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[1] Contributed paper, not presented at the workshop.

RESEARCH PAPERS

Biomass Studies
Outside the United States

Moderator: James T. Bones

PREDICTION ERROR IN TREE BIOMASS REGRESSION

FUNCTIONS FOR WESTERN CANADA

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Abstract

Biomass equations were derived for eight commercial tree species in the Boreal Forest Region of western Canada, using two regression functions based on diameter, and a combination of diameter and height. The model based on diameter and height regression function gave excellent predictions when validated using independent data; R^2 obtained for the predictions based on this regression function for regional and Alberta applications were 0.99 and 0.97 for trembling aspen, and balsam fir had R^2 values of 0.96 for both the regional and Alberta applications.

Introduction

Biomass equations are increasingly being used for deriving forest biomass tables and inventories. Individual species equations are available also to provide biomass information pertaining to all or part of a tree as a renewable energy source. Extensive biomass data have been accumulated in North America over recent years for most of the forest tree species, however, little attention has been given to assessment of estimation errors and bias inherent in the use of biomass equations for such predictions.

Estimation errors can occur due to many sources. Sampling methods used for collection of data, choice of a regression function on which the prediction equation is to be based, and the lack of fit contribute to most of these errors. The precision and accuracy of prediction equations need to be known to avoid misleading interpretation.

A study was undertaken in the Boreal Forest Region of western Canada to determine and compare errors of estimation when prediction equations derived from two different regression functions are used to obtain biomass information. The objectives of the study were as follows:

1. Determine the accuracy of prediction equations as derived from individual prairie provinces (Alberta, Saskatchewan, and Manitoba) and the combined provinces (regional) data sets.

2. Compare the errors of prediction when equations from an individual province are used in other prairie provinces.

3. Assess the accuracy and bias inherent in the use of prediction equations based on two different regression functions when validated using an independent data set in Alberta.

Methods

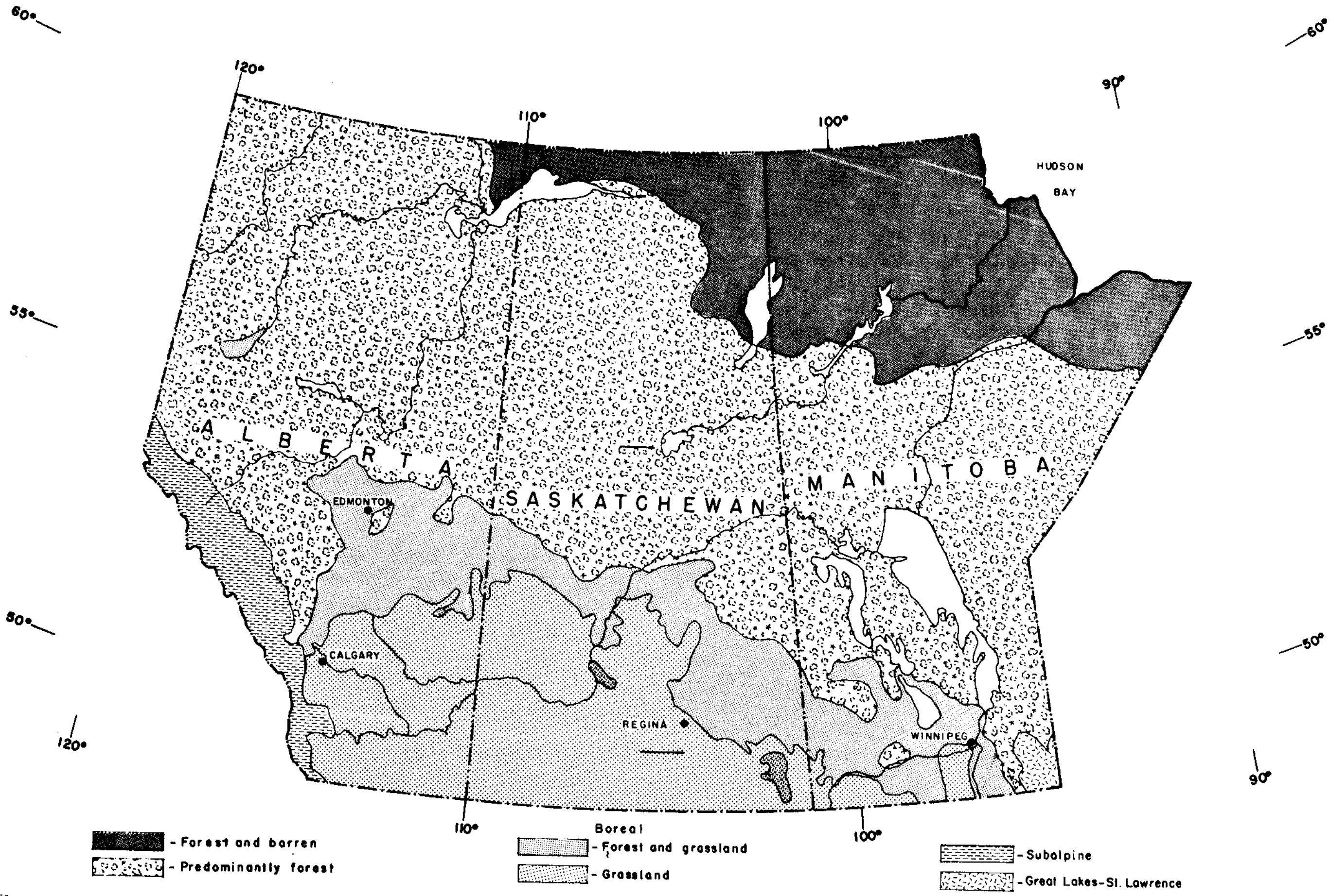
Field and Laboratory Procedures

The tree species tested in the study were five softwoods and three hardwoods. The softwoods were jack pine (*Pinus banksiana Lamb.*), black spruce (*Picea mariana* (Mill.) BSP), white spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Mill.), and tamarack (*Larix laricina* (du Roi) K. Koch). The three hardwoods were trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*P. balsamifera* Marsh.), and white birch (*Betula papyrifera* Marsh.).

Twenty trees of each species were sampled in each of the three prairie provinces (Alberta, Saskatchewan, and Manitoba), for a total of 60 trees per species on a regional basis for the predominantly Boreal Forest Region in western Canada (Fig. 1). The field information recorded included diameter at breast height outside bark (dbhob) at 1.3 m (D), and total height of the tree (H). Sampling was done according to diameter size, by felling five trees per species per province for each of the four diameter classes (0-11, 11-20, 21-30, and 31^+ cm).

After felling the trees, merchantable (dbhob 10 cm or greater) and nonmerchantable (dbhob less than 10 cm) sections of the tree stem were marked. The merchantable stem was cut into four and the nonmerchantable stem into three equal subsections. Length and dbhob measurements were made for each of the subsections, and the tree stem was cut and weighed for fresh weights of individual components. These weights were also determined for the remaining aboveground parts of the felled tree. Subsamples consisting of 1-cm thick disks were obtained for the tree stem sections, and representative subsamples were similarly taken for foliage and live branches. Debarking to separate wood and bark was done for all subsamples, except for live small branches. Ovendry weights were determined after all subsamples were dried at 103°C for 24 hours or until a constant weight was attained. Details on field and laboratory procedures are provided by Singh (1982).

Figure 1. Boreal Forest Region in the prairie provinces of Alberta, Saskatchewan, and Manitoba.



Computer Procedures

Dry/fresh weight and bark/wood dry weight ratios were computed from the volume-weighted data. The

the Smalion formula:

$$V = L(A_t + A_b)/2$$

where L = length of section,

A_t = cross-sectional area at top, and

A_b = cross-sectional area at bottom.

The cross-sectional areas were computed from dbhob measurements. Total volume of the tree stem was obtained by summing the volumes of all component stem sections. Computer subroutines were written in FORTRAN for biomass computations based on field and laboratory data collected in the study (Singh and Campbell 1983).

Regression Functions and Analysis

Two regression functions were used, one based on a combination of D and H, and the other based on D only:

Model I: $W = a_0 + a_1 D^2 H$

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

where W = ovendry biomass of live tree above-ground, and a_0, a_1, ... , a_3 are regression coefficients.

Mean, standard deviation, R^2, SEE (standard error of estimate), % SEE (standard error expressed as percentage of the mean), and residuals (difference between the actual and the fitted value) were calculated for the derived versus the applied regression equations.

Comparisons were made for testing the accuracy of the individual province and regional prediction equations using the data collected for the study and an independent data set available for two hardwood species in Alberta.

Results and Discussions

The R^2 values for the individual province equations for the eight tree species ranged from 0.883 (white birch) to 0.997 (trembling aspen) for Model I, and from 0.934 to 0.997 for Model II (Appendix I). Both species for the highest and the lowest R^2 values were sampled in Saskatchewan. The corresponding range of % SEE values was 35.2 to 5.3, and 28.0 to 6.4, respectively. The regional equations had a R^2 range of 0.943 to 0.988, with the same species in Saskatchewan making up the highest and the lowest ranking. Black spruce (Model I) also showed the highest fit in Alberta (R^2 = 0.997, % SEE = 5.1).

The regional equations based on the combined sample of 60 trees per species showed that the R^2 ranged from 0.943 to 0.988 for Model I, and from 0.956 to 0.977 for Model II (Appendix II). The corresponding % SEE values ranged from 24.2 to 11.2, and from 21.8 to 15.8, respectively. White birch had the lowest and trembling aspen the highest fit in this case as well. The goodness of fit and the associated errors seemed to have averaged out when the three data subsets from the prairie provinces were combined into a single regional set for deriving biomass prediction equations for each species.

The prediction and errors involved in the individual province equations when used in each province are shown in Table 1. A test of the prairies regional equations on the individual province data for each species showed that the provincial equations were slightly better than the regional equations in predicting the actual biomass values (Table 2).

Table 1. Regional equations applied to estimation of ovendry biomass of eight tree species in three individual provinces[a]

Species	Province	Actual Mean	Predicted Mean Model I	Predicted Mean Model II	Predicted R^2 Model I	Predicted R^2 Model II	% SEE Model I	% SEE Model II	Mean Residuals Model I	Mean Residuals Model II
Softwoods:										
Jack pine	Alberta	157.5	162.9	174.7	0.97	0.95	17.8	23.0	-5.4	-17.1
	Saskatchewan	189.1	192.5	178.8	0.98	0.97	12.8	18.0	-3.4	10.3
	Manitoba	197.9	189.0	190.8	0.97	0.97	17.0	17.6	8.9	7.0
Black spruce	Alberta	177.5	182.8	180.5	0.99	0.99	7.5	9.2	-5.4	-3.0
	Saskatchewan	181.6	178.5	180.0	0.997	0.996	5.6	6.7	3.1	1.6
	Manitoba	198.0	195.8	196.6	0.96	0.97	20.0	19.2	2.2	1.4
White spruce	Alberta	220.3	215.5	215.0	0.99	0.99	13.6	13.5	4.7	5.3
	Saskatchewan	183.1	190.1	188.4	0.98	0.97	13.8	18.6	-7.0	-5.3
	Manitoba	212.1	209.7	211.9	0.99	0.99	12.2	12.1	2.3	0.2
Balsam fir	Alberta	191.3	205.8	187.7	0.99	0.99	11.0	12.0	-14.4	3.6
	Saskatchewan	181.5	190.8	180.9	0.97	0.96	18.6	20.5	-9.3	0.6
	Manitoba	161.4	137.6	165.5	0.88	0.98	34.8	14.7	23.8	-4.1
Tamarack	Alberta	157.7	158.8	155.3	0.99	0.99	11.2	10.5	-1.1	2.4
	Saskatchewan	156.5	155.0	159.7	0.97	0.96	15.2	19.8	1.6	-3.2
	Manitoba	158.5	159.0	157.9	0.99	0.99	11.4	11.1	-0.6	0.6
Hardwoods:										
Trembling aspen	Alberta	220.2	233.6	208.2	0.99	0.97	12.6	20.5	-13.4	12.0
	Saskatchewan	195.9	189.2	203.8	0.99	0.99	7.6	9.0	6.7	-7.9
	Manitoba	212.7	206.1	216.9	0.98	0.97	13.1	18.2	6.6	-4.3
Balsam poplar	Alberta	165.5	173.8	161.8	0.97	0.97	17.7	17.8	-8.4	3.7
	Saskatchewan	141.8	142.0	146.2	0.97	0.97	16.7	18.2	-0.2	-4.4
	Manitoba	145.7	137.2	145.1	0.95	0.97	21.4	16.6	8.5	0.6
White birch	Alberta	294.9	288.0	281.6	0.98	0.99	16.1	14.0	6.9	13.4
	Saskatchewan	226.9	235.8	229.6	0.87	0.90	37.3	35.1	-8.9	-2.8
	Manitoba	234.0	231.9	244.9	0.95	0.96	22.6	21.4	2.1	-10.9

a/ Model I: $W = a_0 + a_1 D^2H$
Model II: $W = a_0 + a_1 D + a_2 D^2 + a_3 D^3$
where W is the ovendry weight (kg) of living tree above ground without dead branches, D is diameter (cm) outside bark at breast height, H is total tree height (m), $a_1 \ldots a_3$ are regression coefficients, Residual is actual minus predicted, and % SEE is standard error of estimate expressed as percentage of the mean.

b/ Calculated from actual measurements from species sampled in Alberta, Saskatchewan, and Manitoba.

Table 2. Comparative estimates and errors in prediction when prairies general e quations and individual province equations based on two regression functions are used to predict ovendry biomass of eight species in each province[a]

Species	Equation used for prediction	Alberta Predicted Mean	Alberta R^2	Alberta % SEE	Saskatchewan Predicted Mean	Saskatchewan R^2	Saskatchewan % SEE	Manitoba Predicted Mean	Manitoba R^2	Manitoba % SEE
Model I:										
Softwoods										
Jack pine	Regional	162.94	0.97	17.2	192.48	0.98	12.5	188.95	0.97	17.8
	Provincial	157.52	0.97	16.8	189.08	0.98	12.3	197.89	0.98	15.3
Black spruce	Regional	182.83	0.99	7.2	178.51	0.997	5.7	195.81	0.96	20.2
	Provincial	177.48	0.997	5.8	181.61	0.997	5.1	197.97	0.96	19.9
White spruce	Regional	215.53	0.99	14.0	190.06	0.98	13.3	209.74	0.98	12.4
	Provincial	220.29	0.99	13.1	183.00	0.98	12.1	212.12	0.99	12.2
Balsam fir	Regional	205.77	0.99	10.2	190.83	0.97	17.7	137.55	0.88	40.9
	Provincial	191.31	0.99	7.4	181.50	0.97	16.9	161.39	0.95	23.3
Tamarack	Regional	158.76	0.99	11.1	154.96	0.97	15.3	159.03	0.99	11.3
	Provincial	157.68	0.99	10.8	156.52	0.98	14.3	158.50	0.99	11.2
Hardwoods										
Trembling aspen	Regional	233.60	0.99	11.9	189.18	0.99	7.8	206.08	0.98	13.5
	Provincial	220.20	0.99	10.7	195.90	0.997	5.3	212.63	0.98	12.7
Balsam poplar	Regional	173.84	0.97	16.9	141.97	0.97	16.7	137.16	0.95	22.7
	Provincial	165.43	0.98	16.3	141.78	0.97	16.7	145.68	0.97	17.8
White birch	Regional	288.01	0.98	16.5	235.78	0.87	35.9	231.92	0.95	22.8
	Provincial	294.93	0.98	15.6	226.90	0.88	35.2	233.99	0.95	21.8
Model II:										
Softwoods										
Jack pine	Regional	174.66	0.95	20.7	178.75	0.97	19.1	190.84	0.97	18.3
	Provincial	157.53	0.98	14.5	189.08	0.98	15.5	197.92	0.97	16.8
Black spruce	Regional	180.52	0.99	9.0	180.02	0.996	6.7	196.62	0.97	19.4
	Provincial	177.50	0.995	7.7	181.67	0.99	6.5	197.98	0.97	18.3
White spruce	Regional	215.02	0.99	13.8	188.39	0.97	18.1	211.89	0.99	12.1
	Provincial	220.27	0.99	10.5	183.14	0.97	17.7	212.10	0.99	10.6
Balsam fir	Regional	187.73	0.99	12.2	180.90	0.96	20.5	165.47	0.98	14.3
	Provincial	191.33	0.99	8.0	181.44	0.97	18.7	161.34	0.98	14.2
Tamarack	Regional	155.30	0.99	10.7	159.72	0.96	19.4	157.91	0.99	11.1
	Provincial	157.76	0.99	10.1	156.54	0.96	19.6	158.46	0.99	10.3
Hardwoods										
Trembling aspen	Regional	208.16	0.97	21.7	203.75	0.99	8.7	216.95	0.97	17.9
	Provincial	220.18	0.98	16.2	195.87	0.997	6.4	212.75	0.98	15.4
Balsam poplar	Regional	161.78	0.97	18.2	146.20	0.97	17.6	145.08	0.97	16.6
	Provincial	165.55	0.97	17.5	141.86	0.98	15.4	145.67	0.98	15.2
White birch	Regional	281.55	0.99	14.7	229.65	0.90	34.7	244.90	0.96	20.5
	Provincial	294.87	0.99	11.7	226.86	0.93	28.1	234.00	0.96	20.4

a/ Model I: $W = a_0 + a_1 D^2H$
Model II: $W = a_0 + a_1 D + a_2 D^2 + a_3 D^3$
where W is ovendry weight (kg) of living tree above ground (excluding dead branche s), D is diameter outside bark at breast height (cm), and H is total tree height (m). Mean is predicted mean, and % SEE is standard error of estimate expressed as a percentage of predicted mean.

It is natural to expect that the individual province equations should fit the input data of the same province better than those derived elsewhere. A test was therefore made to see how good the fit for each species was when the equations derived from one province were applied to the independent data sets from the other two provinces Table 3 shows the results of Alberta equations applied to Saskatchewan and Manitoba. In Saskatchewan, the prediction equations based on Model I showed that all species had R^2 for the estimated values of 0.97 or greater, with the exception of white birch (0.86). For Model II, all species had prediction R^2 values of 0.92 or greater, with the exception of white birch (0.88). In Manitoba, the corresponding Model I values were 0.94 or greater, with the exception of balsam fir (0.84); and the Model II prediction R^2 values were 0.92 or higher for all species. The highest fit (R^2 = 0.99 and % SEE = 8.3, as averaged for both models) for the use of Alberta equations in Saskatchewan and Manitoba was for black spruce in Saskatchewan.

The results of Saskatchewan equations applied to the independent data sets for Alberta and Manitoba are shown in Table 4. In Alberta, the R^2 for the estimated values ranged from 0.96 to 0.99 for all species for Model I, and from 0.93 to 0.99 with the exception of white spruce (0.87) for Model II. The corresponding values in Manitoba were as follows: Model I: 0.93 to 0.98, with the exception of balsam fir (0.85); and Model II: 0.93 to 0.99 for all species. Black spruce in Alberta showed the best predictions averaged for the two models (R^2 = 0.99, % SEE = 9.1).

Manitoba equations applied to prediction in other provinces showed results as listed in Table 5. In Alberta, Model I prediction R^2 values ranged from 0.93 to 0.99 for all species, with the exception of balsam fir (0.82). The Model II values ranged from 0.93 to 0.98 for all species. For Saskatchewan, Model I had R^2 values of 0.95 to 0.997 for all species, with the exception of balsam fir (0.79) and white birch (0.85). The corresponding values for Model II ranged from 0.94 to 0.99 for all species, with the exception of white birch (0.88). On the basis of the average taken for both models, trembling aspen in Saskatchewan gave the best predictions (R^2 = 0.99, % SEE = 9.7).

There are two obvious inferences from the error analysis presented in Tables 3 to 5: (1) with the exception of balsam fir and white birch in most cases, the equations from one province applied to another province yielded nearly as good results as the equations for the specific province; and (2) the species with the lowest fit in all such applications over the three individual provinces was balsam fir, based on regression function of Model I. A test on the identity of individual province equations using regression functions of Models I and II showed that the Model I predictions equations were highly significantly different ($P < 0.01$) for both slope and intercept (Singh 1986). There was no such combined difference, at this probability level, for any of the remaining seven species for either model. It was therefore concluded that: (1) selection of a suitable regression function was an important consideration in deriving prediction equations, and (2) most of the separate equations could be combined into single biomass prediction equations for regional application over the Boreal Forest in western Canada.

Fresh data collection for validation purposes is a costly undertaking. A search for biomass data showed that information required for independent testing was available for two hardwoods (trembling aspen and balsam poplar), as reported by Johnstone and Peterson (1980) for six different locations in Alberta. Four of these locations were in the Boreal Forest Region and one each in the Montane Forest Region and the Forest-grassland transition (Rowe 1972). The errors involved in predicting known population parameters for the 254 trees of trembling aspen and 60 trees of balsam poplar are shown in Table 6. It is evident that the regional equations tested in the study showed better or as good a prediction for trembling aspen as the predictions obtained from the individual province (Alberta) equations. The accuracy and the errors for regional vs. Alberta equations in the case of trembling aspen were: R^2 = 0.99 vs. 0.97 (Model I), and 0.95 (Model I and Model II); % SEE = 15.4 vs. 22.2 (Model I), and 30.2 vs. 29.1 (Model II). For balsam poplar, the predictions for regional vs. Alberta equations were almost identical: R^2 = 0.96 vs. 0.96 (Model I), and 0.95 vs. 0.96 (Model II); % SEE = 23.3 vs. 24.8 (Model I), and 28.5 vs. 26.0 (Model II).

The Model I regression function gave better biomass estimates compared to the Model II regression function. For trembling aspen, Model I provided R^2 values of 0.99 vs. 0.95 and % SEE as 15.4 vs. 30.2 for regional equation, and R^2 values of 0.97 vs. 0.95 and % SEE as 22.2 vs. 29.1 for the Alberta equation. The Model I regression function also gave slightly better results for the validation data predictions of balsam poplar, mainly because the regression function of Model I is based on two measurements (D and H), rather than on a single measurement (D), as is the Model II regression function.

Table 3. Alberta equations applied to estimation of ovendry biomass of tree species in other prairie provinces[a]

Species	Province	Actual Mean[b]	Predicted Mean Model I	Predicted Mean Model II	Predicted R^2 Model I	Predicted R^2 Model II	% SEE Model I	% SEE Model II	Mean Residuals Model I	Mean Residuals Model II
Softwoods:										
Jack pine	Saskatchewan	189.1	185.8	163.1	0.98	0.92	12.5	29.4	3.3	26.0
	Manitoba	197.9	182.4	174.0	0.96	0.97	19.9	25.5	5.5	23.9
Black spruce	Saskatchewan	181.6	173.3	175.6	0.99	0.99	8.4	8.1	8.3	6.0
	Manitoba	198.0	190.0	194.3	0.95	0.96	20.9	20.8	8.0	3.7
White spruce	Saskatchewan	183.1	194.1	202.2	0.97	0.94	15.9	24.9	-11.0	-19.2
	Manitoba	212.1	214.3	223.8	0.99	0.97	12.7	18.1	-2.3	-11.8
Balsam fir	Saskatchewan	181.5	176.6	183.4	0.97	0.94	17.6	26.0	4.9	-1.9
	Manitoba	161.4	124.1	166.4	0.84	0.98	40.2	16.6	37.3	-5.0
Tamarack	Saskatchewan	156.5	154.0	162.5	0.97	0.96	16.2	20.3	2.6	-6.0
	Manitoba	158.5	157.9	160.7	0.99	0.99	11.2	11.8	0.5	-2.2
Hardwoods:										
Trembling aspen	Saskatchewan	195.9	176.3	214.3	0.98	0.97	12.9	18.0	19.6	-18.4
	Manitoba	212.7	193.0	231.4	0.98	0.92	16.0	30.1	19.7	-18.7
Balsam poplar	Saskatchewan	141.8	134.9	149.7	0.97	0.97	17.7	19.3	7.0	-7.9
	Manitoba	145.7	130.2	148.4	0.94	0.97	25.0	16.8	15.5	-2.7
White birch	Saskatchewan	226.9	241.0	237.0	0.86	0.88	38.8	37.9	-14.1	-10.1
	Manitoba	234.0	237.0	252.4	0.95	0.95	22.0	22.8	-3.0	-18.4

a/ Model I: $W = a_0 + a_1 D^2H$

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

where W is the ovendry weight (kg) of living tree above ground without dead branches, D is diameter (cm) outside bark at breast height, H is total tree height (m), and $a_1 \ldots a_3$ are regression coefficients; % SEE is standard error of estimate expressed as percentage of the actual mean.

b/ Calculated from actual measurements from species sampled in Alberta, Saskatchewan, and Manitoba.

Table 4. Saskatchewan equations applied to estimation of ovendry biomass of tree species in other prairie provinces[a]

Species	Province	Actual Mean[b]	Predicted Mean Model I	Predicted Mean Model II	Predicted R^2 Model I	Predicted R^2 Model II	% SEE Model I	% SEE Model II	Mean Residuals Model I	Mean Residuals Model II
Softwoods:										
Jack pine	Alberta	157.5	160.4	186.6	0.97	0.91	17.0	31.7	-2.9	-29.0
	Manitoba	197.9	185.7	202.4	0.97	0.97	18.6	17.3	12.2	-4.6
Black spruce	Alberta	177.5	186.0	182.8	0.99	0.99	9.2	9.0	-8.5	-5.3
	Manitoba	198.0	199.2	199.1	0.96	0.96	19.9	19.6	-1.1	-1.1
White spruce	Alberta	220.3	207.1	210.2	0.98	0.98	17.1	15.3	13.1	10.0
	Manitoba	212.1	201.6	206.1	0.98	0.98	14.2	14.0	10.4	6.0
Balsam fir	Alberta	191.3	195.7	187.8	0.99	0.97	8.7	18.4	-4.3	3.5
	Manitoba	161.4	131.0	167.7	0.85	0.98	39.4	15.6	30.4	-6.3
Tamarack	Alberta	157.7	160.5	152.1	0.98	0.99	13.7	11.2	-2.8	5.6
	Manitoba	158.5	160.8	154.7	0.98	0.99	13.4	11.7	-2.4	3.8
Hardwoods:										
Trembling aspen	Alberta	220.2	242.1	201.3	0.98	0.96	16.1	22.4	-21.9	18.9
	Manitoba	212.7	213.5	210.9	0.98	0.97	13.6	19.3	-0.8	1.8
Balsam poplar	Alberta	165.5	173.2	153.5	0.97	0.93	17.3	28.9	-7.8	11.9
	Manitoba	145.7	137.0	143.0	0.95	0.97	21.9	19.2	8.7	2.7
White birch	Alberta	294.9	273.6	243.4	0.96	0.87	22.4	41.4	21.3	51.5
	Manitoba	234.0	223.4	243.2	0.93	0.93	27.2	28.4	10.5	-9.2

a/ Model I: $W = a_0 + a_1 D^2H$

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

where W is the ovendry weight (kg) of living tree above ground without dead branches, D is diameter (cm) outside bark at breast height, H is total tree height (m), and $a_1 \ldots a_3$ are regression coefficients; % SEE is standard error of estimate expressed as percentage of the actual mean.

b/ Calculated from actual measurements from species sampled in Alberta, Saskatchewan, and Manitoba.

Table 5. Manitoba equations applied to estimation of ovendry biomass of tree species in other prairie provinces[a]

Species	Province	Actual Mean[b]	Predicted Mean Model I	Predicted Mean Model II	Predicted R^2 Model I	Predicted R^2 Model II	% SEE Model I	% SEE Model II	Mean Residuals Model I	Mean Residuals Model II
Softwoods:										
Jack pine	Alberta	157.5	170.3	181.7	0.95	0.93	21.7	28.4	-12.8	-24.2
	Saskatchewan	189.1	201.6	185.8	0.97	0.98	16.8	16.0	-12.5	3.3
Black spruce	Alberta	177.5	184.7	182.6	0.99	0.98	9.2	14.7	-7.3	-5.2
	Saskatchewan	181.6	180.3	183.8	0.997	0.99	5.2	10.9	1.3	-2.2
White spruce	Alberta	220.3	217.9	218.2	0.99	0.98	13.6	17.1	2.4	2.1
	Saskatchewan	183.1	192.5	186.7	0.98	0.96	14.2	19.0	-9.4	-3.6
Balsam fir	Alberta	191.3	247.8	182.5	0.82	0.98	43.3	15.4	-56.4	8.8
	Saskatchewan	181.5	228.8	176.1	0.79	0.97	46.5	19.8	-47.3	5.5
Tamarack	Alberta	157.7	158.2	156.4	0.99	0.98	10.8	13.6	-0.5	1.3
	Saskatchewan	156.5	154.5	160.2	0.97	0.96	15.8	21.3	2.0	3.7
Hardwoods:										
Trembling aspen	Alberta	220.2	239.9	205.7	0.98	0.95	14.3	25.6	-19.8	14.4
	Saskatchewan	195.9	195.9	202.0	0.995	0.99	7.1	12.3	0.03	-6.2
Balsam poplar	Alberta	165.5	186.6	169.4	0.93	0.93	27.0	28.6	-21.1	-3.9
	Saskatchewan	141.8	151.0	149.2	0.95	0.94	22.2	25.8	-9.2	-7.4
White birch	Alberta	294.9	293.6	276.7	0.98	0.98	15.9	14.2	1.4	18.2
	Saskatchewan	226.9	238.1	219.4	0.85	0.88	40.0	37.4	-11.2	7.5

a/ Model I: $W = a_0 + a_1 D^2H$
Model II: $W = a_0 + a_1 D + a_2 D^2 + a_3 D^3$
where W is the ovendry weight (kg) of living tree above ground without dead branches, D is diameter (cm) outside bark at breast height, H is total tree height (m), and $a^1 \dots a^3$ are regression coefficients; % SEE is standard error of estimate expressed as percentage of the actual mean.
b/ Calculated from actual measurements from species sampled in Alberta, Saskatchewan, and Manitoba.

Table 6. Comparative estimation errors for regional and individual province (Alberta) equations when validated on an independent data set to estimate ovendry biomass of two poplar species in Alberta[a]

Species	Prediction Equation	N	Actual Mean[b]	Predicted Mean Model I	Predicted Mean Model II	Predicted R^2 Model I	Predicted R^2 Model II	% SEE Model I	% SEE Model II	Mean Residuals Model I	Mean Residuals Model II
Trembling aspen	Regional	254	68.0	68.6	69.8	0.99	0.95	15.4	30.2	-0.6	-1.8
	Alberta	254	68.0	57.2	69.1	0.97	0.95	22.2	29.1	10.8	-1.2
Balsam poplar	Regional	60	49.7	54.3	44.3	0.96	0.95	23.3	28.5	-4.6	5.4
	Alberta	60	49.7	50.7	47.1	0.96	0.96	24.8	26.0	-1.0	2.6

a/ Model I: $W = a_0 + a_1 D^2H$
Model II: $W = a_0 + a_1 D + a_2 D^2 + a_3 D^3$
where W is the ovendry weight (kg) of living tree above ground without dead branches, D is diameter (cm) outside bark at breast height, H is total tree height (m), and $a_1 \dots a_3$ are regression coefficients; % SEE is standard error of estimate expressed as percentage of actual mean.
b/ Calculated from actual measurements from species sampled in Alberta, Saskatchewan, and Manitoba.

Conclusions

The conclusions drawn from the study are:

1. The biomass regression function based on diameter provided prediction equations with low estimation errors; the regression function based on a combination of diameter and height gave slightly better estimates.

2. The range of application of prediction equations derived from a large sample taken from widely distributed sampling locations within an ecoregion is likely to be as good or better than the sample taken from limited locations.

3. Independent data are essential for validation of a model. Validation results showed very high fit, in addition to providing more reliable estimates on the performance of regression functions tested in the study.

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APPENDIX I

Biomass prediction equations for tree species in individual provinces of west-central Canada, based on 20 samples for each species per province

Species	Province	Biomass prediction equation	R^2	% SEE
Softwoods:				
Jack pine	Alberta	$W_1 = -25.75 + 6.498D - 0.1989D^2 + 0.01194D^3$	0.981	14.5
		$W_2 = 5.62 + 0.01749D^2H$	0.971	16.8
	Saskatchewan	$W_1 = 61.22 - 15.310D + 1.2275D^2 - 0.01198D^3$	0.978	15.5
		$W_2 = 6.25 + 0.01775D^2H$	0.985	12.3
	Manitoba	$W_1 = 14.24 - 5.986D + 0.7082D^2 - 0.00371D^3$	0.975	16.8
		$W_2 = 1.71 + 0.01941D^2H$	0.977	15.3
Black spruce	Alberta	$W_1 = 30.18 - 10.322D + 0.9862D^2 - 0.00888D^3$	0.995	7.7
		$W_2 = 4.54 + 0.01810D^2H$	0.997	5.8
	Saskatchewan	$W_1 = 20.84 - 5.755D + 0.6744D^2 - 0.00322D^3$	0.996	6.5
		$W_2 = 4.74 + 0.01897D^2H$	0.997	5.1
	Manitoba	$W_1 = -23.51 + 6.655D - 0.1590D^2 + 0.01201D^3$	0.969	18.3
		$W_2 = 2.33 + 0.01909D^2H$	0.958	19.9
White spruce	Alberta	$W_1 = 47.21 - 13.851D + 1.1396D^2 - 0.01035D^3$	0.992	10.5
		$W_2 = 7.61 + 0.01656D^2H$	0.987	13.1
	Saskatchewan	$W_1 = -1.07 - 0.633D + 0.3165D^2 + 0.00245D^3$	0.969	17.7
		$W_2 = 11.39 + 0.01524D^2H$	0.984	12.1
	Manitoba	$W_1 = 5.56 - 1.944D + 0.3273D^2 + 0.00366D^3$	0.991	10.6
		$W_2 = 11.76 + 0.01605D^2H$	0.986	12.2
Balsam fir	Alberta	$W_1 = -15.64 + 3.657D - 0.0632D^2 + 0.01011D^3$	0.995	8.0
		$W_2 = 2.07 + 0.01532D^2H$	0.995	7.4
	Saskatchewan	$W_1 = 18.23 - 7.804D + 0.8077D^2 - 0.00689D^3$	0.970	18.7
		$W_2 = 13.59 + 0.01474D^2H$	0.972	16.9
	Manitoba	$W_1 = 11.76 - 4.565D + 0.5177D^2 - 0.00118D^3$	0.983	14.1
		$W_2 = 4.42 + 0.01970D^2H$	0.947	23.3
Tamarack	Alberta	$W_1 = 20.22 - 6.754D + 0.7244D^2 - 0.00601D^3$	0.991	10.1
		$W_2 = 8.89 + 0.01784D^2H$	0.988	10.8
	Saskatchewan	$W_1 = 23.93 - 7.219D + 0.7110D^2 - 0.00556D^3$	0.962	19.6
		$W_2 = -0.93 + 0.01936D^2H$	0.977	14.3
	Manitoba	$W_1 = -18.18 + 3.723D + 0.0287D^2 + 0.00649D^3$	0.989	10.3
		$W_2 = 8.28 + 0.01798D^2H$	0.985	11.2
Hardwoods:				
Trembling aspen	Alberta	$W_1 = 24.26 - 6.433D + 0.5800D^2 + 0.00247D^3$	0.981	16.2
		$W_2 = -9.11 + 0.01909D^2H$	0.990	10.7
	Saskatchewan	$W_1 = 5.02 - 2.278D + 0.3691D^2 + 0.00411D^3$	0.997	6.4
		$W_2 = 0.55 + 0.02011D^2H$	0.997	5.3
	Manitoba	$W_1 = 11.32 - 5.253D + 0.7389D^2 - 0.00479D^3$	0.980	15.4
		$W_2 = 9.44 + 0.01919D^2H$	0.985	12.7
Balsam poplar	Alberta	$W_1 = 0.54 - 1.921D + 0.4346D^2 - 0.00200D^3$	0.975	17.5
		$W_2 = 10.38 + 0.01324D^2H$	0.975	16.3
	Saskatchewan	$W_1 = 31.85 - 10.205D + 0.9447D^2 - 0.01114D^3$	0.979	15.4
		$W_2 = 13.74 + 0.01362D^2H$	0.972	16.7
	Manitoba	$W_1 = -5.16 + 1.235D + 0.1149D^2 + 0.00513D^3$	0.979	15.2
		$W_2 = 6.27 + 0.01540D^2H$	0.968	17.8
White birch	Alberta	$W_1 = 24.48 - 7.202D + 0.7906D^2 - 0.00160D^3$	0.990	11.7
		$W_2 = 0.53 + 0.02602D^2H$	0.979	15.6
	Saskatchewan	$W_1 = 110.55 - 39.002D + 3.1177D^2 - 0.04645D^3$	0.934	28.0
		$W_2 = 18.50 + 0.02255D^2H$	0.883	35.2
	Manitoba	$W_1 = 13.04 - 5.423D + 0.6400D^2 + 0.00075D^3$	0.964	20.4
		$W_2 = -9.31 + 0.02677D^2H$	0.954	21.8

a/ Model I: $W_1 = a_0 + a_1 D^2H$
Model II: $a_0 + a_1 D + a_2 D^2 + a_3 D^3$
where W is the ovendry weight (kg) of living tree above ground (excluding dead branches), D is the diameter outside bark at breast height (cm), and H is total tree height (m).

APPENDIX II

Prairies regional equations for biomass prediction derived from 60 trees per species in the three provinces

Species	Biomass Prediction Equation[a]	R^2	% SEE
Softwoods:			
Jack pine	$W_1 = 4.09 + 0.01829D^2H$	0.975	15.3
	$W_2 = 13.87 - 4.998D + 0.5954D^2 - 0.00159D^3$	0.967	17.9
Black spruce	$W_1 = 4.06 + 0.01871D^2H$	0.982	12.9
	$W_2 = 6.70 - 3.040D + 0.5131D^2 - 0.00047D^3$	0.984	12.4
White spruce	$W_1 = 8.88 + 0.01609D^2H$	0.984	12.8
	$W_2 = 10.39 - 3.749D + 0.4906D^2 + 0.00018D^3$	0.983	13.5
Balsam fir	$W_1 = 13.57 + 0.01556D^2H$	0.952	21.5
	$W_2 = 8.15 - 3.034D + 0.4074D^2 + 0.00112D^3$	0.978	14.9
Tamarack	$W_1 = 5.89 + 0.01833D^2H$	0.982	12.2
	$W_2 = 16.08 - 5.135D + 0.5945D^2 - 0.00358D^3$	0.980	13.3
Hardwoods:			
Trembling aspen	$W_1 = 1.41 + 0.01933D^2H$	0.988	11.2
	$W_2 = 21.73 - 7.304D + 0.7545D^2 - 0.00307D^3$	0.977	15.8
Balsam poplar	$W_1 = 12.23 + 0.01380D^2H$	0.966	18.0
	$W_2 = 6.54 - 3.432D + 0.5021D^2 - 0.00295D^3$	0.974	16.3
White birch	$W_1 = 2.89 + 0.02520D^2H$	0.943	24.4
	$W_2 = 30.26 - 10.591D + 1.0458D^2 - 0.00686D^3$	0.956	21.8

a/ Model I: $W_1 = a_0 + a_1 D^2H$
Model II: $W_2 = a_0 + a_1 D + a_2 D^2 + a_3 D^3$
where W is ovendry weight (kg) of living tree above ground (excluding dead branches), D is the diameter outside bark at breast height (cm), and H is total tree height (m).

FOREST BIOMASS STUDIES

IN FRANCE

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Several research institutes or universities, as well as forest managers, are interested in biomass production and estimation. This paper discusses research under way in the field of biomass production, in traditional forestry (high forest, coppice with standards, simple coppice) as well as in "future" forestry, such as short rotation coppice or "modified conventional forestry".

Introduction

Although some forest biomass studies had been initiated in the late sixties (RIEDACKER, 1968) they never lead to real research programs in forest institutes before the creation of government agencies interested in the use of biomass for energy production. First the COMES (Commissariat à l'Energie Solaire), "solar energy agency", wich became later AFME (Agence Française pour la Maîtrise de l'energie), "french energy agency", produced financial incentives for research oriented towards biomass production. The European Economic Community later became interested in biomass production and launched several european research programs.

In France, the global afforested area represents approximately one-fourth of the country : 14 million hectares. One-third of the forest consists of conifers, and two-thirds of broadleaves, of which 2.5 million hectares are treated as simple coppice and 4.25 million hectares as coppice-with-standards.

The ownership of French forests is divided into 1.7 M ha state owned, 2.5 M ha managed by the state, and 10.8 privately owned, by one and a half million owners. Private property is very diverse, and private forests larger than 100 ha only amount to 2 M ha. (AUCLAIR, 1982).

Research is undertaken at different levels by basic and applied institutes : universities, CNRS (Centre National de la Recherche Scientifique) : the "scientific research institute", INRA (Institut National de la Recherche Agronomique) : "agricultural research institute", AFOCEL (Association Forêt-Cellulose) : "pulp and paper association", CEMAGREF (Centre d'Etude du Machinisme Agricole, du Génie Rural et des Eaux et Forêts) for machinery and applied research.

Two main research areas concern forest biomass : existing forest stands, and short rotation forestry (TEISSIER DU CROS, 1985).

1 - Forest biomass in existing stands

Forest stands under simple coppice or coppice-with-standards management have not been harvested regularly since the 1940's. These stands produce mostly poor quality timber, and have a low volume (or biomass) production. The first studies have concerned biomass inventories.

One government institution : IFN (Inventaire Forestier National) has the charge of the total French forest inventory, estimating for the total French forest area standing volume, current annual increment, number of trees, and area occupied by each forest species, for each forest region, and for different ownerships.

This comprehensive survey gives estimates of "large timber volume" (LTV), which only concerns stem volume down to a diameter of 7 cm. Several studies have been undertaken to convert LTV into total aboveground woody biomass in these poor quality stands as well as in Oak high forest. Simple weighted linear regressions were applied on a selection of sample trees in Central France, giving the following results (AUCLAIR and BIGE, 1984 ; AUCLAIR and CABANETTES, 1983 ; BISCH, 1985).

- for coppiced trees, from simple coppice or from coppice-with-standards :

$$B = 0.569\ LTV + 7.9$$

- for oak standards from coppice-with-standards :

$$B = 1.011\ LTV - 74.0$$

- for oak from traditional high forest :

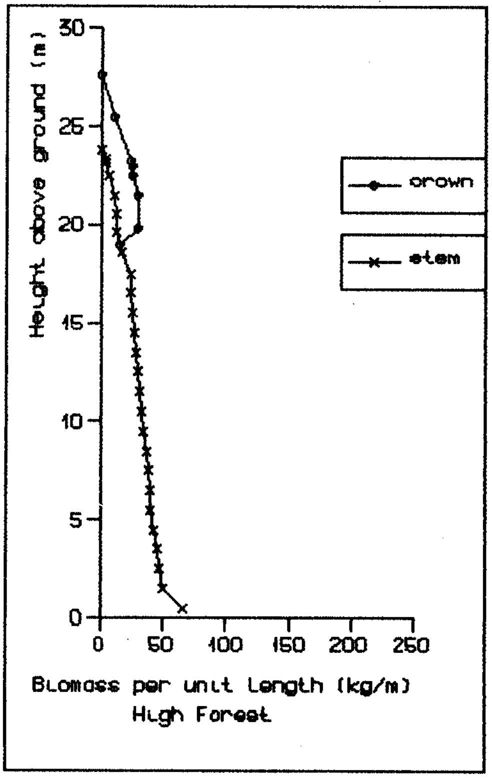
$$B = 0.729\ LTV - 3.3$$

where B = total above-ground woody biomass (kg)
LTV = "large timber volume" (dm^3)

The distribution of biomass inside each individual tree has been studied, to compare the effect of high-forest or coppice-with-standards treatment on the larger oak trees. The results in figure 1 show that in high-forest, trees are higher and have smaller crowns (BISCH and AUCLAIR, 1987).

Coppice, which produces mostly poor quality wood which may be used for industry or energy, has been quite extensively studied, and some biomass production curves are now being published for Sweet Chestnut or Black Locust as in figure 2 (PAGES, 1986).

The above equations have also been used to convert traditional high forest volume yield tables (PARDE, 1962) into biomass yield tables (BISCH, 1987).



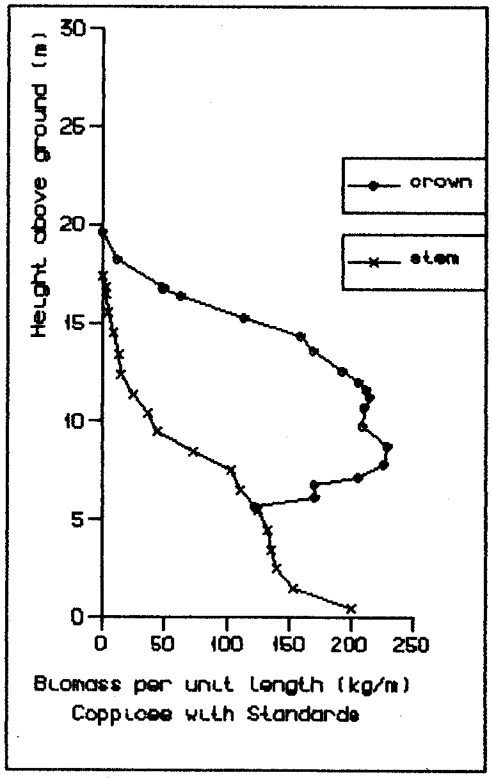


Figure 1 : Biomass profiles for Oak

	High Forest	Coppice-with-standards
age	122	121
DBH	34 cm	60 cm
Biomass	841 kg	2 873 kg

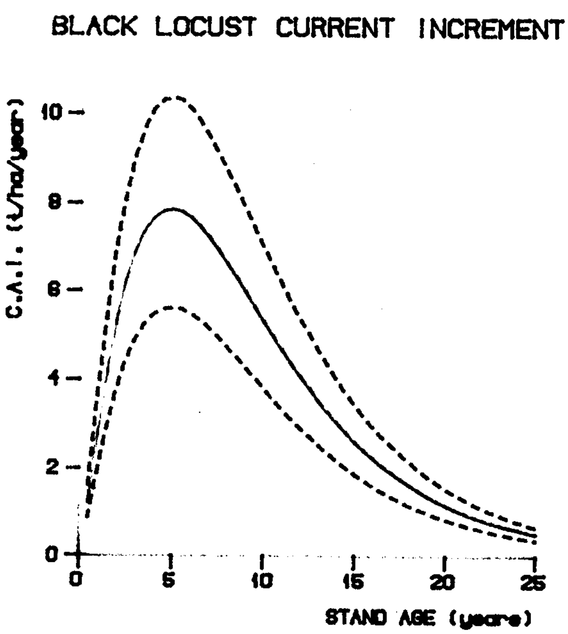


Figure 2 : Standing biomass production curves for traditional Robinia coppice in Central France.

- solid line : mean for the region,
- dashed lines : maximum and minimum values

2 - Short rotation forestry

There is a wide potential for new forest plantations on marginal forest or agricultural sites. One important program concerns genetic selection and improvement for short-term biomass production, with quite a large number of tree species : poplars, larch, Sitka spruce, red oak, yellow poplar, sugi, alder, black locust.

Silvicultural aspects concern establishment, cultivation, and harvesting of short rotation forestry, including both coppice or short rotation single-stem biomass production.

Competition aspects of short rotation coppice have involved the use of "Nelder fans" : figure 3 shows growth curves of one-year rotation black cottonwood coppice. It shows a decrease in production from one rotation to the next, more important for closer than for wider spacings. This decrease was not observed for two-year rotations (AUCLAIR, 1986 a).

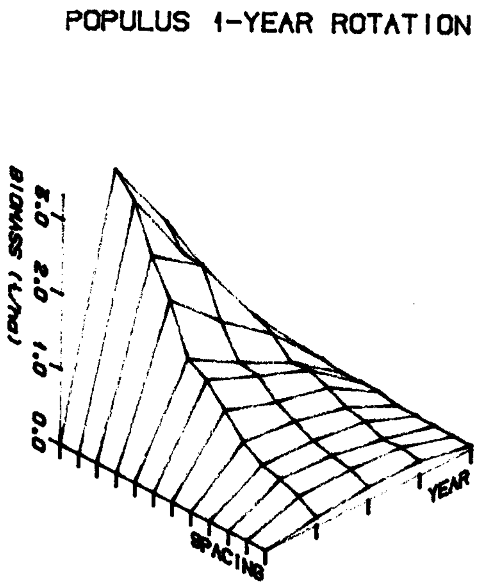


Figure 3 : Short rotation Populus trichocarpa annual production, from a Nelder design. Spacings vary from 0.15 m to 1.5 m.

Some economic studies have been undertaken to compare various degrees of intensification in biomass production, from a traditional "low-cost : low-return" extensive coppice forestry to short rotation intensive coppice production. Up to now most economic studies concerning biomass have focused on energy production, and it seems that the present current wood price cannot compete with oil if intensive cultivation is practised on forest land (AUCLAIR, 1985).

Attention is now turning to agricultural land for biomass production, with a new type of "modified conventional forestry" : some trials have been established with genetically selected improved trees for multiple use (biomass for industry or energy, and high quality lumber), with modern highly mechanized techniques.

Most research on short rotation forestry for biomass production, or for multiple use, is only quite recent, and most experimental plots have not yet given many results, in particular those concerning coppice. Some plots are still being established.

3 - The scientific background

Although most french studies concerning the physiology and growth of forest trees are oriented towards high quality lumber production, several laboratories have been interested in forest biomass production. Most of these studies concern coppice, either treated in short rotation with the aim of producing biomass, or traditional coppice which can have several different uses. This second type, treated in 20- to 30-year rotations can contribute precious information for biomass-oriented short rotation coppice.

A working party gathering research scientists and forest professionals has been meeting every year since 1982 to discuss the scientific basis of coppice production. The topics studied concern :

- bud formation
- early growth and shoot demography
- gas exchange
- carbohydrate reserves
- nutrient cycling
- nitrogen fixation
- root systems
- fine root production
- root-shoot interactions
- pests and diseases

A summary of the results is presented in papers by AUCLAIR (1986 a, 1986 b).

Conclusions

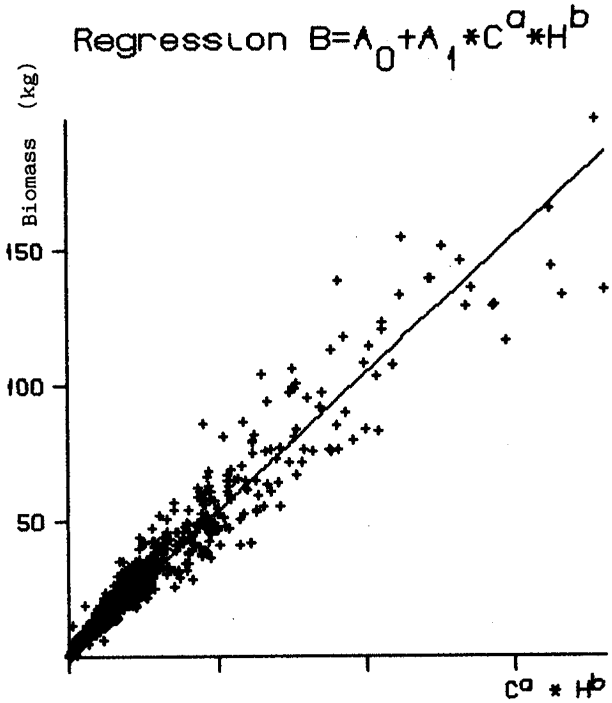
Since the first research studies impulsed by government incentives in the late seventies, a number of publications have concerned traditional forestry, mostly with the use of results of the French national forest survey. Some trials have been established in existing stands to test techniques aimed at increasing biomass production and the impact of these techniques on the nutrient balance.

Studies on short rotation forestry, concerning genetic selection and improvement, silvicultural techniques and environmental problems (including nutrient cycling, pests and diseases), have lead to the establishment of over 50 hectares of trials oriented towards basic research, as well as an additional 240 hectares oriented towards development.

All these biomass studies have lead to the construction of a data base for improving biomass regressions. Non-linear weighted regressions have been used, giving quite satisfactory results (figure 4) with an equation of the following form :

$$B = a_0 + a_1 D^{\alpha} H_d^{\beta}$$

where B = biomass
D = diameter at breast height
H_d = stand dominant height



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BIOMASS STUDIES IN EUROPE--AN OVERVIEW

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Research on estimating biomass components of forests have long tradition, in the last two decades considerable progress has been made to provide information on the biomass of entire stands. Research projects can be defined in three major classes (1) biological studies, (2) wood utilization studies (whole tree utilization, weight scaling) and (3) biomass energy. Information on many species for different sites and stand structures is available but few reliable data on the biomass potential of large regions or countries exist, showing the need for including biomass information in national inventories or conducting special biomass inventories.

Biomass studies have gained worldwide increasing attention and support. Within the last few years the literature on such studies has increased tremendously, each year many new projects are reported and new data published.

Several bibliographic studies were made for a review of the literature, such as Keays (1971) who reviewed estimation procedures and results for the main components of tree biomass separately. Hitchcock & McDonnell (1979) cite 280 references, and Pardé (1981) reviewed biomass research in a forestry Abstract review Article. Cannell reports a total of about 300 projects of which 131 are european studies, another review was done by Cupi (1982).

During recent years many symposia and workshops were conducted, the corresponding proceedings contain a good selection of study reports. The set of volumes put out by the IUFRO working group that was initiated by Harold Young should be mentioned especially, the IUFRO biomass studies 1973, Oslo biomass studies 1976. In addition the proceedings from the biomass conference in Orleans, France, in 1983 contain a set of papers dealing with biomass studies in Europe, a special conference of studies in Scandinavia was conducted in 1979 in Umea, Sweden, the papers are presented in Albrektson et al (1980). Egnéus and Ellegard present papers of a conference in 1984 conducted in Sweden that deal also with forest biomass.

In the following presentation an overview of european forest biomass studies will be given, however I cannot claim to provide a complete coverage, due to the large number of published studies and due to the diversity of sources (in several languages), often in form of local research reports. Some important and valuable publications will have been missed for which I apologize to the authors, they can be sure that such omissions are unintentional. No russian references are being considered as literature in russian is difficult to gain access to, however in Forestry Abstracts many reviews are listed.

This overview is main by concerned with mensurational aspects, and not with problems of wood utilization or biological considerations. Foresters are traditionally concerned with measuring trees and forests to determine their potential use. Over time one has to consider various utilization standards, and various wood uses. Estimating the availability of fuel wood was quite important for a long time in european forest history (in some parts this is gaining again in importance). Volume estimates therefore often included information on branch and twig volume or percent.

One of the first foresters to deal with what we consider now biomass (or a part there of) was the German forester Hartig, who in 1896 studied the relation of the weight of branches incl. needles to wood increment on the basis of 5 spruce trees in Würzburg, and stressed the importance of weight measurements.

Tischendorf from Austria described in 1922 how to measure the various tree biomass components solid wood, branch and twig volume, and bark. The yield tables of Grundner-Schwappach 1922 include information of branches and twigs in percent of stem volume for age classes, diameter, and height classes. Measurement of root and stock volume was made by Prebler and Kunze, and Vanselow (1941) gives a detailed treatment of measuring tree components by volume and weight, incl. specific gravity, weight increment and others.

For two sites the figures were calculated for model trees, the data for the Wiener Wald site are shown in table 1. Vanselow states that a ranking of volume yield or increment is not equal to a ranking of weight yield or increment, thus recognizing the importance of weight studies. He discusses the importance of measuring the entire organic substance (i.e. biomass) incl. wood, leaves, needles, seed, roots. A detailed discussion of weight measures and specific gravity determination is given by Trendelenburg 1939 and other books on forest utilization.

The most detailed studies on components of forest biomass were done by Burger in Switzerland between 1922 and 1953. These studies were for many years the main data base for a large number of other projects and were cited quite often. Burger studied both single trees and stands for many tree species, different ages and site classes. A summary of the data on leaf mass and leaf surface is given by Pelz (1969); Pardé (1980) lists data on the density of wood that was reported by Burger, many other authors referred to these studies.

TABLE 1 Fresh weight of leaves and surface areas of several species for dbh classes (Burger 1922).

	diameter class (cm)									
	10		20		30		40		50	
	kg	m^2	kg	m^2	kg	m^2	kg	m^2	kg	m^2
Spruce selection forest	5,7	29,6	21,8	113,4	48,0	249,6	85,5	444,6	132,4	688,5
Fir selection forest	6,9	42,1	31,2	190,3	65,9	402,0	111,8	682,0	163,0	994,0
Fir even age forest	6,6	40,0	23,9	133,8	52,6	294,6	88,0	492,8	129,0	722,4
Pine	4,4	24,2	11,6	63,8	21,1	116,1	34,5	189,8	51,7	284,4
Larch	2,4		5,4		10,4		17,5		28,0	
Beech	3,1	62,0	9,1	182,0	18,7	374,0	34,3	686,0	54,0	1080,o
Oak	2,7	35,1	7,8	101,4	17,7	230,1	33,0	429,0	52,0	676,0
Douglas Fir	5,2	33,0	6,2	39,0	20,0	126,0	50,2	321,0	-	-

TABLE 2 Weight and increment of trees from Wiener Wald (Vanselow, 1939)

	Beech	Oak	Spruce	Fir	Pine	Larch
Volume (m^3) age 110	0,3454	0,6529	1,6524	1,479	1,5643	1,5544
Spec. gravity kg/cm^3	570	570	390	370	420	490
Total weight of wood	197	372	644	547	657	386
Average increment kg	2,2	4,1	7,1	6,1	7,3	8,5

Table 2 gives a summary of leaf mass and surface for several tree species for dbh classes based on the studies of Burger.

In Denmark Boysen-Jensen (1932) and Møller (1945) reported on studies and results related to biomass.

Tree properties, wood density, specific gravity on one side and biological aspects on the other were studied in many projects in most european countries for many years, rather independent and without references to each other.

Major impetus for biomass research came from several sources:

- growing environmental awareness called for more and detailed information on the natural resources.
- utilization standards and new harvesting methods (weight scaling, complete tree harvesting), changed and required studies on the entire tree.
- energy shortage - the energy crisis in the early 70's lead to a large number of projects dealing with forest biomass as energy source.

The projects of the first type, shortly called biological projects, were conducted in most countries in Europe, the studies were rather varied in objective, methodology and reported results, so that they really are not comparable. With the initiation of the International Biological Program 1963, the number of research studies in this field increased even further, but much better coordinated, directly in form of projects in the IBP program and in form of other studies that were modeled after these projects. In the following some of the projects will be discussed.

In the IBP program a total of 31 research sites in Europe (table 3) were included, constituting the woodlands data set. The detailed analyses, study setup and a listing of the entire data set is given by Reichle (1981), Cannel (1982) published a set of data showing the results of biomass studies from a large number of international projects.

An analysis of these results shows the diversity of these data, they hardly can be used to draw any definite conclusions on the availability of biomass resources. It is remarkable that a large number of the studies dealt with young stands, sampling procedures and measurement techniques differed considerable.

Table 3. IBP study sites in Europe.

Country	Number of study sites
Belgium	1
CSR	1
Denmark	1
Finland	1
France	3
Hungary	1
Netherlands	1
Poland	3
Rumania	4
Spain	1
Sweden	6
United Kingdom	1
West-Germany	7

Individual tree biomass in most cases was determined by weighing the components, sampling procedures were used rather infrequently. Schöpfer (1961) for example used a multistage sampling procedure to estimate total crown and needle mass. The studies determined either fresh weight or oven dry weight. Total biomass for a stand was determined either by the mean tree method by diameter classes or by regression estimates.

The mean tree method as used by Wright and Will (1958), Ovington (1957), and others selects trees of average size (mostly the tree average basal area). A number of trees with diameters close to the diameter of the tree is then chosen, felled and the total biomass measured. The actual number of trees measured varies from 1 to about 10, for reliable estimate at least 5-10 should be chosen (Madgwick and Satoo 1982). This mean tree method is consistent with methods used in the estimation of stand volumes (however for volume (biomass) estimation the tree of average volume (biomass), approximated by the Weise tree - 40% of the distribution from the upper end-might be more appropriate).

The accuracy of this estimate is difficult to ascertain, as few complete biomass inventories of entire stands exist, but it must be noted that in many cases too few trees were measured to provide sufficient precision. This mean tree method gives only an estimate of the total biomass of the stand, and no distribution over size classes.

Ovington and Madgwick (1959), Vyskot (1983), Mounet (1978) and others determine diameter classes for the stand and determine the mean tree biomass for each diameter class. The total biomass then is calculated by multiplying mean tree values by the number of trees per hectare in each diameter class. Vyskot (1972) divided the stand into 3 classes and sampled 5 dominant, 5 codominant and 5 subdominant trees for biomass. Total stand biomass then was calculated by multiplying the respective biomass by the number of trees in that class.

Attiwill and Ovington (1968) compare alternative methods of deriving stand estimates by the mean tree method, by taking 4 observations in each of 5 diameter classes and by taking the average biomass from regression estimates, they find deviations about -3% for method 2, -8% for method 1 and -11% for method 3.

The use of regression models for estimating the total biomass per hectare is reported by many authors. Albrektson (1980), Decei (1981) and others use a model with diameter as independent variable, Anderson (1981), Ellenberg (1981) a.o. us D^2H, Mounet (1978) and Ranger (1978) use the circumference.

Models used for deriving these regression equations ranged from linear model of the type

$B=b_o+b_1D_2$
$B=b_o+b_1D^2H$ where B=biomass
D=DBH
H=height

to nonlinear models (Attiwill and Ovington (1968)

$DW=b_o.D^{b_1}$
where DW=dry weight

The model $y=b_o.X^{b_1}$
where y=biomass
X=diameter or circumference at breast height

has also been used extensively.

The majority of studies seem to develop nonlinear models, the allometric equations have been introduced into ecological research long time ago and are well established. The bias inherent in this estimation is not in all cases recognized and corrected. The linear models generally are not appropriate as one of the basic assumptions of the OLS estimate, the homogeneity of variance, is not fulfilled.

The use of weighted least squares analyses for biomass studies as reported in the literature is not widespread.

With respect to biomass functions and tables one notes a large number of equations, all of which cannot be listed here. With these tables such as developed by Hellrigl (1974) in Italy for silverfir or Ranger (1978) in France for corsican pine, Kestemont (1975) in Belgium for several stands, a large number of tables are published in Sweden as part of a biomass table project, one can predict the biomass production of stands, some even can be used to construct biomass yield tables. Other tables were reported by Vyskot (1981) and others.

The data base for these biomass yield tables in many cases is much smaller than the data base for standard yield tables, however they give some insight in the biomass production over time. Estimation of stock and root biomass is reported from various silvicultural or ecological studies on the root system of tree species (Köstler 1950) and from the special biomass studies (Vyskot 1972 and others). The measurement problems here are quite large, and reliable data difficult to obtain. As Pardé (1980) points out only the larger roots are of practical importance for possible utilization, making the estimation procedure somewhat more easy to implement. However if ecological objectives are most important then also the small roots have to be considered which are less than 2 mm (data of this kind are not as complete as it should be, but many studies were done as reported by Hermann in a review of the literature). The root biomass can be related to DBH, diameter at stumpheight, or the total height, in addition population and site variables will influence root biomass.

Several attempts have been made to derive biomass information from stand timber inventory estimates. Some of these conversions are based on detailed studies such as the equations developed by Auclair (1984) in France, who sampled 96 stands of coppice to derive an equation of the form

$$BST = b_o+b_1VBF$$

I.N.R.A. projects developed methods to determine the aboveground biomass in coppice stands allowing a reliable estimate. Ruprich (1981) discusses the possibilities of converting inventory data with equations taken from special studies and the literature, in part going back to the data reported by Burger (1922-53). For entire Tschechoslowakia the LESPROJECT estimated the total biomass by converting inventory data. Similar estimations are reported by Dauber and Kreutzer (1979) and Kramer and Krüger (1981) for Germany.

Some of the studies cited above were made to estimate the energy potential of forest, special studies on energy plantation are numerous, however they will not be reviewed here, as the mensurational aspects are not of significance there. There are many studies on forest biomass from the standpoint of forest utilization, the dry weight for the various components are listed, specific gravity and complete tree utilization discussed.

Gislerud (1974), Hakkila (1975), Eskilson (1972) and Palenius (1974) studied specific gravity of the various tree components separate for diameter classes.

Wernius (1975) listed tables giving the percentages of dry weight for the biomass components of spruce and pine, Hakkila (1977) developed regression equations for biomass for bole, branches and the complete tree. Schäfer (1977) studied biomass production in young pine stands in the southern Germany to predict potential utilization and May (1976) made a similar study in the Lüneburger Heide.

Most of these studies used similar measurement techniques and calculation procedures as mentioned above, therefore they will not be reviewed in detail here.

After the energy crisis 1973 an increasing amount of attention has been given to the use of forest biomass as source of energy, many research projects were initiated after that time. For example the european common market initiated biomass projects in 1975, in three phases. The first phase, that ran to 1985 intended to utilize side products from forestry and agriculture, without change of the present land use, in the second phase energy plantations were planned and in the third phase these plantations would be increased considerably if deemed necessary.

Within that program several projects were initiated, the majority with the objective of determining energy potential of trees and forests. Another project that can be listed here is the Swedish Energy Forest Project. With the increasing concern about nuclear energy it can be expected that research on biomass from agriculture and forestry will become even more important in the future.

The plans for utilization of the forest resource at high intensities resulted in concerns that the site might be degraded over time as much more of the production is taken out and less is recycled into the soil.

Krapfenbauer (1981) for example conducted in Austria an inventory of biomass and nutrient elements in 4 spruce stands at the ages of 10, 45, 52 and 63. For these stands he developed linear regression models for DBH, height, volume, and biomass for several tree components and the distribution of the nutrient elements.

The general agreement among many forest nutritionists seems to indicate that on extreme sites with complete utilization one has to monitor the site quality carefully and in some cases has to fertilize or restrict the utilization, but that, taken over an entire rotation the additional removal on many sites does not result in site degradation as long as not the entire annual biomass production (leaves etc.) is harvested.

Information on biomass for many trees and stands in Europe is available, the large number of studies made during the last few years is quite impressive the bibliography, which certainly is not exhaustive comprises more than 180 entries. Large scale inventories of forest biomass on a regional or national level have to be conducted to yield reliable estimates on the total forest resources.

The data on biomass production reported in the literature are not comparable, as they were derived by different procedures, many of the studies were very detailed and provided information on the reliability of the estimates, others were designed to yield approximate estimates only. For the major species one can find information on biomass production at various ages, and in some cases for different sites. This information can be quite valuable for estimating biomass for the given study site, however it does not suffice for the estimation for a larger area, for example during a forest inventory. Factors for converting traditional forest inventory estimates, mostly relating to wood production, to biomass estimates can be derived from these studies, as several reports show, the extrapolation to other data, however, can yield only rough estimates or educated guesses.

It would seem necessary to conduct such inventories, either in combination with national forest inventories (which are done in most european countries) or separately, comprehensive inventory models need to be developed to accurately predict biomass for entire countries of entire Europe as basis for an efficient use of the natural reosurces.

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SUBSAMPLING TREES FOR BIOMASS

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A sampling procedure for estimating total forest weight of coniferous trees is presented. The weight of the bole including bark is estimated by simple ratio estimates of volume/weight on the basis of five discs that are selected along the stem with a probability proportional to estimated volume. For the estimation of crown weight branches are selected with a probability proportional to branch dimension. Regression estimates for branch weight were derived using weighted least squares, the estimate of the total tree weight yielded for the 16 trees that were included in the study a small negative bias.

The estimation of the biomass production of forest ecosystems is becoming increasingly important. Forest inventory estimates are often required to include information on biomass. For some regions biomass information is available in biomass regression equations or tables, however, these estimates may or may not be applicable for a given case.

The fresh weight of an individual tree may be determined by weighing all components or by sampling. For large trees weighing of the entire tree may become quite time consuming and laborious. To minimize field work sampling procedures may be applied.

In this paper a sampling method is presented that allows the estimation of the fresh weight of coniferous trees. This study is part of several pilot studies to identify opitmal sampling procedures for estimating above ground biomass in the school forest of the University of Freiburg/Germany.

The study was conducted in a 20 year old spruce stand in the school forest. The stand was homogeneous, the crowns relatively uniform developed. Sixteen sample trees were selected in the diameter range from 11 to 16 cm. These sample trees were felled by the same procedures, care was taken to minimize crown damage. For all trees the above ground biomass (stem, branches, twigs and needles) was determined in two steps. First, the green (fresh) weight of the entire tree was determined by measuring volume of the stem and total weight of the all components, and secondly, a sample of the main components was taken to calculate conversion factors from volume to weight and fresh to dry weight, respectively (for this, the samples were dried at 103^{o} for 72 hours).

This paper will only refer to the estimational fresh weight, subsampling for oven dry weight is commonly done in most biomass studies. The main purpose of the study was not to determine overall biomass of the stand or to develop tables, but to provide information as pilot study with regard to some sampling alternatives in this area. Other studies, on a smaller scale, compared additional methods (Weber 1983). The estimation of total above ground biomass is separated into two parts, estimation of stem biomass and of crown biomass.

Estimating Stem Biomass

The procedure for estimating the stem biomass was the same for both methods. The process was defined in two stages. In the first stage the volume of the stem to a minimum diameter of 3 cm was calculated by sections. This volume measurement had to be converted to weight by determining the relative density or by taking a sample for which the conversion factor could be directly measured as ratio volume to fresh weight. The second alternative was chosen, at five locations along the stem wood discs were taken, the location was selected by a PPS procedure. Random numbers were drawn, and compared with the cumulative volume at this point, the probability of any one location being selected was proportional to the volume, the location along the stem for taking samples was calculated in the field with a HP 33 hand held calculator. At these 5 points, discs were taken for which the conversion factors were determined.

The results (Table 1) show very little deviation from the true weight, the results vary between 90% and 110% of true weight.

Table 1.--Accuracy of bole weight estimation

Tree No.	Bole Weight (kg) True	Estimated
1	127.9	113.8
2	73.1	65.6
3	63.5	59.7
4	114.3	113.4
5	72.3	67.8
6	128.9	125.4
7	154.2	159.5
8	67.2	66.7
9	120.4	129.0
10	63.9	64.7
11	51.5	49.0
12	85.2	82.2
13	84.5	78.4
14	132.8	126.7
15	76.4	78.2
16	136.2	125.8
Total	1552.3	1505.9

Sampling Procedure for Crown Weight

Crown weight was determined by two methods, a cross section method and by a PPS procedure. The cross section method, also used for estimating logging residue, determined the volume of branch and twig piles, by using a ratio estimate, the total weight can be determined. In this study the results, however, were severly biased. Therefore, only the second method was developed further.

The biomass of a crown of a coniferous species can be determined by sampling branches and estimating the weight by regression of branch diameter and length to weight. Several studies have found that this relationship is sufficiently close to be used for estimation. For large crowns, the number of branches can be determined by a sampling procedure, several methods have been described in literature (Schopfer 1981, Valentine et al. 1984).

In the present study the crowns were relatively small, and branches easily could be counted, a sampling procedure to determine the total number would have been more time consuming than complete enumeration. Sample branches had to be selected for deriving the regression estimates. From a sufficiently large sample, regression estimates are derived for single branches with branch weight as dependent and branch basis diameter and branch length as independent variables.

The branches to be weighed were selected by PPS sampling, the probability of selection was determined by the dimension of the branch. Previous observation suggested that branch dimension (diameter and length) for this population was closely related to stem diameter (i.e. the location of the branch in the crown). This assumption may not be true for other population.

The probability of selection, therefore, was determined proportional to the stem diameter, the sampling process was conducted in two stages. In the first stage the location along the stem was determined randomly with a probability proportional to stem diameter, the next closest node to this point was selected, and from this node a branch was randomly chosen for measurement. The procedure can be described as two stage sampling with PPS selection on the first stage and an unequal number of secondary units (branches) per primary (node).

The regression model selected was of the form

$$W = b_o + b_1 D^2 L$$

where
W = branch weight
D = branch base diameter
L = branch length

A plot of the data showed that one assumption of ordinary least squares, the homogeneity of variances was not fulfilled. Therefore, a weighted least squares method was used.

The regression coefficients for estimating branch weight are listed in Table 2.

Table 2.--Regression coefficients for estimating branch weight ($W=b_o+b_1D^2L$)

Tree	b_o	b_1
1	-.00593	.12396
2	.0555	.11149
3	-.01959	.12967
4	-.00962	.12637
5	.03441	.09492
6	-.02668	.10536
7	-.09962	.13863
8	.06554	.05411
9	.07806	.09999
10	.01860	.12178
11	.03586	.08597
12	.02767	.11980
13	.08619	.06848
14	.04392	.10792
15	.09882	.09027
16	.10094	.10064

The branch base diameters were determined only for a small sample, therefore, these distributions were smoothed before they were converted to a entire tree basis.

The total fresh weight of the crowns were estimated by applying these single tree equations to the tree data. The results (Table 3) show that there is a negative bias of about 11% for the 16 trees, probably in part due to the fact that small branches not in a hode have not been counted.

Additional studies are being made to show the source of this bias and to find a sampling procedure more accurate. The dry weight subsequently was estimated by taking a subsample of 5 branches from each tree that were dried at 103^o C for 72 hours, simple ratio estimates were used to convert to ATRO weight.

Combining the estimation of bole and crown weight (Table 4), the total tree weight (above ground) could be estimated with a negative bias of about 5%.

Further studies will be conducted to develop more accurate and efficient methods to estimate crown weight as sampling crown weight can result in significant reductions of biomass inventory cost.

Table 3.--Accuracy of estimating crown weight

Tree	Crown Weight (kg) True	Estimated
1	34.7	33.0
2	20.7	16.0
3	14.3	13.5
4	36.9	34.7
5	20.8	19.0
6	36.7	24.1
7	61.8	56.7
8	16.8	11.2
9	41.7	36.4
10	25.8	26.8
11	13.8	8.9
12	25.1	27.5
13	21.1	18.5
14	40.8	34.6
15	16.6	17.1
16	36.1	38.5
Total	463.7	.5

Table 4.--Accuracy of estimating total weight

Tree	Total Weight (kg) True	Estimated
1	162.6	146.8
2	93.8	81.6
3	77.8	73.2
4	151.2	148.1
5	93.1	86.8
6	165.6	149.5
7	216.0	216.2
8	84.0	77.9
9	162.1	165.4
10	89.7	91.5
11	65.3	57.9
12	110.3	109.7
13	105.6	96.9
14	173.6	161.3
15	93.0	95.3
16	172.3	164.4
Total	2016.0	1922.5

Conclusions

Total above ground biomass may be estimated by sampling within trees. The sampling procedure suggested for estimating stem weight is a selection proportional to volume (PPS), the stem parts with higher volumes are sampled more heavily. The results of this estimation procedure were satisfactory for the 16 trees studied, suggesting that direct total weight measurements of the stem could be substituted by sampling. No separation of wood and bark was made in this study.

For estimating total crown biomass branches were sampled, with a selection probability approximately proportional to the size of the branch (for the given population stem diameter instead of branch diameter or length could be used for determing selection probabilities). The total number of branches were counted, total crown biomass was calculated based on this weighed sample, the accuracy was quite satisfactory, suggesting that total tree biomass can be accurately predicted by sampling instead of weighing all the components.

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SIMPLE BIOMASS REGRESSION EQUATIONS FOR

SUBTROPICAL DRY FOREST SPECIES

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Simple linear regression equations were developed for the sixteen major forest species of the dry forests of the Dominican Republic. Diameter at 0.5 meters above ground is the easiest to use independent variable and total green biomass and usable green biomass are the dependent variables. Usable biomass is that portion of the tree above the stump and greater than 2.5 centimeters, which are the common usage limits for firewood and charcoal production. Correlation coefficients squared of about 0.95 were achieved for most species.

Subtropical Dry Forests

The subtropical dry forests of the Dominican Republic (DR) have long served as the most important fuelwood source for the rural poor of the nation and are now being considered by the Dominican government as a supplemental energy source for the country. Comprising approximately 5,905 square kilometers or 12 percent of the nations land area (Jennings and Ferrerias 1979), the subtropical dry forests are a major resource to the Dominican Republic. To establish sound management practices and policies for that nations dry forests, it is necessary to adapt a forest inventory methodology that will assess the total above ground forest biomass and the biomass usable for fuelwood.

The vast majority of the biomass regression equations reported to date are for predicting green and dry weights of tree components (leaves, branches, stems and/or roots) for single stem broadleaf or conifer species in the temperate regions. Very few biomass studies have been conducted in the subtropical dry forests and no regression equations have been developed that predict the biomass weight of the species found within these dry forest ecosystems where the scarcity of fuelwood is most acute and the utilization of the tree components above ground is most common.

Sample Data

The field data for the biomass equations were collected from June - September, 1984. Sample trees were selected randomly throughout the 850 hectare experimental dry forest in Mao, DR. The twenty species found in the northwestern subtropical dry forest of the Dominican Republic that are considered important for firewood or charcoal making and/or are abundant in the forest were sampled. The common, scientific and family names of the twenty species are found in Table 1.

Table 1

Common, scientific and family names of species included in the biomass study of the dry forest of Mao, Dominican Republic

Common Name	Scientific Name	Family Name
Almácigo	Bursera simaruba	Burseraceae
Aroma	Acacia macracantha	Mimosaceae
Baitoa	Phyllostylon brasiliensis	Ulmaceae
Bayahonda	Acacia tortuosa	Mimosaceae
Brucón	Cassia emarginata	Caesalpiniaceae
Cafetán	Palicourea alpina	Rubiaceae
Cambrón	Prosopis juliflora	Mimosaceae
Candelón	Acacia scleroxyla	Mimosaceae
Ciguamo	Krugiodendron ferreum	Rhamnaceae
Cinazo	Pithecellobium circinale	Mimosaceae
Frijol	Capparis spp.	Capparidaceae
Guaconejo	Amirys spp.	Rutaceae
Guatapanal	Caesalpinia coriaria	Caesalpiniaceae
Guayacán	Guaiacum officinale	Zygophyllaceae
Mostazo	Capparis flexuosa	Capparidaceae
Quina	Exostema caribaeum	Rubiaceae
Sangretoro	Maytenus buxifolia	Celastraceae
Tabacuelo	Pictetia spinifolia	Fabaceae
Trejo	Rheynosia uncinata	Fabaceae
Uvero	Coccoloba leoganensis	Polygonaceae

All sample trees had the following measurements taken:

1. Diameter at 0.5 meters above ground level recorded to the nearest 0.1 centimeter (DKH). This diameter is referred to as "diameter at knee height."

2. Diameter at 1.3 meters from the root collar recorded to the nearest 0.1 centimeter (DBH).

3. Crown diameter recorded to the nearest 0.1 meter (CD). Before felling the tree, this variable was measured with a metric tape. The average of two measurements, one in the north-south and the other in the east-west direction, was recorded on the tally sheet. In all directions the outer edge of the crown was considered to be the last green leaf.

4. Total height recorded to the nearest 0.1 meter (TH). After felling the tree with an axe, the total height was measured. To account for variable stump heights, the total height measurement was made from the point on the stem previ-

ously marked at 0.5 meters to the last green leaf on the crown and then adding 0.5 meters.

5. Green weight of the total live biomass above ground recorded to the nearest pound (GWT).

6. Green weight of the usable biomass recorded to the nearest pound (GWU). This is all the aerial parts of the tree having a diameter greater than or equal to 2.5 centimeters. This minimum diameter is generally considered by the Dominican forestry personnel to be the smallest diameter used by the local people for firewood or for making charcoal.

A circular spring scale was used to measure the green weight of the trees cut in the field. The scale was hung from a portable metal tripod. A collapsible 1.5 meter and 1.5 meter square platform was then hung with nylon ropes from a hook on the bottom of the scale on which the biomass was supported.

Distinctions were made between:

- all living aerial portions of the tree (GWT) and

- all living woody parts of the tree with a diameter greater than 2.5 centimeters (GWU).

Results And Discussion

For each specie, the average dimensions measured for the trees in the field are shown in Table 2.

The first two columns of Table 2 show the number of stems that were measured at 0.5 and 1.3 meters above ground level, respectively. The comparison of these two columns gives an indication of those species whose stems may be more likely to fork between 0.5 and 1.3 meters.

For the twenty species combined, there are approximately 1300 stems per hectare having a DBH greater than or equal to 4.0 centimeters. Figure 1 shows that nearly half of these stems have a DKH that falls in the 4-6 centimeter range. The frequency of small stemmed trees illustrates the typical configuration of the dry land forests of this region with many small stemmed trees per hectare. The mean DKH of all stems measured in the sample data was 7.8 centimeters. The largest DKH measured was 34.0 centimeters for a single stemmed *Bursera simaruba*.

The mean height of all the stems measured in the sample data was 6.0 meters. Figure 2 illustrates that more than sixty percent of the stems measured had total heights between 5 and 7 meters indicating the relatively low canopy of the dry land forests. The tallest tree measured was the same *Bursera simaruba* as mentioned above with a total height of 10.5 meters.

Table 2

Summary statistics for 20 species measured in the dry forest Mao, Dominican Republic

Specie	Number of stems measured at 0.5 m.	Number of stems measured at 1.3 m.	DKH range cm.	$\overline{DKH}$ cm.	DBH range cm.	$\overline{DBH}$ cm.	Hgt range m.	$\overline{Hgt}$ m.	Percentage of Usable Biomass (%)
Bursera simaruba	20	20	5.5-34.0	15.5	4.5-32.0	14.6	3.8-10.5	7.0	87
Acacia macracantha	3	4	5.4-14.7	9.0	4.9-10.9	7.2	5.5-7.2	6.6	75
Phyllostylon brasiliensis	104	115	4.3-18.5	7.1	3.4-17.4	5.9	4.1-9.6	6.1	64
Acacia tortuosa	1	1	6.8	6.8	5.5	5.5	6.5	6.5	78
Cassia emarginata	11	11	4.1-11.6	6.3	4.1-10.5	5.9	5.5-6.6	6.0	60
Palicurea alpina	15	18	4.8-12.6	6.2	4.0-10.3	5.1	4.4-6.6	5.3	57
Prosopis juliflora	12	12	4.5-15.0	6.8	4.2-10.9	5.9	4.2-8.0	6.1	75
Acacia scleroxyla	25	33	4.7-28.8	9.5	4.0-20.8	7.7	4.7-9.8	6.4	71
Krugiodendron ferreum	2	2	5.0-5.7	5.4	4.6-4.7	4.7	4.7-4.8	4.8	59
Pithecellobium circinale	10	10	4.1-8.1	5.6	4.1-6.8	5.2	5.7-6.5	6.1	63
Capparis spp.	2	4	12.0-13.0	12.5	7.6-10.5	9.0	4.9-5.6	5.3	73
Amirys spp.	7	9	4.6-9.9	6.8	4.1-8.4	5.8	4.3-6.4	5.0	55
Caesalpinia coriaria	3	4	9.2-12.5	10.8	8.3-10.3	9.0	4.7-6.4	5.5	55
Guaiacum officinale	13	15	4.8-8.3	6.3	3.5-7.2	4.9	3.2-5.5	3.9	69
Capparis flexuosa	5	6	4.3-6.9	5.3	3.4-5.4	4.5	3.8-6.1	5.0	48
Exostema caribaeum	18	20	4.7-11.2	6.7	3.0-8.1	5.2	5.6-8.0	6.7	74
Maytenus buxifolia	2	3	7.0	7.0	4.2-5.5	4.7	3.4-4.6	4.0	57
Pictetia spinifolia	3	3	5.5-7.0	6.0	4.3-5.7	5.0	3.6-5.5	4.6	79
Rheynosia uncinata	1	1	4.6	4.6	4.2	4.2	3.7	3.7	62
Coccoloba leoganensis	1	1	5.7	5.7	5.5	5.5	5.3	5.3	45
TOTAL	258	292	4.1-34.0	7.8	3.0-32.0	6.6	3.2-10.5	6.0	71

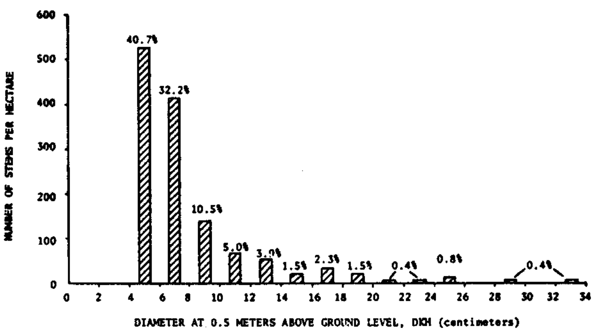

Figure 1. Diameter distribution for stems with a DBH greater than or equal to 4.0 centimeters in ten 200 m^2 sample plots of the Mao subtropical dry forest.

The percentage of the total green weight biomass that is usable for firewood or making charcoal is also shown in Table 2. The ratio of the usable to total green weight biomass shown in Table 2, estimates what percentage of the total above ground portion of the stem for a particular species is considered usable for firewood or making charcoal. High percent values such as those of Bursera simaruba, Acacia macracantha and Prosopis juliflora indicate that if used for fuelwood, the major part of the above ground portion of the stem would normally be utilized. Low percent values, on the other hand like those of Coccoloba leoganensis, Capparis flexuosa and Caesalpinia coriaria demonstrate that a large part of each of these species total above ground biomass are of the crown portions having a diameter less than 2.5 centimeters. The above ground portions having a diameter less than 2.5 centimeters are considered "unusable" biomass for firewood or charcoal making.

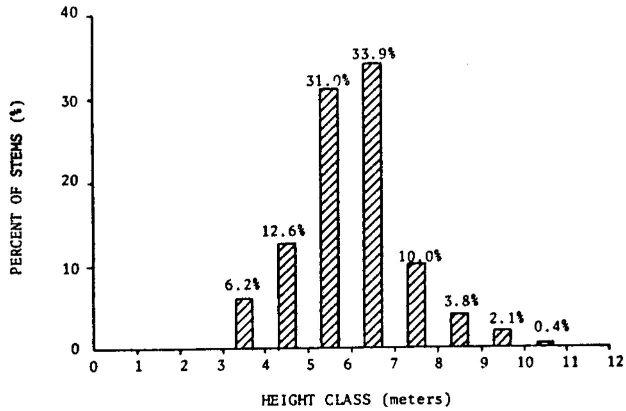

Figure 2. Height distribution for stems with a DBH greater than or equal to 4.0 centimeters in the ten 200 m^2 sample plots of the Mao subtropical dry forest.

Biomass Regression Equations

Tables 3 and 4 present the regression coefficients and sample statistics of the prediction equations to estimate the green weight of the usable biomass or the portions having a diameter greater than or equal to 2.5 centimeters for sixteen individual species and three combined species. During the development of these equations a double logarithmic transformation was used to ensure that the variances were homogeneous.

Table 3 presents the simple linear regression equations, with the independent variables that yield the highest r^2. Seven of the ten independent variables considered, give the highest r^2 value in all seventeen biomass equations. Each equation in Table 3 is of the form:

$$\ln\ (\text{weight}) = b_0 + b_1 * \ln\ (X_i)$$

where:

weight=green weight in pounds of the usable biomass.

X_i:X_1=basal area of stem at 0.5 meters above ground level, (DKHBA).

X_2=basal area of stem at 0.5 meters above ground level times total stem height, (DKHBA * TH).

Table 3

Simple linear regression coefficients and statistics for predicting green weight of the usable biomass of subtropical dry forest species in Mao, Dominican Republic with the regression model:

$$\ln\ (\text{usable weight}) = b_0 + b_1 + \ln\ (X_i)^{1/}$$

Specie[2]	Coefficients		X_i	Statistics			
	b_0	b_1		n	$S_{y.x}$[3]	r^2	DKH Range (cm)
Bursera simaruba Almacigo	7.191616	1.110368	X_2	36	0.146939	.9898	4.0-34.0
Acacia macracantha Aroma	7.633640	1.043212	X_3	23	0.183606	.9831	4.0-30.0
Phyllostylon brasiliensis Baitoa	7.096829	1.038230	X_2	56	0.144541	.9849	4.0-29.0
Cassia emarginata Brucon	10.008809	1.208762	X_1	26	0.178667	.9574	4.0-16.0
Policurea alpina Cafetan	9.592580	1.125651	X_1	18	0.277910	.8287	4.0-12.0
Prosopis juliflora Cambron	7.518781	0.999669	X_4	22	0.168407	.9827	4.0-30.0
Acacia scleroxyla Candelon	7.762502	1.112649	X_4	46	0.173730	.9854	4.0-29.0
Pithecellobium circinale Cinazo	8.804170	1.315341	X_4	23	0.211858	.8732	4.0-8.0
Capparis spp. Frijol	7.334954	1.053208	X_2	21	0.116820	.9880	4.0-19.0
Amirys spp. Guaconejo	7.661575	1.111198	X_2	21	0.111727	.9759	4.0-11.0
Caesalpinia coriaria Guatapanal	7.882536	1.079668	X_5	24	0.184299	.9822	4.0-24.0
Guaiacum officinale Guayacan	11.386864	1.464382	X_1	24	0.201363	.9156	4.0-10.0
Exostema caribaeum Quina	4.797154	0.820955	X_6	29	0.166601	.9528	4.0-14.0
Maytenus buxifolia Sangretoro	7.850758	1.120838	X_2	22	0.180072	.9516	4.0-14.0
Pictetia spinifolia Tabacuelo	7.390734	1.088975	X_2	13	0.177935	.8886	4.0-7.0
Coccoloba leoganensis Uvero	5.701871	0.974551	X_6	26	0.189499	.9657	4.0-18.0
Others	6.480793	1.157791	X_7	11	0.285666	.8381	4.0-8.8

[1] X_i = independent variable where:

X_1 = DKHBA X_3 = DKHBA * CD X_5 = DBHBA * CD X_7 = DBHBA * TH^2
X_2 = DKHBA * TH X_4 = DBHBA * TH X_6 = DKHBA * TH^2

[2] Common name of species as referred to in northwestern Dominican Republic
[3] Standard error of the estimate in natural log (ln) form.

X_3=basal area of stem at 0.5 meters above ground level times crown diameter, (DKHBA * CD).

X_4=basal area of stem at 1.3 meters above ground level times total stem height, (DBHBA * TH).

X_5=basal area of stem at 1.3 meters above ground level times crown diameter, (DBHBA * CD).

X_6=basal area of stem at 0.5 meters above ground level times total stem height squared, (DKHBA * TH^2).

X_7=basal area of stem at 1.3 meters above ground level times total stem height squared, (DBHBA * TH^2).

The umbrella-like crown canopy and multi-stemmed nature of many species in the natural dry forests make it difficult, time consuming and expensive to accurately measure the total height or crown diameter of a standing tree. Therefore, the regression equations shown in Table 4 for each specie, predict the green weight of the usable biomass with the independent variable being the basal area of the stem at 0.5 meters

Table 4

Simple linear regression coefficients and statistics for predicting green weight of the usable biomass of subtropical dry forest species in Mao, Dominican Republic with the regression model:

$$\ln(\text{usable weight}) = b_0 + b_1 + \ln(\text{DKHBA})$$ [1]

Specie[2]	Coefficients b_0	Coefficients b_1	Statistics n	Statistics $S_{y.x}$[3]	Statistics r^2	DKH Range (cm)
Bursera simaruba Almácigo	10.304117	1.354212	36	0.201718	.9807	4.0-34.0
Acacia macracantha Aroma	10.926375	1.312754	23	0.286349	.9590	4.0-30.0
Phyllostylon brasiliensis Baitoa	10.119439	1.243693	56	0.175208	.9778	4.0-29.0
Cassia emarginata Brucón	10.008809	1.208762	26	0.178667	.9574	4.0-16.0
Palicurea alpina Cafetán	9.592580	1.125651	18	0.277910	.8287	4.0-12.0
Prosopis juliflora Cambrón	9.803672	1.137246	22	0.288090	.9493	4.0-30.0
Acacia scleroxyla Candelón	11.106018	1.409781	46	0.270065	.9646	4.0-29.0
Pithecellobium circinale Cinazo	11.074430	1.320648	23	0.270181	.7938	4.0-8.0
Capparis spp. Frijol	10.047913	1.272722	21	0.149780	.9803	4.0-19.0
Amirys spp. Guaconejo	10.624340	1.323345	21	0.127177	.9688	4.0-11.0
Caesalpinia coriaria Guatapanal	11.733678	1.575985	24	0.276606	.9600	4.0-24.0
Guaiacum officinale Guayacán	11.386864	1.464382	24	0.201363	.9156	4.0-10.0
Exostema caribaeum Quina	9.717862	1.171786	29	0.285535	.8613	4.0-14.0
Maytenus buxifolia Sangretoro	10.699403	1.357645	22	0.237306	.9160	4.0-14.0
Pictetia spinifolia Tabacuelo	11.290882	1.495389	13	0.212988	.8403	4.0-7.0
Coccoloba leoganensis Uvero	10.226620	1.189277	26	0.292904	.9181	4.0-18.0
Others	11.351772	1.393268	11	0.433486	.6271	4.0-8.8

[1] DKHBA is the basal area at 0.5 meters above ground level expressed in square meters (m^2).
[2] Common name of species as referred to in northwestern Dominican Republic
[3] Standard error of estimate in natural log (ln) form.

above ground level, DKHBA. The basal area at knee height was chosen as the independent variable because it showed the highest correlation to stem biomass for most species. Also DKHBA is the fastest and easiest variable to measure of all the variables considered. The equations in Table 3 have smaller standard error of the estimates and higher r^2 as compared to those of Table 4 which indicate that Table 3 regression equations will give a more precise estimate of the usable and total biomass for stems within the specified diameter ranges of each species. However, in using equations of Table 3 another variable (height, crown diameter or diameter at breast height) must be measured in the field for each stem. This increases the amount of necessary field work and the overall cost of the sampling procedures. Also, in comparing Table 3 with Table 4 in most cases, the increase in the r^2 from using a variety of independent variables as required by Table 3 results in little improvement of the r^2 over using DKHBA as a uniform independent variable. For inventorying stands with mixed species, probably the set of equations having the same independent variable, i.e., DKHBA, would be best. In cases where just one or two species are of interest, however, it might be more feasible to use the equations yielding the most precise estimates.

Summary

Regression equations with simple to measure independent variables were developed for the 19 dry land forest species that will serve as the basic parameters for the inventory process.

These regression equations utilize a single parameter of measurement; the easiest of these to field measure is diameter at 0.5 meters (DKHBA) as the prediction variable of biomass for each species. DKHBA is a new concept of measurement that allows fewer measurements per tree than the standard diameter at 1.3 meters used for single-stemmed trees of the temperate zone. DKHBA is well above root collar swell for these small diameter trees and below most of the thorny branches that make measurement difficult. Almost all the squared correlation coefficients (r^2) were .90 or more.

Using the biomass regression equations shown in Tables 3 and 4 on inventory data will provide accurate biomass estimates of the material commonly used for firewood and making charcoal in the native dry forests of the Dominican Republic.

Inventories of the dry land forests can now be conducted in an efficient, accurate manner to determine biomass for each area. These areas can then be regulated to provide the continuing, renewable fuelwood energy needs of the Dominican Republic.

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