln Y = a+b ln X	3.5-17.9 for high quality site and 1.9-8.3 for low quality site	1980s	OD	S, Br, F, S+Br, total, Branch wood and foliage by stem sections	Applegate *et al.*, 1988a
39	*Pinus roxburghii*	Mid-hills	,, ,,	3.5-17.9 for high quality site	1980s	OD	S, Br, F, S+Br, total, Branch wood and foliage by stem section	Applegate *et al.*, 1988b
40	*Pinus roxburghii*	Siwalik or Churia Hills, Inner Terai	Various models (see in supplement table)	10.5-27.7	1980s	G, OD		Joshi, 1985
41	*Pinus wallichiana*	Mid-hills	Ln W = a+b Ln DBH	2-51	1980s	G	S, Br, F	Thompson *et al.*, 1988
42	*Pterocarpus marsupium*	Eastern and western Terai	,, ,,	4-33	2001-2010	G	S, Br, F	Acharya *et al.*, 2003
43	*Pyrus pashia*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
44	*Quercus floribunda*	Mid-hills	,, ,,	2-51	1980s	G	S, Br, F	Thompson *et al.*, 1988
45	*Quercus lanuginosa*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
46	*Quercus leucotricophora*	Mid-hills	,, ,,	2-14	1990s	G, OD	S, Br, F, S+Br, total	DoF, 1996
47	*Quercus glauca*	Mid-hills	,, ,,	1-20	1990s	G	S, Br, F	Tamrakar, 1999
48	*Rhododendron arboreum*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
49	*Rhus wallichii*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
50	*Schima wallichii*	Mid-hills	,, ,,	3-14	1990s	G, OD	S, Br, F, S+Br, total	DoF, 1996
51	*Schima wallichii*	Mid-hills	,, ,,	1-26	1990s	G	S, Br, F	Tamrakar, P. R., 1999
52	*Shorea robusta* (Terai Sal)	Terai	,, ,,	3-20	1980s	G	S, Br, F	Thompson *et al.*, 1988
53	*Shorea robusta*	Central Terai	Ln (M) = a'+b Ln (dbh) for od stem and fresh branch Ln (M or BKM) = a'+ b Ln (dbh)+c Ln (h), for od stem and bark	15.2-81.7	1990s	OD for S, bark and G for branch	S, Br, bark	Laamanen *et al.*, 1995
54	*Shorea robusta*	Eastern and western Terai	Ln (W) = a'+b Ln DBH	4-35	2001-2010	G	S, Br, F	Acharya *et al.*, 2003
55	*Viburnum coriaceum*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
56	*Wendlandia coriacea*	Mid-hills	,, ,,	2-25	1980s	G	S, Br, F	Thompson *et al.*, 1988
57	*Dalbergia latifolia*	Eastern Terai	,, ,,	3-20	2001-2010	G	S, Br, F	Thapa, 2004

58	*Tectona grandis*	Western Terai	,, ,,	-	1990s	G	S+Br, F	Thapa and Gautam, 2005 Source
NTFPs								
59	*Cinnamomum tamala*	Mid-hills	Ln W = a'+b Ln DBH	6.2-16.5	2001-2010	OD for foliage and G for other components	S, Br, F and bark	Poudel *et al*., 2011
60	*Daphne bholua* and *D. papyracea*	High Mountain	-	Top height: 1.01-5 m	-	G and air dry	Bark (gm)/plant	Forestry Services cited in TISC, 2000
Bamboos								
61	*Bambusa nutans* subsp. *nutans*	Eastern Terai	Ln (W) = a+b Ln (D^2L), D is the diameter at 15 cm, L is the vertical length of the culm	D_{15}: 4-11 Height: 5-16 m	2001-2010	G for culm and foliage, OD for culm, foliage and total	Culm, F and total	Oli, 2003
62	*B. nutans* subsp. *cupulata*	Eastern Terai	,, ,,	D_{15}: 4-9 cm Height: 5-18 m	2001-2010	G for culm, foliage, OD for culm, Br, F	Culm, Br, F	Oli and Kandel, 2005
63	*Bambusa tulda*	Eastern Terai	,, ,,		2001-2010	G for culm, foliage, OD for culm, Br, F	Culm, Br, F	Oli, 2005
64	*Dendrocalamus hookeri*	Far-western Terai	,, ,,	D_{15}: 4-10 Height: 5-18 m -	2001-2010	G for culm, foliage, OD for culm, Br, F	Culm, Br, F	Oli and Kandel, 2006

W refers to green or oven dry weight of tree components (biomass) in kg; DBH refers to over bark diameter at breast height (measured at 1.3 m above ground) in cm; M refers to oven-dry mass of the stem with bark (kg); d refers to diameter at breast height; h refers to height of tree in m; BKM refers to oven-dry mass of the bark of the stem (kg); $$ for *Cassia siamea*, basal diameter (BD) used as a predictor variable.

Y refers to oven dry weight of the branch component (branch and foliage) in grams and X is the stub-diameter in mm

Similarly for standing biomass, Y refers to oven-dry weight of stem, branch, foliage, stem plus branch and total biomass, X refers to diameter at breast height in cm; oven-dry branch and foliage biomass are calculated at different lengths of the stem, i. e. 0-10, 10-20, 20-40, 40-60, 60-80, 80-100% of total stem

Supplement of Appendix 1 for *Pinus roxburghii*

Components	Equation type: Fresh weight	Equation type: Oven dry weight	Remarks
Branch, branch wood, branch bark, foliage: Eight models compared			
Branch	$Y = a+b X^2$		Y = fresh weight of branch in gms and X = basal diameter in cm
Branch wood	$Y = a+bX+c X^2$	$Y = a+b X^2$	,, ,,
Branch bark	$Y= a+bX+cX^2+dX^3$	$Y = a+bX+c X^2$	,, ,,
Foliage	$Y= a+bX+cX^2+dX^3$	$Y = a+bX+c X^2$	,, ,,
Individual whorl components (whorl, whorl wood, whorl bark, whorl foliage): Eleven models compared			
Whorl	$Y = a+b X_1^2 *X_2$		Y= component weight in a whorl in gram; X_1= mean branch length in a whorl in m; X_2= number of branches in a whorl
Whorl wood	$Y = a+b X_1^2*X_2$; Alternative model, $Ln Y = a'+b Ln X_1$	$Y = a+b X_1^2*X_2$; Alternative model, $Ln Y = a'+b Ln X_1$	,, ,,
Whorl bark	$Ln Y = a'+b_1 LnX_1*LnX_2$; Alternative model, $Ln Y = a'+b Ln X_1$	$Y = a+b X_1^2*X_2$; Alternative model, $Ln Y = a'+b Ln X_1$	,, ,,
Whorl foliage	$Y = a+b X_1^2*X_2$; Alternative model, $Ln Y = a'+b Ln X_1$	$Y = a+b X_1^2$; Alternative model, $Ln Y = a'+b Ln X_1$	,, ,,
Crown components (crown, crown wood, crown bark, crown foliage): Nineteen models compared			
Total crown	$Ln Y = a'+b LnX_2+c LnX_3$; alternative model, $Ln Y= a'+b LnX_3$		Y = crown components (fresh or oven dry) mass (grams); X_3 = diameter at breast height (cm); X_2 = reciprocal of the height to the crown base; X_1= crown base diameter in cm
Crown wood	$Ln Y = a'+b LnX_2+c LnX_3$; alternative model, $Ln Y= a'+b LnX_3$	$Y=X_3/(a+bX_3+cX_3^2)$	,, ,,
Crown bark	$Ln Y= a'+b LnX_3$	$Ln Y = a'+b LnX_2+c LnX_3$; alternative model, $Ln Y= a'+b LnX_3$	,, ,,
Crown foliage	$Ln Y= a'+b LnX_3$	$Ln Y = a'+b LnX_1+c LnX_3$	,, ,,
Tree and stem components (tree, stem bole, bole wood, bole bark): Three models compared			
Tree (total above-ground weight)	$Y = a+b DBH^2* H$; alternative model, $Y = a+b DBH^2$		Y = Fresh mass of tree in grams; DBH = diameter at breast height in cm; H = total height in m
Stem bole	$Y = a+b DBH^2* H$; alternative model, $Y = a+b DBH$		,, ,,
Bole wood	$Y = a+b DBH^2* H$; alternative model, $Y = a+b DBH$	$Y = a+b DBH^2 *H$; alternative model, $Y = a+b DBH^2$	,, ,,
Bole bark	$Y = a+b DBH^2 + cH$; alternative model, $Y = a+b DBH$	$Y = a+b DBH^2$	,, ,,

Source: Joshi, (1985)

Appendix 2: Information related to allometric equations for mixed species

SN	Scientific name	Physiographic region	Model	DBH range (cm)	Period	Equations (green-G, oven-dry-OD weight)	Equations for tree components	Source
1	*Eurya acuminate, Myrsine capitellata, M. semiserrata, Symplocos* spp. and others	Mid-hills	Ln W = a+b Ln DBH	1-20	1990s	G	Stem (S), Branch (Br), Foliage (F)	Tamrakar, 1999
2	*Lyonia ovalifolia, Engelhardia spicata, Sapium insigne, Rhus succedanea, Rhus javonica, Phyllanthus emblica*	Mid-hills	,, ,,	1-20	1990s	G	S, Br, F	Tamrakar, 1999
3	*Syzigium cumuni, Myrica esculenta, Myrsine capitellata, Machilus spp., Ficus nemoralis, Michelia kisopa, Lithocarpus spicata* and others	Mid-hills	,, ,,	1-20	1990s	G	S, Br, F	Tamrakar, 1999
4	*Shorea robusta, Terminalia alata, Syzigium cumuni, Adina cordifolia, Pterocarpus marsupium, Anogeissus latifolia, Lagerstroemia parviflora, Garuga pinnata, Myrsine semiserrata, M. capitellata, Mallotus philippinensis, Cassia fistula, Dalbergia latifolia, Syzigium cerasoides, Hollarhena antidyscentrica, Gmelina arborea* (associates of *S. robusta* forest)	Eastern and western Terai	,, ,,	4-35	2001-2010	G	S, Br, F	Acharya *et al.*, 2003
5	Terai Mixed hardwood species: *T. alata, S. cumuni, A. cordifolia, Albizzia spp., P. marsupium, A. I atifolia, L. parviflora, G. pinnata, M. semiserrata, M. capitellata, M. philippinensis, C. fistula, D. latifolia, S. cerasoides, H. antidyscentrica, G. arborea*	Eastern and western Terai	,, ,,	4-33	2001-2010	G	S, Br, F	Acharya *et al.*, 2003