BIOMASS EQUATIONS FOR SIX MAJOR TREE SPECIES OF THE NORTHWEST TERRITORIES

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ABSTRACT

Biomass data obtained from 336 trees representing six major species of the Northwest Territories were used to derive regression equations for estimating ovendry biomass for stem and nonstem components. The predictor variables were the diameter at breast height outside bark and the total height of the tree. Prediction equations based on three models were derived for merchantable stem, nonmerchantable stem, live large branches, and live small branches including foliage. The best estimates were provided by a multiple regression model using five predictor variables. Equations are included for predicting total ovendry biomass of living tree above ground with and without foliage. Also presented are 95% confidence bands for the ovendry biomass weight prediction and pie diagrams for the stem and nonstem biomass dry weights.

RESUME

On a utilisé les données sur la biomasse de 336 arbres comprenant six espèces importantes des Territoires du Nord-Ouest pour établir des équations de régression permettant d'estimer la biomasse anhydre de la tige et des autres parties de l'arbre. Les variables retenues sont le diamètre à hauteur de poitrine avec écorce et la hauteur totale de l'arbre. À l'aide de trois modèles différents, on a établi des équations pour quatre composants différents, soit la tige marchande, la tige non marchande, les grosses branches vivantes et les petites branches vivantes, y compris le feuillage. Les meilleures estimations ont été celles d'un modèle à régressions multiples utilisant cinq variables. Le document comprend des équations pour le calcul de la biomasse anhydre totale des parties aériennes des arbres vivants, avec et sans feuillage. Il présente également des bandes de confiance à 95% pour le calcul du poids de la biomasse anhydre et des diagrammes montrant la répartition de la tige et des autres parties de l'arbre d'après le poids net de leur biomasse.

FOREWORD

ENFOR is the acronym for the Canadian Government's ENergy from the FORest (Energie de la FORêt) program of research and development aimed at securing the knowledge and technical competence to facilitate in the medium to long term a greatly increased contribution from forest biomass to our nation's primary energy production. This program is part of a much larger federal government initiative to promote the development and use of renewable energy as a means of reducing our dependence on petroleum and other nonrenewable energy sources.

The Canadian Forestry Service (CFS) administers the ENFOR Biomass Production program component which deals with such forest-oriented subjects as inventory, harvesting technology, silviculture and environmental impacts. (The other component, Biomass Conversion, deals with the technology of converting biomass to energy or fuels, and is administered by the Renewable Energy Branch of the Department of Energy, Mines and Resources). Most Biomass Production projects, although developed by CFS scientists in the light of ENFOR program objectives, are carried out under contract by forestry consultants and research specialists. Contractors are selected in accordance with science procurement tendering procedures of the Department of Supply and Services. For further information on the ENFOR Biomass Production program, contact

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or a CFS research laboratory.

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INTRODUCTION

Conventional forest inventories usually provide volume estimates of forest trees and their components according to specified diameter limits. Such inventories do not give estimates of forest biomass for determining the potential of the forest resource as a source of energy, fodder, or other by-product. Biomass inventory estimates can be made if mass equations are developed for various tree species and incorporated into the existing inventory appraisal and compilation procedures.

In addition to providing the needed mechanism for determining the energy potential of forests, biomass equations are also necessary for evaluating management practices, e.g., assessing alternative types of harvesting operations in terms of biomass yield and residues (Lavigne and van Nostrand 1981). Also, if the forests are to be managed for biomass production, their present and potential capacities have to be evaluated first by the development of equations for individual tree biomass of each species (Alemdag and Horton 1981). Further, prediction equations for the branch and foliage components are important for appraising fire behavior of forest fuels and for preparing prescriptions for prescribed burning (Brown et al. 1977).

Biomass information currently available for tree species in the Northwest Territories is incomplete and fragmented. The main purpose of this study was to collect biomass field data and to develop a set of equations applicable to a broad range of tree sizes for six major tree species in the Northwest Territories.

METHODS

A total of 336 trees of six species were sampled around Hay River, Fort Smith, and Fort Simpson in the Northwest Territories during the summer of 1981:

White spruce (*Picea glauca* (Moench) Voss)
Black spruce (*Picea mariana* (Mill.) B.S.P.)
Jack pine (*Pinus banksiana* Lamb.)
Tamarack larch (*Larix laricina* (Du Roi) K. Koch)
Trembling aspen (*Populus tremuloides* Michx.)
Balsam poplar (*Populus balsamifera* L.)

Sampling was done on 61 white spruce, 51 black spruce, and 56 of each of the other species.

Field Procedures

The fieldwork involved the selection, felling, measurement, weighing, and subsampling of trees selected over a range of four diameter classes: less than 10 cm, 11-20 cm, 21-30 cm, and greater than 30 cm.

The field procedure (Figs. 1. and 2) was as follows:

1. The height to breast height (1.3 m) and to stump (0.3 m) was marked by a flagging tape.

2. Diameter outside bark (dob) was measured with diameter tape at stump height and at breast height (dbh).

3. Crown width measurement was taken from beneath the standing tree; two measurements at right angle to each other were averaged.

4. The tree was felled, and the age at stump height was determined.

5. The base of the live crown was marked, and dob was measured at that point.

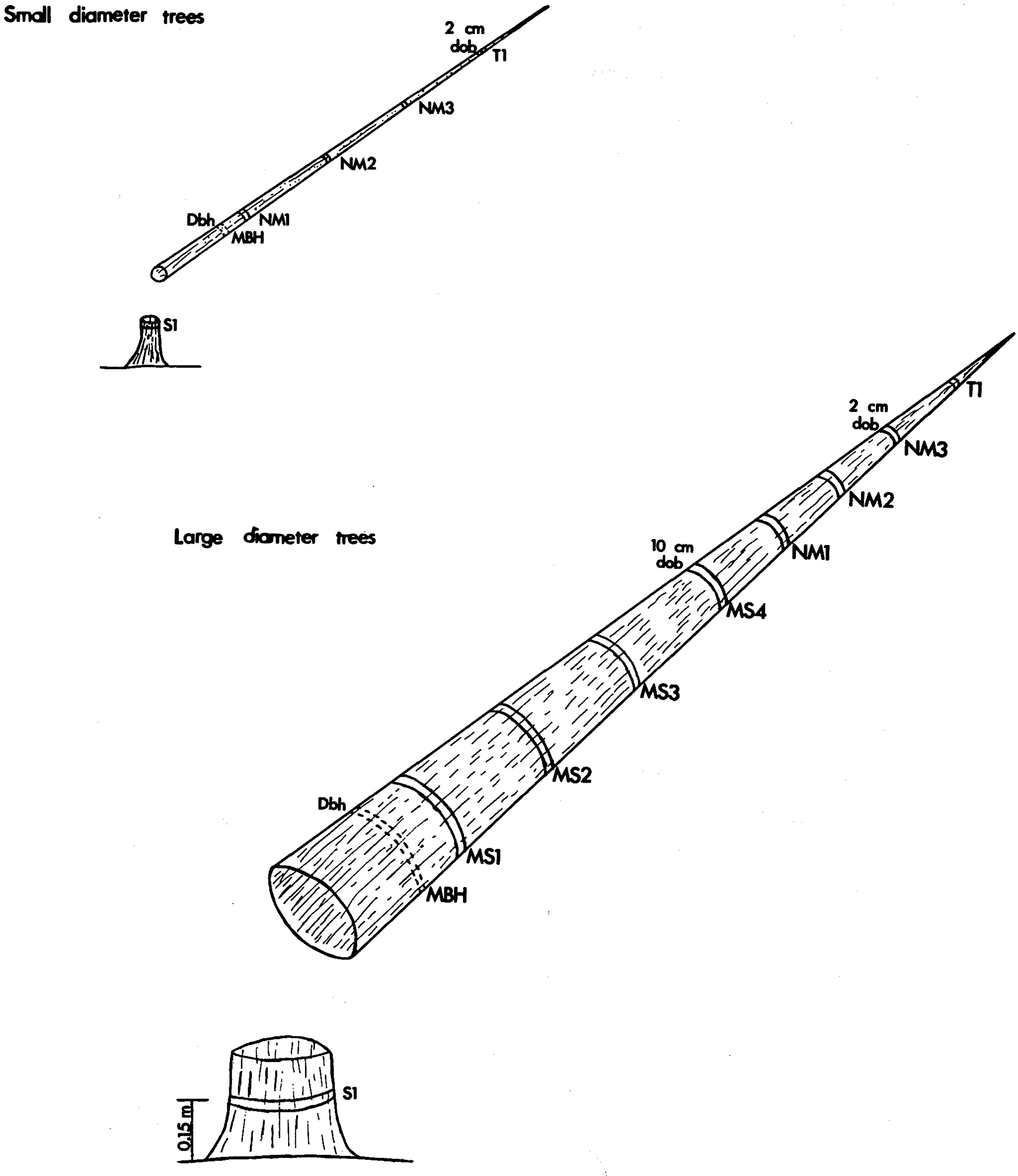

Figure 1. Location of stem subsamples taken from the merchantable and nonmerchantable trees.

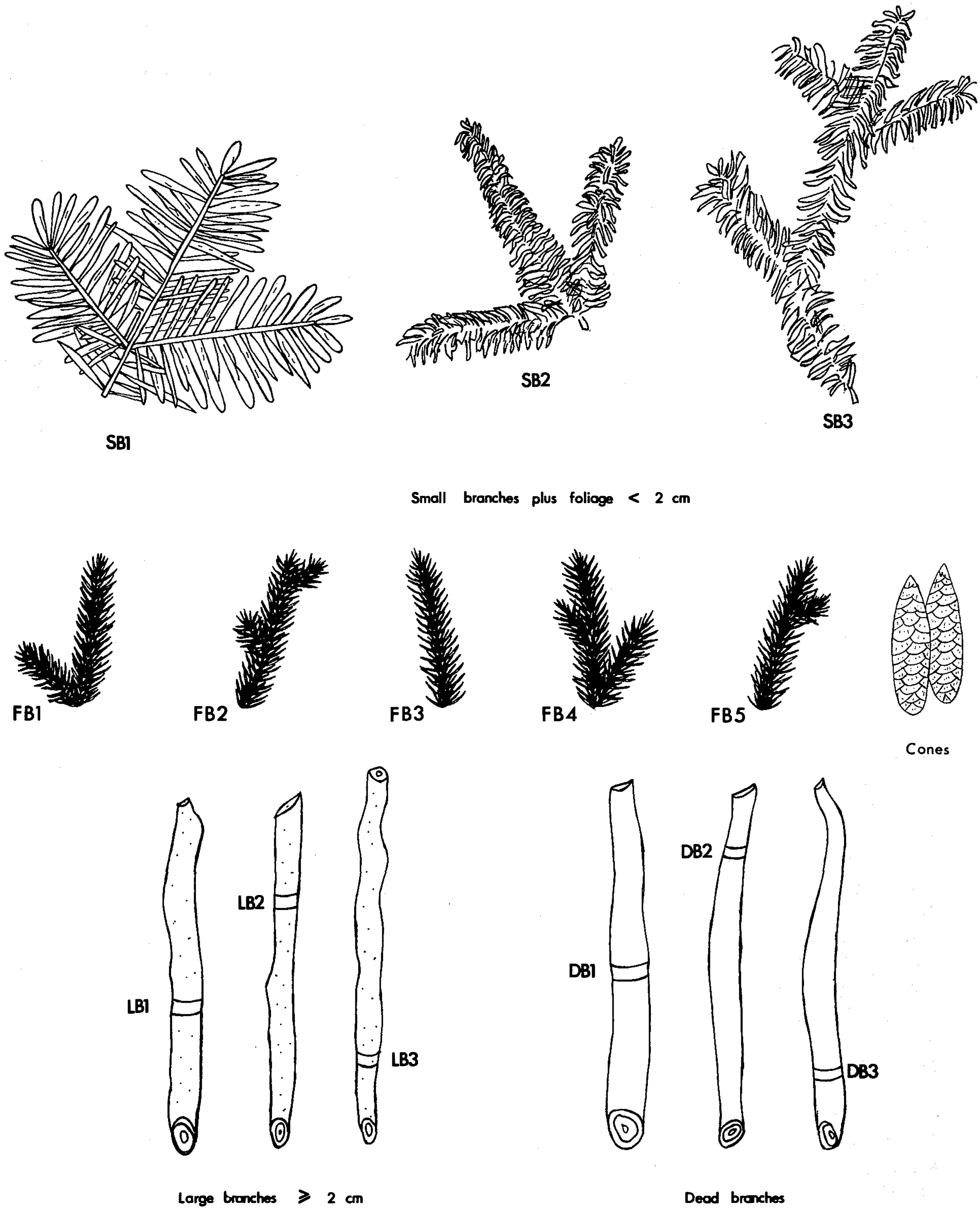

Figure 2. Location of nonstem subsamples taken from the tree canopy.

6. Cones, if present, were removed and weighed, and a subsample of approximately 20 g was obtained for moisture content and dry mass determinations.

7. The tree was limbed, and all branches were sorted into separate piles of dead and live branches on a plastic sheet or tarp. Live branches were further separated into two subcategories: (1) branches <2 cm dob and foliage and (2) branches ≥2 cm dob. Total fresh mass was determined on-site for each of the subcategories.

8. Subsamples were taken from live small branches <2 cm dob plus foliage (SB1, SB2, SB3), live large branches ≥2 cm dob (LB1, LB2, LB3), and dead branches (DB1, DB2, DB3). Fresh mass for all subsamples was determined in the field to the nearest 0.1 g.

9. For white spruce, jack pine, and black spruce, all branches <2 cm dob plus foliage were further separated into branches ≤0.5 cm dob plus foliage as a separate subset for special requirements. Total fresh mass was taken immediately for the live and the dead categories.

10. For the 0-0.5 cm dob size class under item 9, five random subsamples (FB1, FB2, FB3, FB4, FB5) were taken from the live pile and an equal number of subsamples (FDB1, FDB2, FDB3, FDB4, FDB5) were taken from the dead category. Each sample was immediately placed in a separate tin and the lid was sealed securely with masking tape.

11. On the felled and limbed tree stem, the points were marked where the stem bole measured 10 cm dob and 2 cm dob. The heights to 10 cm dob and 2 cm dob were measured with tape.

12. Four equidistant points from stump height to 10 cm dob top were located on the main stem. These were flagged and measured with diameter tape successively along the stem (MS1, MS2, MS3, MS4), and the height for each was determined.

13. Three equidistant points from 10 cm dob top to 2 cm dob top were similarly located (NM1, NM2, NM3), flagged, and measured for their diameters and heights.

14. For the 2 cm dob top to the tip of the tree stem, the midpoint (T1) was located and flagged, and the diameter and height were measured.

15. The tree stem was cut and weighed for total fresh mass of merchantable stem (dob ≥10 cm) and nonmerchantable stem (dob 10 cm to 2 cm and 2 cm to tip) and for stump mass (ground level to stump height).

16. Stem subsamples of 1-cm thick disks were taken at the flagged stem locations (S1, MBH, MS1, MS2, MS3, MS4, NM1, NM2, NM3, T1) and placed immediately in paper bags. Their fresh mass was immediately determined to the nearest 0.1 g.

17. In the case of small trees (0-10 cm dob size class), flagged locations were S1, MBH, NM1, NM2, NM3, and T1 along the tree stem. For the stem and nonstem subsamples the procedures were otherwise identical.

18. Regardless of tree size, a disk subsample was always taken at breast height.

Pollock and Leblanc (1981) have described in detail related information for the data collection phase.

Laboratory Procedure

The subsamples collected in the field were brought to the laboratory to be analyzed.

All disk subsamples were debarked, and the bark and wood from each were oven-dried for 48 hours at 103 ± 2°C, or until a constant mass was reached. The ovendry mass was measured to the nearest 0.1 g.

The live small branches <2 cm dob plus foliage subsamples (SB1, SB2, SB3) were similarly oven-dried to a constant mass. When dry, the needles or leaves were separated from the wood, and dry mass was determined separately for wood and foliage to the nearest 0.1 g. The dead branch subsamples (DB1, DB2, DB3) were not debarked; their ovendry mass was determined to the nearest 0.1 g.

For the remaining subsamples (FB1, FB2, FB3, FB4, FB5, FDB1, FDB2, FDB3, FDB4, FDB5), the fresh and ovendry masses of the subsamples were determined and recorded to the nearest 0.1 g.

Computations

Biomass information for individual stem sections and nonstem components was obtained from the subsamples and field data by using the procedures previously described (Singh 1982). Computer subroutines for biomass computation are also available (Singh 1983).

The computations consisted of deriving volume-weighted dry/fresh mass ratios and volume-weighted bark/wood dry mass ratios for the disk subsamples obtained from the stems; only the unweighted ratios were computed for the nonstem components. These ratios were used to estimate the dry mass of each component and to partition it into dry mass of wood and dry mass of bark.

All stem and nonstem components, with the exception of dead branches, were summed to yield the dry mass of the entire tree above ground. The tree top less than 2 cm dob was not treated as a separate component but is included in the living tree above-ground biomass. Live branches less than 0.5 cm dob are a subset of live branches less than 2 cm dob. As the foliage occurred primarily on small branches, this component refers to branches <2 cm dob (and <5 cm dob) only.

Regression Analysis

The ovendry biomass data for a species were divided into eight categories: stump, tree stem ≥10 cm dob, tree stem <10 cm but ≥2 cm dob, live branches ≥2 cm dob, live branches <2 cm dob plus foliage, live branches <0.5 cm dob plus foliage, living tree above ground without foliage, and living tree above ground with foliage.

Three models based on diameter at breast height (D) and total height of the tree (H) were selected for deriving biomass prediction equations by the method of least squares:

(Model 1)

$$W = a_0 + a_1 D + a_2 D^2 + a_3 D^3$$

(Model 2)

$$W = a_0 + a_1 D + a_2 H + a_3 D^2 H + a_4 D^2 + a_5 D^3$$

(Model 3)

$$W = a_0 + a_1 D^2 H$$

Mean, standard deviation, R^2, and standard error of estimate were also obtained.

Confidence Bands

For each species, confidence bands at the 95% probability level were computed for the prediction mass estimated by the third-degree polynomial (Model 1). Confidence limits were calculated and plotted separately for the mean and the individually predicted values. These are shown in Figure 3.

Pie diagrams for each species (Fig. 4) were plotted to depict the ovendry biomass of the tree species components. The pie diagrams are based on the proportion (expressed as a percentage) of the ovendry biomass of stem and nonstem components in the total ovendry biomass of the entire tree above ground.

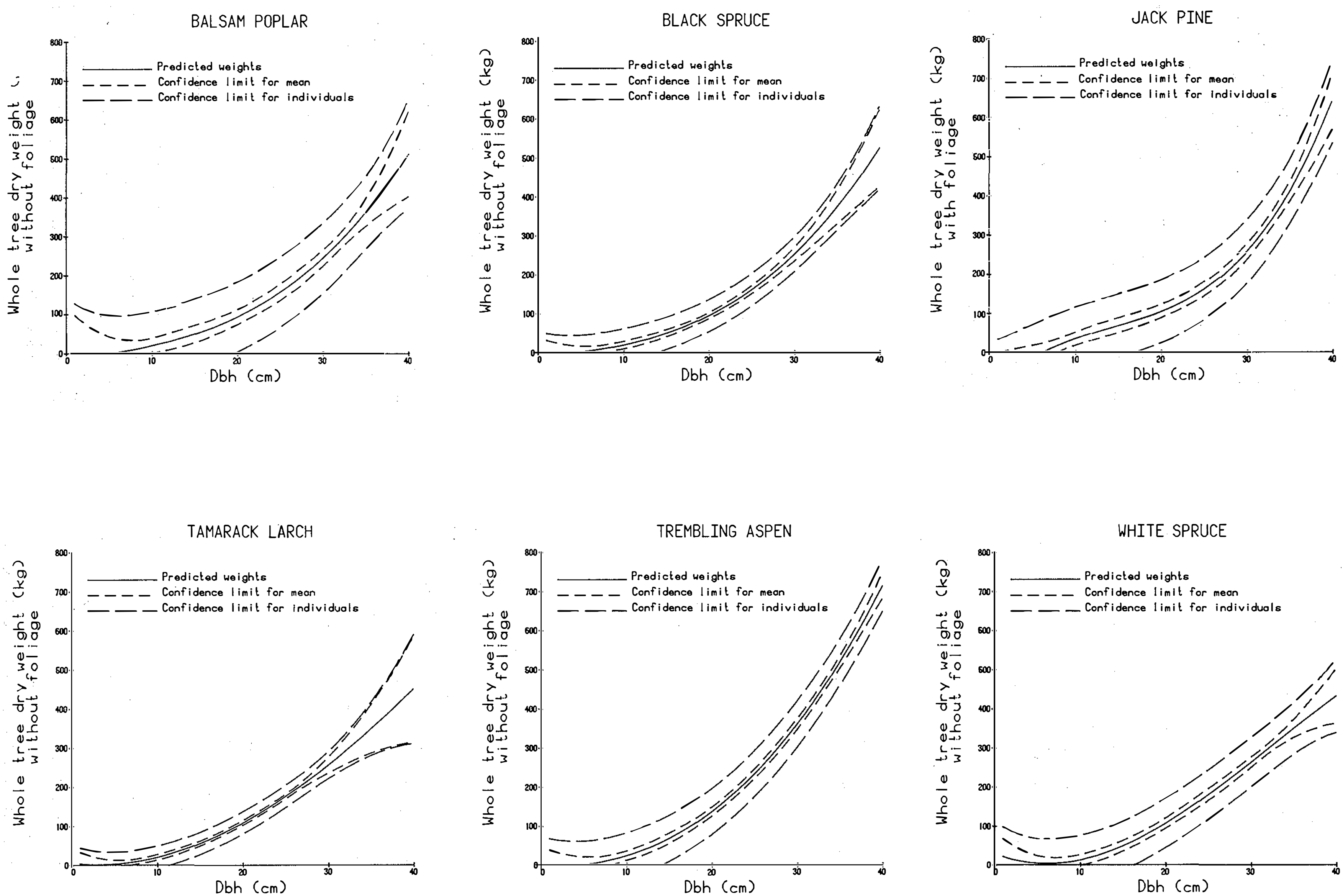

Figure 3. Confidence bands (95%) for the predicted mean and individual dry weight biomass of the entire tree above ground for the six tree species.

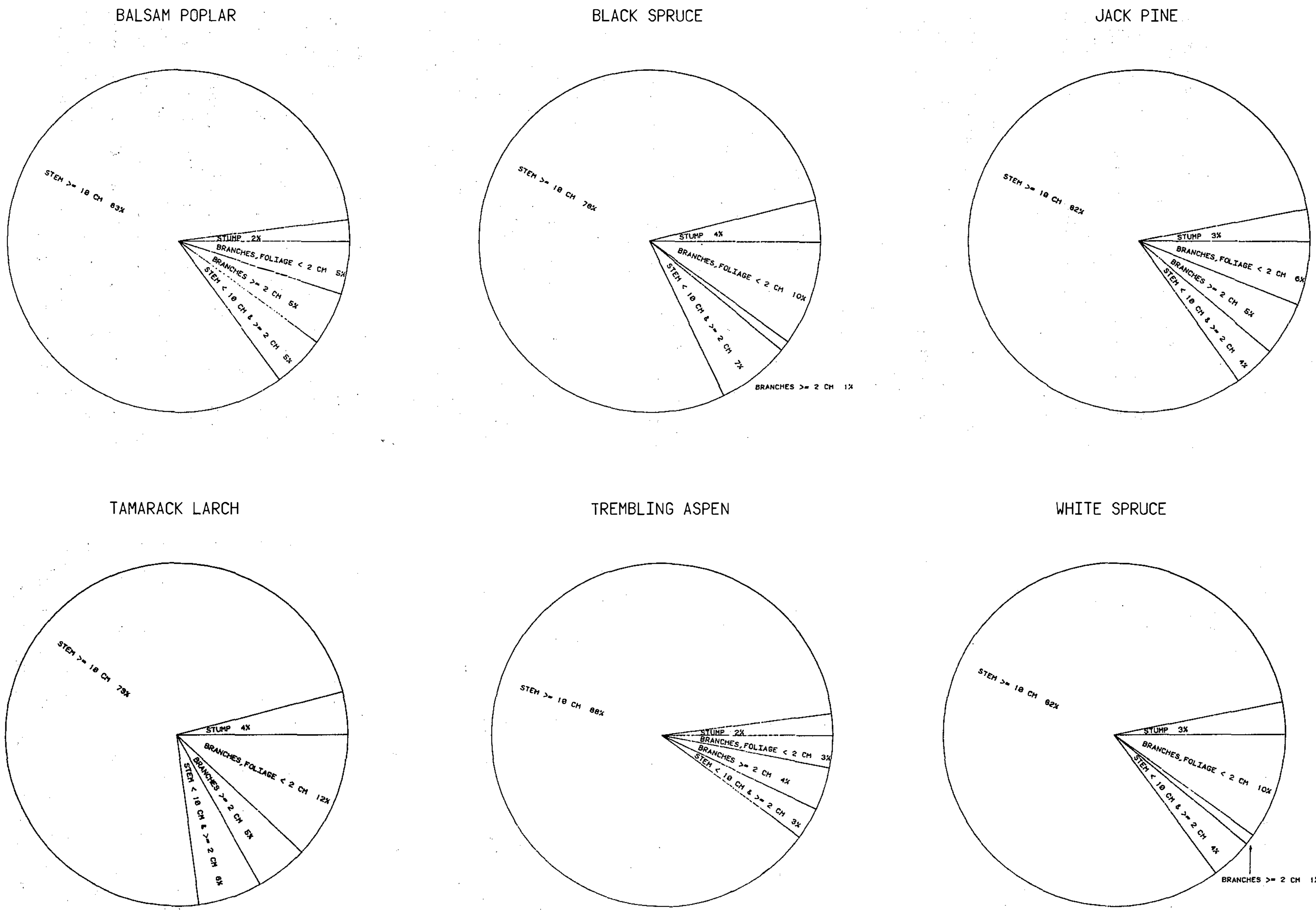

Figure 4. Pie diagrams for the stem and nonstem components of the six tree species.

RESULTS AND DISCUSSION

The prediction equations obtained for white spruce, black spruce, jack pine, tamarack larch, trembling aspen, and balsam poplar are listed in Tables 1 to 6, respectively. Each table also shows the mean ovendry biomass and the standard deviation for the stem and nonstem components of a tree species according to their wood and bark contents. These components include stump, stem ≥10 cm dob, stem <10 cm but ≥2 cm dob, and live branches ≥2 cm dob. Because the small branches were not separated into wood and bark, the live branches <2 cm dob component shows the ovendry mass of wood and bark collectively.

These tables provide information for the living tree ovendry biomass aboveground tree components. Separate equations were derived for predicting the ovendry biomass of the living trees above ground with and without foliage.

Generally the best predictions were obtained using Model 2 (with five predictor variables), followed by Model 3. Both of these models use D and H as predictors. The coefficient of determination for Model 2 ranged from 0.90 to 0.98 for the living tree above ground with foliage and from 0.90 to 0.99 without foliage. The corresponding ranges for Model 3 were 0.89 to 0.98 and 0.89 to 0.99.

Model 1, using the single measurement of D, gave nearly as good results. The range of the coefficient of determination for this model was 0.89 to 0.97 for both the living tree above ground with foliage and without foliage. This model offers convenience and reliability when only the dbh measurements are available.

All three models provide better fit for predicting the ovendry biomass of the living tree above ground without foliage than for that with foliage. Further, the merchantable stem component, which constitutes the bulk of the tree, is better predicted than the nonmerchantable stem and nonstem components.

Although the models are additive, the equations based on them may not be because of unequal replication; additivity is valid only when the required components have the same number of samples (N). A slight discrepancy may result when combining or separating tree components having unequal replicates.

Among the sampled tree species, the biomass of conifers is generally better predicted than that of hardwoods. This may be due to the fact that conifers are more regular and compact in form, especially with regards to the tree boles, than the hardwoods.

The weight loss that occurs in the six tree species when dried to a constant weight is depicted by the bar diagram (Fig. 5) showing a comparison of the fresh and ovendry biomass of each species. Although the fresh weight varies according to field conditions, the bar diagrams indicate the greater weight of the green biomass. The listed biomass equations give estimates of ovendry biomass for a given size of tree. The field forester has to provide for the extra weights involved in green biomass. Thus, the information depicted in the bar diagrams will help in solving logistical problems of harvesting and transporting green biomass from the forest.

In spite of the excellent fit obtained for the six species, the results should be used with caution in the varied locations of such a vast land mass as the Northwest Territories. The biomass predictions would be more reliable for sites geographically close and ecologically similar to the forests around Hay River, Fort Smith, and Fort Simpson, where the field samples for the six tree species were collected. Further, the equations should not be used for predicting biomass of very small trees (<6 cm dob) because of lack of adequate samples in this range.

ACKNOWLEDGMENTS

The field data collection and laboratory determinations were done by Timmerlinn Ltd. under an ENFOR contract. A. Irwin and D. Campbell provided assistance in data analysis and computer plotting of the confidence bands and pie diagrams. Special appreciation is expressed to S. Lux for assistance in making field data checks and for many helpful suggestions during the course of this study.

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Table 1. Equations for predicting biomass (kg) of white spruce

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Stump	Wood	5.55	5.30	$W_1 = -3.32168 + 1.00108D - 0.06027D^2 + 0.00134D^3$	0.74	2.76	61
				$W_2 = -2.10561 + 0.38600D + 0.25094H - 0.00075D^2H - 0.02725D^2 + 0.00120D^3$	0.77	2.65	
				$W_3 = 1.02251 + 0.00044D^2H$	0.63	3.27	
	Bark	0.60	0.46	$W_1 = -0.10676 + 0.04464D - 0.00136D^2 + 0.00003D^3$	0.63	0.28	
				$W_2 = 0.06095 - 0.03357D + 0.02798H - 0.00010D^2H + 0.00308D^2 + 0.00001D^3$	0.70	0.26	
				$W_3 = 0.24269 + 0.00003D^2H$	0.52	0.32	
Stem ⩾10 cm	Wood	138.65	99.04	$W_1 = 89.29843 - 18.85425D + 1.20430D^2 - 0.01487D^3$	0.89	33.98	47
				$W_2 = -44.10126 + 5.86650D - 0.40303H + 0.01521D^2H - 0.24580D^2 + 0.00044D^3$	0.98	14.27	
				$W_3 = -2.73083 + 0.01076D^2H$	0.97	16.68	
	Bark	17.03	11.06	$W_1 = 7.02434 - 1.76537D + 0.13231D^2 - 0.00178D^3$	0.92	3.27	
				$W_2 = 1.92391 - 1.01252D + 0.23837H + 0.00057D^2H + 0.07293D^2 - 0.00105D^3$	0.94	2.82	
				$W_3 = 1.60429 + 0.00117D^2H$	0.93	2.99	
Stem <10⩾2 cm	Wood	5.50	2.51	$W_1 = -5.75891 + 2.38647D - 0.12619D^2 + 0.00192D^3$	0.55	1.72	61
				$W_2 = -5.26856 + 1.77247D + 0.50649H - 0.00037D^2H - 0.11400D^2 + 0.00203D^3$	0.61	1.63	
				$W_3 = 6.17276 - 0.00007D^2H$	0.06	2.45	
	Bark	1.39	0.57	$W_1 = -1.10549 + 0.46637D - 0.02220D^2 + 0.00031D^3$	0.53	0.40	
				$W_2 = -0.93254 + 0.34150D + 0.07788H - 0.00011D^2H - 0.01771D^2 + 0.00031D^3$	0.55	0.40	
				$W_3 = 1.48631 - 0.00001D^2H$	0.03	0.57	
Live branches ⩾2 cm	Wood	1.79	3.47	$W_1 = 0.79094 - 0.15290D + 0.00345D^2 + 0.00016D^3$	0.44	2.67	61
				$W_2 = 2.55744 - 0.88834D + 0.20201H - 0.00101D^2H + 0.05032D^2 - 0.00010D^3$	0.61	2.26	
				$W_3 = -0.24927 + 0.00020D^2H$	0.31	2.91	
	Bark	0.58	1.00	$W_1 = 0.31885 - 0.06876D + 0.00261D^2 + 0.00002D^3$	0.53	0.70	
				$W_2 = 0.75483 - 0.25212D + 0.05188H - 0.00025D^2H + 0.01417D^2 - 0.00004D^3$	0.65	0.61	
				$W_3 = -0.08970 + 0.00007D^2H$	0.40	0.78	

Table 1 continued.

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Live branches <2 cm	Wood & Bark	7.59	8.12	$W_1 = 4.08661 - 1.09919D + 0.08616D^2 - 0.00128D^3$	0.61	5.18	61
				$W_2 = 1.83323 + 0.47182D - 0.95319H + 0.00142D^2H + 0.02765D^2 - 0.00123D^3$	0.64	5.12	
				$W_3 = 0.88881 + 0.00066D^2H$	0.61	5.14	
	Foliage	10.91	10.76	$W_1 = 7.39953 - 1.90196D + 0.14434D^2 - 0.00221D^3$	0.69	6.16	
				$W_2 = 3.36217 + 0.67749D - 1.44923H + 0.00250D^2H + 0.03903D^2 - 0.00204D^3$	0.73	5.81	
				$W_3 = 1.40879 + 0.00093D^2H$	0.69	6.01	
Live branches <0.5 cm with foliage		11.92	12.26	$W_1 = 6.43730 - 1.64976D + 0.13363D^2 - 0.00205D^3$	0.59	8.10	61
				$W_2 = 2.86403 + 0.44003D - 1.07036H + 0.00217D^2H + 0.04004D^2 - 0.00180D^3$	0.62	7.94	
				$W_3 = 1.91795 + 0.00098D^2H$	0.59	7.91	
Living tree above ground with foliage[b]		154.03	138.47	$W_1 = 36.56038 - 10.62749D + 0.93837D^2 - 0.01032D^3$	0.94	33.48	61
				$W_2 = 5.88664 + 0.51735D - 1.72141H + 0.01727D^2H + 0.12130D^2 - 0.00512D^3$	0.98	18.09	
				$W_3 = 8.47531 + 0.01427D^2H$	0.98	18.77	
Living tree above ground without foliage[b]		143.00	129.14	$W_1 = 28.94398 - 8.66436D + 0.78950D^2 - 0.00803D^3$	0.95	30.65	61
				$W_2 = 2.30491 - 0.13145D - 0.23557H + 0.01477D^2H + 0.07760D^2 - 0.00299D^3$	0.99	15.40	
				$W_3 = 7.02154 + 0.01333D^2H$	0.99	15.78	

[a] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[b] Coefficients are not additive because living tree above ground includes stem <2 cm.

Table 2. Equations for predicting biomass (kg) of black spruce

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Stump	Wood	3.36	2.34	$W_1 = -0.37149 + 0.15553D + 0.00347D^2 + 0.00002D^3$	0.85	0.94	51
				$W_2 = -0.37004 + 0.24766D - 0.06553H + 0.00047D^2H - 0.00323D^2 - 0.00009D^3$	0.86	0.92	
				$W_3 = 1.21179 + 0.00046D^2H$	0.82	1.01	
	Bark	0.58	0.42	$W_1 = 0.07007 - 0.00843D + 0.00323D^2 - 0.00005D^3$	0.70	0.24	
				$W_2 = 0.04223 + 0.07416D - 0.06206H + 0.00018D^2H - 0.00062D^2 - 0.00008D^3$	0.72	0.23	
				$W_3 = 0.23288 + 0.00007D^2H$	0.65	0.25	
Stem ⩾10 cm	Wood	74.85	59.49	$W_1 = -86.73482 + 12.49766D - 0.51453D^2 + 0.01377D^3$	0.88	21.89	37
				$W_2 = 33.38519 + 10.31168D - 11.91231H + 0.03834D^2H - 0.45963D^2 - 0.00475D^3$	0.96	12.67	
				$W_3 = -8.13114 + 0.01312D^2H$	0.94	14.53	
	Bark	10.46	7.57	$W_1 = -11.11392 + 1.45387D - 0.04609D^2 + 0.00129D^3$	0.89	2.60	
				$W_2 = 0.24086 + 1.30541D - 1.17044H + 0.00369D^2H - 0.04322D^2 - 0.00046D^3$	0.94	2.01	
				$W_3 = -0.01072 + 0.00166D^2H$	0.93	2.06	
Stem <10⩾2 cm	Wood	5.96	2.70	$W_1 = -9.16680 + 3.25669D - 0.18256D^2 + 0.00292D^3$	0.61	1.74	51
				$W_2 = -8.76791 + 2.39758D + 0.65800H - 0.00103D^2H - 0.15055D^2 + 0.00297D^3$	0.63	1.72	
				$W_3 = 6.55149 - 0.00013D^2H$	0.05	2.66	
	Bark	1.33	0.57	$W_1 = -1.77146 + 0.66639D - 0.03758D^2 + 0.00061D^3$	0.53	0.40	
				$W_2 = -1.71359 + 0.56826D + 0.07656H - 0.00002D^2H - 0.03484D^2 + 0.00059D^3$	0.57	0.40	
				$W_3 = 1.40933 - 0.00002D^2H$	0.02	0.57	
Live branches ⩾2 cm	Wood	0.74	1.29	$W_1 = -0.09993 + 0.04832D - 0.00705D^2 + 0.00033D^3$	0.79	0.62	51
				$W_2 = -0.17597 + 0.22720D - 0.13621H + 0.00027D^2H - 0.01423D^2 + 0.00030D^3$	0.79	0.62	
				$W_3 = -0.35687 + 0.00023D^2H$	0.70	0.71	
	Bark	0.26	0.45	$W_1 = 0.03879 - 0.00273D - 0.00116D^2 + 0.00009D^3$	0.78	0.22	
				$W_2 = 0.01413 + 0.04686D - 0.03816H + 0.00005D^2H - 0.00288D^2 + 0.00009D^3$	0.79	0.22	
				$W_3 = -0.12290 + 0.00008D^2H$	0.69	0.26	

Table 2 continued.

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Live branches <2 cm	Wood & Bark	4.24	4.70	$W_1 = 3.45083 - 0.98611D + 0.09234D^2 - 0.00180D^3$	0.40	3.75	51
				$W_2 = 3.02697 - 0.20369D - 0.60616H + 0.00045D^2H + 0.06766D^2 - 0.00171D^3$	0.42	3.77	
				$W_3 = 1.84442 + 0.00051D^2H$	0.25	4.11	
	Foliage	6.67	8.11	$W_1 = 6.75746 - 1.82978D + 0.16446D^2 - 0.00326D^3$	0.31	6.93	
				$W_2 = 5.47193 + 0.95756D - 2.13386H + 0.00340D^2H + 0.05998D^2 - 0.00344D^3$	0.34	6.93	
				$W_3 = 3.16270 + 0.00075D^2H$	0.18	7.41	
Live branches <0.5 cm with foliage		6.72	7.84	$W_1 = 5.62589 - 1.44161D + 0.13407D^2 - 0.00261D^3$	0.31	6.73	51
				$W_2 = 4.47745 + 1.02188D - 1.88733H + 0.00290D^2H + 0.04264D^2 - 0.00273D^3$	0.33	6.74	
				$W_3 = 3.13426 + 0.00077D^2H$	0.20	7.07	
Living tree above ground with foliage[b]		87.09	78.95	$W_1 = 1.51752 - 0.96880D + 0.29833D^2 + 0.00092D^3$	0.92	22.67	51
				$W_2 = -3.23543 + 14.68156D - 11.70067H + 0.03887D^2H - 0.46999D^2 - 0.00591D^3$	0.96	16.06	
				$W_3 = 8.93214 + 0.01670D^2H$	0.95	17.88	
Living tree above ground without foliage[b]		78.41	73.97	$W_1 = -6.71986 + 1.45939D + 0.06920D^2 + 0.00566D^3$	0.93	20.01	51
				$W_2 = -9.70442 + 13.34999D - 8.81847H + 0.03456D^2H - 0.56072D^2 - 0.00101D^3$	0.98	11.86	
				$W_3 = 4.41826 + 0.01581D^2H$	0.97	12.94	

[a] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[b] Coefficients are not additive because living tree above ground includes stem <2 cm.

Table 3. Equations for predicting biomass (kg) of jack pine

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Stump	Wood	4.88	3.99	$W_1 = 3.42372 - 0.60844D + 0.04533D^2 - 0.00062D^3$	0.86	1.51	56
				$W_2 = 3.46153 - 0.44635D - 0.10397H + 0.00010D^2H + 0.03871D^2 - 0.00058D^3$	0.87	1.53	
				$W_3 = 1.66801 + 0.00043D^2H$	0.73	2.08	
	Bark	0.63	0.56	$W_1 = 0.23059 - 0.03046D + 0.00289D^2 - 0.00003D^3$	0.77	0.28	
				$W_2 = 0.36385 - 0.07126D + 0.00743H + 0.00002D^2H + 0.00482D^2 - 0.00007D^3$	0.77	0.28	
				$W_3 = 0.18562 + 0.00006D^2H$	0.73	0.29	
Stem ⩾10 cm	Wood	128.08	107.79	$W_1 = -487.8290 + 74.71140D - 3.34814D^2 + 0.05297D^3$	0.87	39.67	42
				$W_2 = -95.19032 + 15.19710D - 1.33066H + 0.01728D^2H - 0.65902D^2 + 0.00696D^3$	0.99	12.13	
				$W_3 = -4.36888 + 0.01342D^2H$	0.98	14.62	
	Bark	9.97	7.39	$W_1 = -31.19068 + 4.63292D - 0.19366D^2 + 0.00297D^3$	0.86	2.88	
				$W_2 = -10.62382 + 1.15436D + 0.15349H + 0.00073D^2H - 0.03812D^2 + 0.00043D^3$	0.94	1.94	
				$W_3 = 1.14012 + 0.00089D^2H$	0.93	2.02	
Stem <10⩾2 cm	Wood	6.08	4.05	$W_1 = -1.86339 + 2.22077D - 0.13135D^2 + 0.00206D^3$	0.45	3.09	56
				$W_2 = -3.50778 + 0.37079D + 1.34584H - 0.00157D^2H - 0.05802D^2 + 0.00178D^3$	0.65	2.49	
				$W_3 = 7.94310 - 0.00025D^2H$	0.24	3.56	
	Bark	0.81	0.43	$W_1 = -0.02344 + 0.23084D - 0.01352D^2 + 0.00021D^3$	0.44	0.33	
				$W_2 = -0.14316 + 0.08009D + 0.10780H - 0.00012D^2H - 0.00752D^2 + 0.00018D^3$	0.56	0.30	
				$W_3 = 1.00835 - 0.00003D^2H$	0.25	0.38	
Live branches ⩾2 cm	Wood	6.84	12.20	$W_1 = 3.43493 - 0.61063D + 0.01572D^2 + 0.00059D^3$	0.63	7.64	56
				$W_2 = -8.97232 + 1.10353D + 0.58130H - 0.00284D^2H - 0.07849D^2 + 0.00344D^3$	0.78	6.03	
				$W_3 = -0.65617 + 0.00100D^2H$	0.43	9.33	
	Bark	1.46	2.75	$W_1 = 1.62496 - 0.33039D + 0.01557D^2 - 0.00009D^3$	0.53	1.93	
				$W_2 = -0.91975 - 0.01698D + 0.14254H - 0.00060D^2H - 0.00217D^2 + 0.00049D^3$	0.65	1.69	
				$W_3 = -0.08620 + 0.00020D^2H$	0.36	2.22	

Table 3 continued.

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Live branches <2 cm	Wood & Bark	4.37	4.75	$W_1 = 0.05524 + 0.01034D + 0.00625D^2 + 0.00009D^3$	0.74	2.51	56
				$W_2 = -0.73490 + 0.01576D + 0.10039H - 0.00024D^2H + 0.00454D^2 + 0.00024D^3$	0.74	2.54	
				$W_3 = 0.76954 + 0.00048D^2H$	0.65	2.84	
	Foliage	6.35	7.38	$W_1 = -1.52595 + 0.43497D - 0.02076D^2 + 0.00071D^3$	0.72	4.03	
				$W_2 = 0.26564 - 0.15100D + 0.12279H + 0.00021D^2H + 0.00683D^2 + 0.00019D^3$	0.73	4.04	
				$W_3 = 0.50034 + 0.00078D^2H$	0.71	4.01	
Live branches <0.5 cm with foliage		6.05	6.80	$W_1 = -3.39675 + 0.84270D - 0.04459D^2 + 0.00109D^3$	0.77	3.33	56
				$W_2 = -2.73257 + 0.41174D + 0.17608H - 0.00004D^2H - 0.02553D^2 + 0.00083D^3$	0.78	3.37	
				$W_3 = 0.55080 + 0.00073D^2H$	0.74	3.50	
Living tree above ground with foliage[b]		139.08	142.66	$W_1 = -95.54713 + 21.16062D - 1.04327D^2 + 0.02434D^3$	0.93	38.98	56
				$W_2 = -10.03116 + 1.94553D + 0.51378H + 0.01529D^2H - 0.08825D^2 + 0.00238D^3$	0.98	18.93	
				$W_3 = 6.05712 + 0.01767D^2H$	0.98	18.70	
Living tree above ground without foliage[b]		128.64	131.18	$W_1 = -100.6194 + 22.15374D - 1.10697D^2 + 0.02475D^3$	0.94	33.64	56
				$W_2 = -22.90004 + 5.26399D + 0.11665H + 0.01423D^2H - 0.26272D^2 + 0.00498D^3$	0.99	13.22	
				$W_3 = 5.93029 + 0.01630D^2H$	0.99	13.56	

[a] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[b] Coefficients are not additive because living tree above ground includes stem <2 cm.

Table 4. Equations for predicting biomass (kg) of tamarack larch

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Stump	Wood	4.34	3.14	$W_1 = -1.31396 + 0.46666D - 0.02274D^2 + 0.00071D^3$	0.80	1.46	56
				$W_2 = -0.90324 + 0.03135D + 0.26579H - 0.00054D^2H - 0.00280D^2 + 0.00066D^3$	0.80	1.48	
				$W_3 = 0.93770 + 0.00061D^2H$	0.77	1.52	
	Bark	0.57	0.37	$W_1 = 0.32809 - 0.06442D + 0.00666D^2 - 0.00013D^3$	0.70	0.21	
				$W_2 = 0.35574 - 0.09406D + 0.01820H - 0.00004D^2H + 0.00801D^2 - 0.00013D^3$	0.70	0.21	
				$W_3 = 0.20020 + 0.00007D^2H$	0.66	0.22	
Stem ⩾10 cm	Wood	81.64	45.98	$W_1 = -106.98385 + 13.82626D - 0.44639D^2 + 0.01003D^3$	0.91	14.08	42
				$W_2 = -169.42513 + 21.34748D + 2.91221H + 0.00445D^2H - 1.03397D^2 + 0.01941D^3$	0.94	11.62	
				$W_3 = -3.11604 + 0.01165D^2H$	0.94	11.55	
	Bark	9.60	5.01	$W_1 = -12.92173 + 1.59119D - 0.03912D^2 + 0.00070D^3$	0.88	1.83	
				$W_2 = -18.96285 + 2.06040D + 0.43080H - 0.00001D^2H - 0.08044D^2 + 0.00153D^3$	0.90	1.71	
				$W_3 = 0.65323 + 0.00123D^2H$	0.88	1.75	
Stem <10⩾2 cm	Wood	6.40	2.47	$W_1 = -8.26237 + 2.98840D - 0.16958D^2 + 0.00292D^3$	0.45	1.88	56
				$W_2 = -8.41792 + 2.65759D + 0.35306H + 0.00003D^2H - 0.16963D^2 + 0.00307D^3$	0.50	1.83	
				$W_3 = 5.98493 + 0.00008D^2H$	0.02	2.47	
	Bark	1.26	0.46	$W_1 = -1.59929 + 0.57169D - 0.03208D^2 + 0.00055D^3$	0.51	0.33	
				$W_2 = -1.61617 + 0.52961D + 0.04397H + 0.00000D^2H - 0.03199D^2 + 0.00057D^3$	0.53	0.33	
				$W_3 = 1.15548 + 0.00002D^2H$	0.03	0.46	
Live branches ⩾2 cm	Wood	4.91	6.89	$W_1 = -0.79439 + 0.30205D - 0.03900D^2 + 0.00179D^3$	0.59	4.56	56
				$W_2 = -0.71159 + 0.61059D - 0.30918H + 0.00003D^2H - 0.04099D^2 + 0.00168D^3$	0.59	4.63	
				$W_3 = -1.25157 + 0.00111D^2H$	0.52	4.79	
	Bark	1.34	1.78	$W_1 = -0.00971 + 0.01716D - 0.00496D^2 + 0.00035D^3$	0.62	1.14	
				$W_2 = -0.46937 + 0.38331D - 0.18667H + 0.00056D^2H - 0.02544D^2 + 0.00044D^3$	0.63	1.14	
				$W_3 = -0.34731 + 0.00030D^2H$	0.59	1.15	

Table 4 continued.

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Live branches <2 cm	Wood & Bark	9.60	8.47	$W_1 = -0.31315 - 0.04581D + 0.04686D^2 - 0.00074D^3$	0.55	5.82	56
				$W_2 = -0.14304 - 0.09712D - 0.00798H - 0.00018D^2H + 0.05317D^2 - 0.00080D^3$	0.55	5.94	
				$W_3 = 2.01016 + 0.00137D^2H$	0.53	5.88	
	Foliage	4.83	4.09	$W_1 = 2.95150 - 0.79206D + 0.07539D^2 - 0.00141D^3$	0.61	2.62	
				$W_2 = 2.22149 - 0.06991D - 0.42522H + 0.00094D^2H + 0.04072D^2 - 0.00129D^3$	0.62	2.65	
				$W_3 = 0.97374 + 0.00070D^2H$	0.58	2.66	
Living tree above ground with foliage[b]		101.97	78.60	$W_1 = 7.06302 - 3.01775D + 0.48754D^2 - 0.00329D^3$	0.97	14.71	56
				$W_2 = -0.63192 - 2.33241D + 1.85838H + 0.00739D^2H + 0.22708D^2 - 0.00034D^3$	0.98	12.80	
				$W_3 = 6.32169 + 0.01728D^2H$	0.97	13.22	
Living tree above ground without foliage[b]		96.89	75.18	$W_1 = 4.67782 - 2.38151D + 0.42265D^2 - 0.00211D^3$	0.97	13.86	56
				$W_2 = -2.38734 - 2.36219D + 2.26460H + 0.00657D^2H + 0.19275D^2 + 0.00075D^3$	0.98	11.73	
				$W_3 = 5.28648 + 0.01655D^2H$	0.97	12.10	

[a] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[b] Coefficients are not additive because living tree above ground includes stem <2 cm.

Table 5. Equations for predicting biomass (kg) of trembling aspen

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Stump	Wood	5.01	5.60	$W_1 = 2.00364 - 0.48139D + 0.03727D^2 - 0.00042D^3$	0.69	3.20	56
				$W_2 = 2.02490 - 0.69840D + 0.13599H - 0.00016D^2H + 0.04453D^2 - 0.00042D^3$	0.69	3.26	
				$W_3 = 0.63598 + 0.00040D^2H$	0.67	3.26	
	Bark	0.97	1.00	$W_1 = 0.53325 - 0.11868D + 0.00874D^2 - 0.00011D^3$	0.72	0.55	
				$W_2 = 0.53062 - 0.07834D - 0.02512H + 0.00004D^2H + 0.00729D^2 - 0.00011D^3$	0.72	0.56	
				$W_3 = 0.17134 + 0.00007D^2H$	0.68	0.57	
Stem ≥10 cm	Wood	181.52	143.46	$W_1 = -224.76940 + 27.72903D - 0.91499D^2 + 0.01740D^3$	0.97	27.03	42
				$W_2 = -204.88144 + 17.85055D + 4.72908H - 0.00019D^2H - 0.64122D^2 + 0.01462D^3$	0.97	25.20	
				$W_3 = -1.26104 + 0.01251D^2H$	0.96	28.12	
	Bark	38.24	31.17	$W_1 = 5.44633 - 1.50271D + 0.11466D^2 - 0.00029D^3$	0.97	5.62	
				$W_2 = 14.19919 - 2.72898D + 0.11792H + 0.00127D^2H + 0.14148D^2 - 0.00121D^3$	0.98	5.17	
				$W_3 = -1.60726 + 0.00273D^2H$	0.97	5.54	
Stem <10≥2 cm	Wood	5.60	2.49	$W_1 = -1.50000 + 1.65193D - 0.08613D^2 + 0.00121D^3$	0.54	1.73	55
				$W_2 = -1.44663 + 1.23489D + 0.26488H - 0.00020D^2H - 0.07377D^2 + 0.00119D^3$	0.57	1.72	
				$W_3 = 6.93566 - 0.00012D^2H$	0.30	2.10	
	Bark	2.01	0.74	$W_1 = -0.80394 + 0.52779D - 0.02535D^2 + 0.00035D^3$	0.32	0.63	
				$W_2 = -0.78127 + 0.55107D - 0.01418H + 0.00008D^2H - 0.02710D^2 + 0.00033D^3$	0.33	0.63	
				$W_3 = 2.12328 - 0.00001D^2H$	0.03	0.74	
Live branches ≥2 cm	Wood	6.85	10.96	$W^1 = 5.70758 - 1.45303D + 0.08862D^2 - 0.00100D^3$	0.54	7.66	56
				$W_2 = 5.21436 - 4.22711D + 1.64427H - 0.00562D^2H + 0.23801D^2 - 0.00000D^3$	0.82	4.87	
				$W_3 = -0.02780 + 0.00062D^2H$	0.43	8.36	
	Bark	3.74	5.50	$W_1 = -0.10925 + 0.02406D - 0.00398D^2 + 0.00037D^3$	0.77	2.69	
				$W_2 = -0.23386 - 0.44948D + 0.27571H - 0.00115D^2H + 0.02451D^2 + 0.00060D^3$	0.83	2.40	
				$W_3 = -0.65606 + 0.00040D^2H$	0.70	3.06	

Table 5 continued.

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Live branches <2 cm	Wood & Bark	4.77	4.82	$W_1 = 0.21260 - 0.05935D + 0.01750D^2 - 0.00021D^3$	0.60	3.13	56
				$W_2 = -0.01112 - 0.55846D + 0.27924H - 0.00165D^2H + 0.05437D^2 + 0.00015D^3$	0.77	2.41	
				$W_3 = 1.53423 + 0.00029D^2H$	0.49	3.47	
	Foliage	2.71	2.38	$W_1 = -0.92280 + 0.19377D + 0.00201D^2 - 0.00008D^3$	0.48	1.76	
				$W_2 = -0.97389 + 0.49255D - 0.18991H + 0.00011D^2H - 0.00637D^2 - 0.00006D^3$	0.50	1.77	
				$W_3 = 1.37371 + 0.00012D^2H$	0.35	1.94	
Living tree above ground with foliage[b]		196.42	200.40	$W_1 = -2.86334 - 0.76994D + 0.32606D^2 + 0.00362D^3$	0.98	29.05	56
				$W_2 = -1.63418 - 10.54079D + 6.15624H - 0.00571D^2H + 0.63281D^2 + 0.00328D^3$	0.98	28.43	
				$W_3 = 7.53108 + 0.01709D^2H$	0.97	36.98	
Living tree above ground without foliage[b]		193.70	198.91	$W_1 = -1.94053 - 0.96372D + 0.32405D^2 + 0.00370D^3$	0.98	28.58	56
				$W_2 = -0.66028 - 11.03334D + 6.34615H - 0.00582D^2H + 0.63918D^2 + 0.00333D^3$	0.98	27.84	
				$W_3 = 6.15737 + 0.01697D^2H$	0.97	36.33	

[a] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[b] Coefficients are not additive because living tree above ground includes stem <2 cm.

Table 6. Equations for predicting biomass (kg) of balsam poplar

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Stump	Wood	3.40	2.78	$W_1 = -0.91961 + 0.19658D - 0.00143D^2 + 0.00007D^3$	0.72	1.51	56
				$W_2 = -2.30150 + 0.95303D - 0.32839H + 0.00037D^2H - 0.03286D^2 + 0.00033D^3$	0.73	1.52	
				$W_3 = 0.72436 + 0.00028D^2H$	0.70	1.54	
	Bark	0.85	0.62	$W_1 = 0.26045 - 0.05971D + 0.00691D^2 - 0.00012D^3$	0.74	0.32	
				$W_2 = -0.09325 + 0.13764D - 0.08765H + 0.00009D^2H - 0.00104D^2 - 0.00006D^3$	0.75	0.32	
				$W_3 = 0.26746 + 0.00006D^2H$	0.68	0.35	
Stem ⩾10 cm	Wood	115.44	80.75	$W_1 = -104.42686 + 14.06092D - 0.50586D^2 + 0.01104D^3$	0.87	30.71	42
				$W_2 = -166.10971 + 31.98780D - 4.62496H + 0.00995D^2H - 1.39830D^2 + 0.02003D^3$	0.88	29.94	
				$W_3 = -9.22583 + 0.01009D^2H$	0.86	30.80	
	Bark	30.93	21.54	$W_1 = -6.31395 - 0.02521D + 0.06460D^2 - 0.00025D^3$	0.85	8.74	
				$W_2 = -23.64943 + 5.03902D - 1.38598H + 0.00247D^2H - 0.17511D^2 + 0.00215D^3$	0.86	8.73	
				$W_3 = -1.93648 + 0.00266D^2H$	0.84	8.78	
Stem <10⩾2 cm	Wood	5.93	3.07	$W_1 = -9.85163 + 3.38267D - 0.18058D^2 + 0.00273D^3$	0.65	1.85	55
				$W_2 = -8.68194 + 2.55478D + 0.45064H - 0.00012D^2H - 0.15714D^2 + 0.00257D^3$	0.68	1.81	
				$W_3 = 7.96923 - 0.00022D^2H$	0.35	2.50	
	Bark	2.11	0.77	$W_1 = -1.97616 + 0.80572D - 0.04112D^2 + 0.00060D^3$	0.45	0.59	
				$W_2 = -1.65211 + 0.55395D + 0.14535H - 0.00001D^2H - 0.03498D^2 + 0.00057D^3$	0.52	0.56	
				$W_3 = 2.43605 - 0.00004D^2H$	0.14	0.72	
Live branches ⩾2 cm	Wood	4.81	9.00	$W_1 = 2.53974 - 0.43874D + 0.01382D^2 + 0.00029D^3$	0.41	7.13	56
				$W_2 = -2.43287 + 1.84482D - 0.75921H + 0.00189D^2H - 0.11071D^2 + 0.00142D^3$	0.44	7.05	
				$W_3 = -1.80143 + 0.00070D^2H$	0.41	6.99	
	Bark	3.94	8.35	$W_1 = 0.90750 - 0.03694D - 0.01403D^2 + 0.00077D^3$	0.39	6.73	
				$W_2 = -2.99911 + 1.78821D - 0.62644H + 0.00144D^2H - 0.11105D^2 + 0.00164D^3$	0.41	6.74	
				$W_3 = -1.82487 + 0.00061D^2H$	0.36	6.73	

Table 6 continued.

Tree component		Mean	Standard deviation	Equation[a]	R^2	Standard error of estimate	N
Live branches <2 cm	Wood & Bark	4.87	5.71	$W_1 = -1.14631 + 0.46918D - 0.03135D^2 + 0.00087D^3$	0.59	3.77	56
				$W_2 = -3.57778 + 1.66213D - 0.44480H + 0.00082D^2H - 0.09025D^2 + 0.00139D^3$	0.60	3.79	
				$W_3 = -0.02041 + 0.00052D^2H$	0.56	3.84	
	Foliage	3.22	3.04	$W_1 = -1.47799 + 0.42815D - 0.02290D^2 + 0.00054D^3$	0.69	1.74	
				$W_2 = -2.90805 + 1.36583D - 0.48905H + 0.00018D^2H - 0.05138D^2 + 0.00074D^3$	0.72	1.67	
				$W_3 = 0.51499 + 0.00029D^2H$	0.60	1.94	
Living tree above ground with foliage[b]		136.00	128.60	$W_1 = -19.78931 + 4.01599D - 0.05686D^2 + 0.00744D^3$	0.89	44.25	55
				$W_2 = -64.76640 + 23.04832D - 5.61381H + 0.01724D^2H - 1.15929D^2 + 0.01751D^3$	0.90	42.44	
				$W_3 = -1.29892 + 0.01472D^2H$	0.89	42.82	
Living tree above ground without foliage[b]		132.91	126.10	$W_1 = -18.16371 + 3.56164D - 0.03293D^2 + 0.00690D^3$	0.89	43.48	55
				$W_2 = -61.33261 + 21.50109D - 5.08824H + 0.01687D^2H - 1.09619D^2 + 0.01667D^3$	0.90	41.56	
				$W_3 = -1.79052 + 0.01444D^2H$	0.89	41.80	

[a] W_1, W_2, and W_3 are dry weight biomass (kg) as estimated from Model 1, Model 2, and Model 3, respectively. D and H are diameter outside bark at breast height (cm) and the total height of the tree (m).

[b] Coefficients are not additive because living tree above ground includes stem <2 cm.

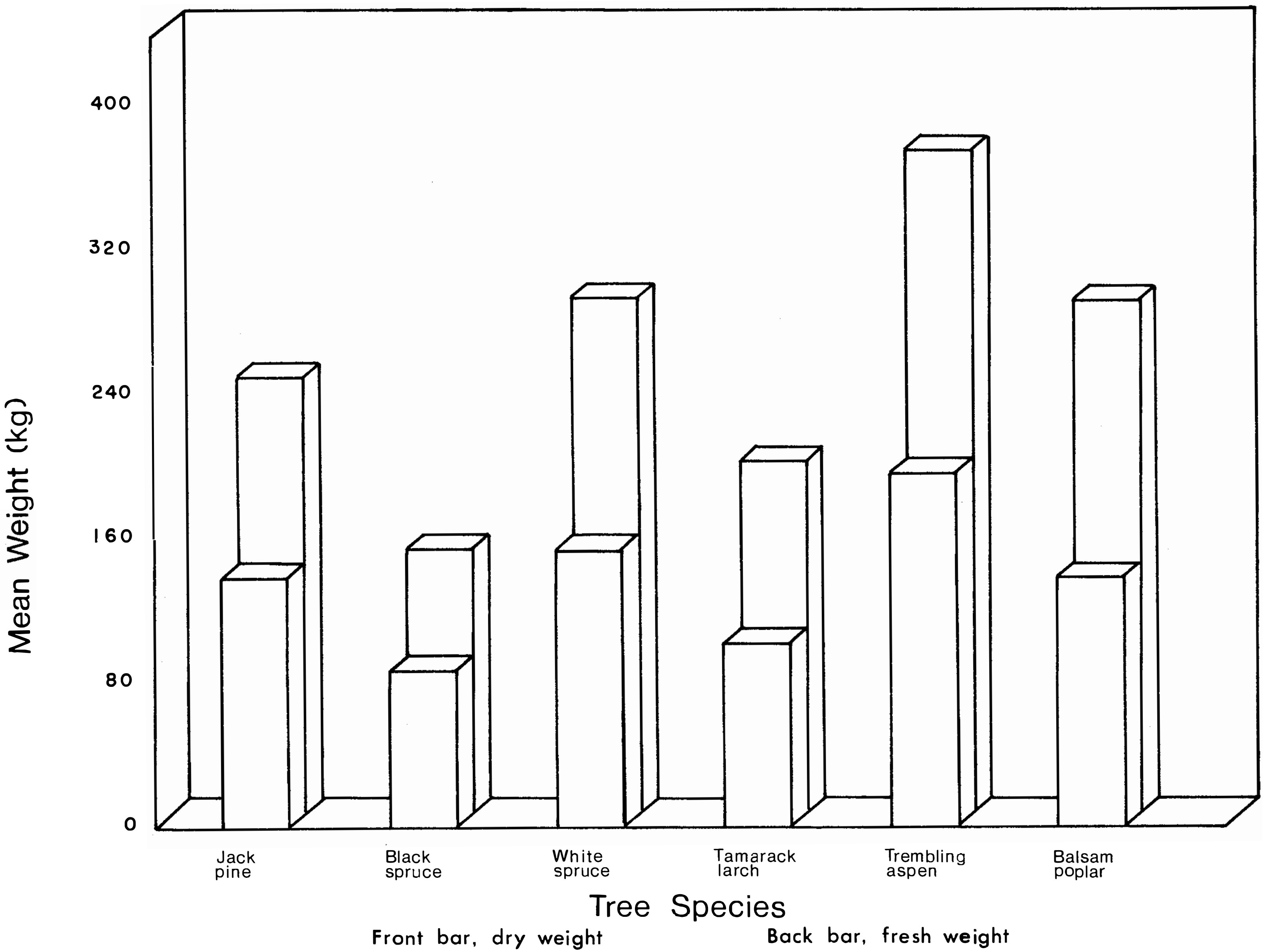

Figure 5. Fresh and dry weight biomass of the six tree species.