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Equations for estimating above-ground nutrient content of six eastern Canadian hardwoods

L. Chatarpaul, D.M. Burgess, and I.R. Methven

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EQUATIONS FOR ESTIMATING ABOVE-GROUND NUTRIENT CONTENT OF SIX EASTERN CANADIAN HARDWOODS

Information Report PI-X-55

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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 dependence on petroleum and other non-renewable energy sources.

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or a CFS research laboratory.

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ABSTRACT

Nutrient concentrations and biomass of various components of six eastern Canadian hardwood species, representing a range of diameter and height classes, were determined and used to estimate nutrient masses for each species and for components. One hundred and fifty (6 species x 5 components x 5 nutrients) linear regression equations were developed using nutrient mass, diameter, and height data.

Nutrient concentrations varied widely among components, with twigs/leaves, for example, containing 14 times as much nitrogen (1.246% to 0.087%) and 17 times as much phosphorous (0.137% to 0.008%) as the stem wood. Generally, twigs/leaves accounted for the highest percentage of nitrogen and phosphorous, stem wood had had the most potassium and magnesium, and stem bark contributed the greatest amount of calcium.

The single equations, with few exceptions, had high r^2 and low SEE%, showing good fit of data to the simple linear model. The equations for all components (except twigs/leaves) of trembling aspen, sugar maple, red maple, and ironwood were not significantly different ($P < .05$) and could therefore be combined into a single equation. However, those of red oak and white birch were significantly different. The application of the four-species combined equations to stand data showed nutrient removals by full-tree harvesting could increase by 56% to 111% with the percentage increase in the order P = N > Mg > K = Ca.

RÉSUMÉ

Les concentrations et biomasses des substances nutritives dans diverses composantes des arbres pour six espèces feuillues de l'est du Canada ont été déterminées et ont servi à estimer les masses des substances nutritives par espèce et par composante. Les arbres d'étude représentaient une gamme de classes de diamètre et de hauteur. Cent cinquante équations de régression linéaire (6 espèces x 5 composantes x 5 substances nutritives) ont été établies à partir des données sur la masse des substances nutritives, le diamètre et la hauteur.

On a constaté que les concentrations des substances nutritives variaient considérablement d'une composante à l'autre. Par exemple, les rameaux et feuilles contenaient 14 fois plus d'azote (1,246 à 0,087 %) et 17 fois plus de phosphore (0,137 à 0,008 %) que le bois de la tige. En général, les rameaux et feuilles avaient le plus fort pourcentage d'azote et de phosphore, le bois de la tige renfermait le plus de potassium et de magnésium, et l'écorce de la tige avait la plus forte teneur en calcium.

Les équations simples, sauf quelques exceptions, avaient une valeur élevée pour r^2 et faible pour l'erreur-type d'estimation (SEE %), indiquant un bon ajustement des données au modèle linéaire simple. Les équations pour toutes les composantes (sauf les rameaux et feuilles) du peuplier faux-tremble, de l'érable à sucre, de l'érable rouge et de l'ostryer de Virginie n'étaient pas significativement différentes ($P<0,05$) et pouvaient être combinées en une seule équation. Toutefois, celles du chêne rouge et du bouleau à papier étaient significativement différentes. L'application des équations

combinées (celles des quatre espèces mentionnées) aux données des peuplements permettent de conclure que l'exploitation par arbres entiers peut augmenter de 56 à 111 % l'extraction des substances nutritives dans l'ordre suivant: P = N > Mg > K = Ca.

EQUATIONS FOR ESTIMATING ABOVE-GROUND NUTRIENT CONTENT OF SIX EASTERN CANADIAN HARDWOODS

INTRODUCTION

The forest manager has a large number of harvesting systems to choose from in the removal of forest biomass. These harvesting systems are composed of various combinations of harvesting methods and harvesting functions, and the four basic harvesting methods are short-wood, tree-length, full-tree, and complete-tree. The first two involve removing only the merchantable stems, leaving tops, branches, and foliage on site. The third and fourth options, however, involve removal of all above-ground material or all material, including roots, from the site. With increasing mechanization, the third and fourth options are becoming more and more prevalent. To quote Horncastle (1980): "... full-tree logging has the advantage over other systems from a harvesting standpoint and ... this actually will increase as logging technology and utilization of residues advances." A further economic advantage is the reduction in site preparation costs with the removal of slash.

This trend, which enhances harvesting efficiency and labour productivity, has significant implications for site fertility and biological productivity, because appreciable quantities of organic matter and nutrients are removed from the site (Anon. 1979, Carlisle and Methven 1979, Freedman et al. 1981, Kimmins 1977, Morrison 1980).

Choice of harvesting options, therefore, requires an impact evaluation on soil fertility and site productivity. A vital component of such an evaluation is a quantitative estimate of the biomass and nutrients removed in the various harvesting options. The purpose of this study is to derive prediction equations of nutrient mass for six eastern Canadian hardwood species, using nutrient concentrations and biomass of a sample of trees representing a range of diameter and height classes.

Study area

The study area was located on the Petawawa National Forestry Institute, Chalk River, Ontario - latitude 45° 58 min. N, longitude 77° 32 min. W.

The stands selected for sampling were naturally established, fully stocked, mixed hardwood stands growing on shallow ablation till over bedrock. All sites were well drained, but varied from dry to fresh in moisture regime (Hills and Pierpoint 1960).

Species present in the stands were: trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh.), red maple (*Acer rubrum* L.), red oak (*Quercus rubra* L.), ironwood (*Ostrya virginiana* [Mill.] K. Koch), largetooth aspen (*Populus grandidentata* Michx.), white spruce (*Picea glauca* [Moench] Voss), black spruce (*Picea mariana* [Mill.] B.S.P.), balsam fir (*Abies balsamea* [L.] Mill.), eastern white pine (*Pinus strobus* L.) black ash (*Fraxinus nigra* Marsh.), and American beech (*Fagus grandifolia* Ehrh.). Only the first six species were sampled.

METHODS

Field

A total of eighteen .04 ha plots were established in the stands, and all living trees greater than 5.1 cm diameter at breast height outside bark (dbhob) were tallied by species, dbhob, and total height.

Two or more trees of each species from each 5 cm dbhob class were selected for destructive sampling. Each tree was separated into its component parts: twigs and leaves, live branches, dead branches, merchantable bole, and top. Green weight was taken to the nearest 0.1 kg using a direct reading tensiometer, and sub-samples were returned to the laboratory for oven drying and calculation of dry weight. Details of field sampling can be found in Alemdag (1980, 1981).

Laboratory

Green subsamples were oven-dried at 105°C ± 3° in a forced-draught oven, and oven-dry weight/green weight ratios calculated for conversion of green weights. Oven-dry samples were ground in a Wiley Mill to 40 mesh and subjected to nutrient analyses.

Total nitrogen was determined by the semi-micro Kjeldahl procedure using a sulfuric acid - copper sulfate - potassium sulfate digestion mixture (Bremner 1965). A 0.5 g ground sample was digested with 10 ml of the digestion mixture for two hours at 160°C and then for two hours at 350°C. The digest was cooled and diluted to 75 ml and an aliquot steam distilled into boric acid after the addition of excess sodium hydroxide. The ammonium content of the distillate was then determined by titration against 0.05 N sulfuric acid, using a methyl red - bromocresol green indicator.

For the analysis of phosphorus, potassium, calcium, and magnesium, samples of 0.5 g were allowed to stand overnight in a digestion mixture (10 ml) containing 80% nitric acid and 20% perchloric acid. After pretreatment the samples were digested to completeness (approx. 2 hours). The digested material was diluted to 50 ml and each element determined as follows. Calcium and magnesium were determined in 1% La by atomic absorption. Phosphate was determined using a Technicon Autoanalyser system with colour development with ammonium molybdate - ascorbic acid - sulfuric acid.

Analyses

The analyzed nutrient concentrations (Table 1) were multiplied by the biomass values obtained from the sample trees to yield the respective nutrient masses for each species and component. The resulting data were used to develop sample linear regression equations of the form:

$$N = a + b \cdot (dbh)^2 \cdot h$$

where N is the nutrient mass in grams, and dbh and h are diameter at breast height in centimetres and height in metres, respectively. This resulted in 150 regression equations (6 species x 5 components x 5 nutrient elements).

In an attempt to simplify application, the equations were subjected to a covariance analysis. This analysis was carried out on all species simultaneously, followed by a sequential removal of species from the analysis until the majority of equations showed no significant difference in slope and level at the .05 probability level. Species data were then pooled to develop new combined regression equations.

RESULTS AND DISCUSSION

It is apparent from Table 1 that nutrient concentrations vary widely among components. The twigs and leaves, for example, contain 14 times as much nitrogen (1.246% to 0.087%) and 17 times as much phosphorus (0.137% to 0.008%) as the stem wood. The removal of the former in full tree harvesting, in spite of its low biomass contribution, can result in very significant loss to the site. High concentrations of N, P, K, and Mg in ironwood stems suggest that accumulation of these nutrients in the stem wood of this species.

The single tree equation for each species by nutrient element and component are presented in Tables 2a to 2f. With few exceptions the coefficients of determination are generally high and the estimate of relative error low, showing the good fit of the data to the sample linear model. The exceptions were noted in the twigs and leaves component of trembling aspen and white birch. The removal of red oak in the sequential covariance analysis made the greatest contribution to the increase in the homogeneity of combined equations, followed by white birch. The equations for trembling aspen, sugar maple, red maple, and ironwood for all nutrients and for all components, except twigs and leaves, showed no significant difference at the .05 probability level. The data for these species were pooled and combined regression equations developed (Table 3). Red oak and white birch were significantly different, so these species could not be combined into a single regression. The best combinations with respect to twigs and leaves were white birch, sugar maple, and red maple on the one hand and trembling aspen/ironwood and red oak/ironwood on the other. However, the gains in the coefficients of determination and estimates of relative error were not considered sufficient to warrant a separate set of equations apart from the single- and four-species equations.

The fact that all the nutrient equations for the twigs and leaves component were significantly different for the four-species combinations, while the nutrient equations for the other components were not, indicate that the former is either much more variable or more species specific. The twigs and leaves are a product of a single season's growth and development, and thus reflect the situation in one particular year. The other components reflect an average based on many years of accumulation, where variation due to changes in positions of individual trees within the three dimensional stand structure would tend to be masked.

Differences in site and/or form could explain why the prediction equations for red oak, and to a lesser extent white birch, are so significantly different from the other four species. The individual trees used in the analysis were selected from two stand subtypes designated as red oak-white birch and trembling aspen-maple-white birch. In the former, red oak and white birch contributed 45.1% and 33.8% of the basal area, respectively, and in the latter trembling aspen, red maple, sugar maple, and white birch contributed 54.7%, 18.2%, and 13.9% of the basal area respectively. The red oak-white birch subtype was generally confined to the dry sites and the trembling aspen-maple-white birch to the fresh sites. The processes considered in the absorption and uptake of nutrient ions are highly complex and include basically physical processes such as mass movement and diffusion, and active biological processes involving the expenditure of metabolic energy (Kramer 1969). The relationship with soil moisture is therefore not straightforward, but it is generally accepted that moisture stress is associated with reduced availability and uptake of nutrient ions. However, the mean nutrient concentrations (Table 1) are not significantly different for red oak, so the statistical difference is solely associated with the nutrient mass predictions based on tree size.

The form of the tree species will also determine whether the prediction equations are different. For example, mature oak, unlike aspen, soon loses apical dominance and develops a broad crown with heavy branches. The reason for white birch not bulking could be related to age.

In order to establish the relative importance of each component with respect to nutrient content, the average per cent contribution of each component for each nutrient was calculated for the range of sample trees within each species. Since there was no strong trend associated with tree size, the values were averaged (Table 4). As expected from the nutrient concentrations (Table 1) the differences among components are far less than those for biomass. Nitrogen tended to be evenly distributed among the four components for all species except trembling aspen and ironwood in which the twigs and leaves contained 38% and 40% of the total, respectively. Phosphorus also tended to be fairly evenly distributed, except for sugar maple and ironwood in which 44% and 37% respectively were found in the twigs and leaves, and red oak in which 46% was found in the live branches. With the exception of red maple, stem bark had the highest percentage (≈47%) of calcium, and with the exception of red oak, the greatest percentage of magnesium was in stem wood. Differences within and between species, therefore, may need to be taken into consideration.

Decision-making, with respect to harvesting system impacts on site, needs to be applied to stand tables to ascertain the nutrient removal per hectare. As an example, the four-species combination equations were applied to stand data of the trembling aspen-maple-white birch subtype to provide a comparison between tree-length and full-tree harvesting. As shown in Table 5, nutrient removals by full-tree harvesting increased by 56% to 111% over tree-length harvesting. These figures correspond well with those in the literature (e.g. Boyle and Ek 1972, Alban et al. 1978, Freedman et al. 1981, Hornbeck and Kropelin 1979, Kimmins 1977, Kimmins and Krumlik 1976, Mälkönen 1976, Morrison and Foster 1979, Wells and Jorgensen 1979, White 1974) even though much of it is derived from coniferous species, with nutrient removal being in the order Ca > K ≈ N > Mg > P but the impact or percentage increase as a consequence of full-tree harvesting being in the order P ≈ N > Mg > K = Ca.

As a number of authors have pointed out (Carlisle and Methven 1979, Kimmins 1979, Morrison and Foster 1979, Wells and Jorgensen 1979) the interpretation of different levels of nutrient removal on site productivity is extremely difficult. Ever since the early pioneering work of Ebermayer (1876, quoted by Stone 1979) in Germany and the later stimulus by Rennie (1955) there has been an explosion of interest in nutrient cycling and, more latterly, the impact of silvicultural systems on nutrient budgets and site productivity. This has yielded a tremendous amount of data on nutrient removals and so-called available "pools" of nutrients in different components of the system. However, our understanding of process rates and meaningful knowledge about soil supplies is still minimal. Important advances are being made by simulation modelling of nutrient budgets (e.g. Kimmins and Scoular 1979), but there is still a need for innovative methodologies and the development of a conceptual framework and theory with which to organize and structure the very disparate available information base.

LITERATURE CITED

Alban, D.H.; Perala, D.A.; Schlaegel, B.E. 1978. Biomass and nutrient distributions in aspen, pine and spruce stands on the same soil type in Minnesota. Can. J. Forest Res. 8: 290-299.

Alemdag, I.S. 1980. Manual of data collection and processing for the development of forest biomass relationships. Can. For. Serv., Petawawa Natl. For. Inst., Inf. Rep. PI-X-4.

Alemdag, I.S. 1981. Aboveground-mass equations for six hardwood species from natural stands of the research forest at Petawawa. Can. For. Serv., Petawawa Natl. For. Inst., Inf. Rep. PI-X-6.

Anonymous. 1979. Impact of intensive harvesting on forest nutrient cycling. Symposium Proceedings. State Univ. of New York, College of Environ. Science and For., School of For. Syracuse, N.Y.

Boyle, J.R.; Ek, A.R. 1972. An evaluation of some effects of bole and branch pulpwood harvesting on site macronutrients. Can. J. Forest Res. 2: 407-412.

Carlisle, A.; Methven, I.R. 1979. The environmental consequences of intensive forestry and the removal of whole trees. Pages 108-120 in Proc. Biol. and Sociol. Bases for a Rational Use of Forest Resources for Energy and Organics. USDA Forest Serv., Southeastern For. Exp. Sta., Ashville, N.C.

Freedman, B.; Morash, R.; Hanson, A.J. 1981. Biomass and nutrient removals of conventional and whole-tree clear-cutting of a red spruce-balsam fir stand in central Nova Scotia. Can. J. Forest Res. 11: 249-257.

Hills, G.A.; Pierpoint, G. 1960. Forest site evaluation in Ontario. Ont. Dep. Lands and Forests, Res. Rep. No. 42.

Hornbeck, J.; Kropelin, W. 1979. Nutrient removal and leaching losses from a whole-tree harvest of northern hardwoods. Page 397 in Proc. Impact of Intensive Harvesting on Forest Nutrient Cycling. State Univ. of New York, College of Environ. Science and For., School of For., Syracuse, N.Y.

Horncastle, D.C. 1980. Full-tree logging: advantages. Pulp & Paper Canada. 81(10): 56-60.

Kimmins, J.P. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. Forest Ecol. and Management. 1: 169-183.

Kimmins, J.P.; Krumlik, C.J. 1976. On the question of nutrient losses accompanying whole-tree harvesting. Pages 41-53 in IUFRO-Oslo, Biomass Studies. Univ. of Maine Press, Orono, Me.

Kramer, P.J. 1969. Plant and soil water relationships: a modern synthesis. McGraw-Hill.

Mälkönen, E. 1976. Effect of whole-tree harvesting on soil fertility. Silva Fenn. 10(3): 147-157.

Morrison, I.K. 1980. Full-tree harvesting: disadvantages. Pulp & Paper Canada. 81(10): 49-55.

Morrison, I.K., Foster, N.W. 1979. Biomass and element removal by complete-tree harvesting of medium rotation stands. Pages 111-129 in Proc. Impact of Intensive Harvesting on Forest Nutrient Cycling. State Univ. of New York, College of Environ. Science and For., School of For., Syracuse, N.Y.

Rennie, P.J. 1955. The uptake of nutrients by mature forest growth. Plant and Soil 7: 49-95.

Stone, E.L. 1979. Nutrient removals by intensive harvest - some research gaps and opportunities. Pages 366-386 in Proc. Impact of Intensive Harvesting on Forest Nutrient Cycling. State Univ. of New York, College of Environ. Science and For., School of For., Syracuse, N.Y.

Wells, C.G.; Jorgensen, J.R. 1979. Effect of intensive harvesting on nutrient supply and sustained productivity. Pages 213-230 in Proc. Impact of Intensive Harvesting on Forest Nutrient Cycling. State Univ. of New York, College of Environ. Science and For., School of For., Syracuse, N.Y.

White, E.W. 1974. Whole-tree harvesting depletes soil nutrients. Can. J. Forest Res. 4: 530-535.

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TABLES

Table 1. Concentration of nutrient elements in tree components - Values given are means and standard errors of the nutrients as per cent of ovendry weight

	Stem wood	Stem bark	Live branches	Twigs & leaves
			Nitrogen	
Trembling aspen	0.063±.004	0.286±.013	0.337±.022	1.401±.062
White birch	0.080±.006	0.302±.017	0.241±.017	1.180±.049
Sugar maple	0.087±.006	0.394±.006	0.187±.011	1.009±.058
Red maple	0.083±.007	0.375±.029	0.215±.029	0.998±.080
Ironwood	0.120±.011	0.608±.025	0.256±.014	1.244±.101
Red Oak	0.107±.006	0.331±.014	0.301±.026	1.405±.047
All species (x)	0.087±.003	0.349±.013	0.271±.011	1.246±.033
			Phosphorus	
Trembling aspen	0.006±.000	0.046±.005	0.054±.005	0.133±.004
White birch	0.006±.001	0.024±.002	0.035±.002	0.134±.011
Sugar maple	0.007±.001	0.030±.001	0.020±.001	0.195±.014
Red maple	0.009±.000	0.043±.004	0.030±.004	0.118±.017
Ironwood	0.016±.002	0.035±.002	0.027±.003	0.115±.014
Red oak	0.004±.000	0.018±.002	0.053±.012	0.125±.006
All species (x)	0.008±.000	0.032±.002	0.014±.003	0.137±.005
			Potassium	
Trembling aspen	0.096±.008	0.289±.024	0.318±.018	0.726±.048
White birch	0.061±.005	0.136±.010	0.148±.020	0.748±.033
Sugar maple	0.096±.009	0.430±.019	0.183±.019	0.767±.052
Red maple	0.130±.020	0.227±.019	0.185±.028	0.552±.053
Ironwood	0.206±.124	0.230±.014	0.114±.010	0.612±.064
Red oak	0.128±.008	0.165±.016	0.256±.020	0.732±.020
All species (x)	0.109±.011	0.240±.015	0.223±.012	0.712±.019
			Calcium	
Trembling aspen	0.132±.005	1.169±.075	0.871±.084	0.912±.030
White birch	0.119±.019	1 188±.158	0.624±.085	0.749±.024
Sugar maple	0.232±.032	2.478±.156	0.634±.053	0.882±.025
Red maple	0.167±.030	0.938±.086	0.433±.061	0.660±.048
Ironwood	0.196±.026	2.310±.261	0.690±.074	1.366±.293
Red oak	0.067±.006	2.334±.105	0.943±.117	1.001±.116
All species (x)	0.137±.009	1.700±.094	0.751±.044	0.910±.042

Table 1 (cont'd)

	Stem wood	Stem bark	Live branches	Twigs & leaves
			Magnesium	
Trembling aspen	0.028±.002	0.110±.007	0.132±.009	0.242±.010
White birch	0.028±.004	0.052±.004	0.057±.006	0.239±.012
Sugar maple	0.039±.007	0.064±.006	0.042±.004	0.167±.009
Red maple	0.032±.007	0.054±.005	0.044±.009	0.173±.009
Ironwood	0.041±.005	0.080±.007	0.053±.004	0.230±.012
Red oak	0.007±.001	0.044±.006	0.062±.005	0.179±.009
All species (x)	0.026±.002	0.068±.004	0.073±.005	0.208±.006

Table 2a. Prediction equations based on $dbh^2 \cdot h$ for the nutrient content in grams of trembling aspen

dbh = 5.2 - 41.8 cm; h = 6.7 - 26.3 m; n = 16

	Stem wood	Stem bark	Live branches	Twigs & leaves	Full tree
			Nitrogen		
a	6.2761	3.2388	22.0665	63.5344	95.1273
b	0.0082	0.0096	0.0062	0.0052	0.0292
r^2	0.8883	0.9509	0.8626	0.7459	0.9739
SEE%	31.56	20.80	30.22	30.08	12.59
			Phosphorus		
a	1.5676	1.5317	5.5913	7.5203	16.1685
b	0.0005	0.0011	0.0008	0.0004	0.0028
r^2	0.7868	0.8243	0.7538	0.5014	0.9070
SEE%	40.57	39.63	36.12	40.34	21.67
			Potassium		
a	-8.7738	-1.0422	11.4096	42.0527	43.6469
b	0.0167	0.0093	0.0062	0.0018	0.0340
r^2	0.8558	0.9672	0.8248	0.4663	0.9470
SEE%	39.80	17.37	38.41	39.38	20.38
			Calcium		
a	-1.5653	-6.0577	-3.4096	55.8585	44.8101
b	0.0217	0.0480	0.0206	0.0026	0.0929
r^2	0.9769	0.8504	0.9316	0.4213	0.9318
SEE%	14.46	91.92	25.62	45.40	24.53
			Magnesium		
a	3.5690	-6.8106	1.4955	12.0142	10.2442
b	0.0042	0.0045	0.0030	0.0008	0.0125
r^2	0.8955	0.8653	0.9222	0.6189	0.9718
SEE%	30.25	41.06	26.30	37.16	15.11

Table 2b. Prediction equations based on $dbh^2 \cdot h$ for the nutrient content in grams of white birch

dbh = 7.6 - 32.7 cm; h = 9.8 - 21.5 m; n = 12

	Stem wood	Stem bark	Live branches	Twigs & leaves	Full tree
			Nitrogen		
a	4.2349	7.2465	-44.1270	-14.4369	-47.1158
b	0.0126	0.0077	0.0159	0.0149	0.0512
r^2	0.8429	0.9792	0.7272	0.7336	0.9432
SEE%	35.69	11.18	84.93	60.00	24.24
			Phosphorus		
a	-0.2786	10.6883	-3.9884	-3.1268	-6.7520
b	0.0012	0.0006	0.0018	0.0021	0.0056
r^2	0.9115	0.9460	0.89166	0.6120	0.9042
SEE%	27.85	17.84	58.51	86.70	33.63
			Potassium		
a	-1.2700	1.6759	-45.4358	-5.1507	-50.1808
b	0.0096	0.0037	0.0138	0.0089	0.0360
r^2	0.9303	0.9307	0.6106	0.8507	0.8618
SEE%	24.10	22.24	124.91	39.32	42.70
			Calcium		
a	9.8535	49.7431	-130.8315	-13.1945	-84.3828
b	0.0158	0.0262	0.0457	0.0104	0.0981
r^2	0.8323	0.8664	0.7131	0.8067	0.8552
SEE%	35.77	26.99	89.78	51.11	40.29
			Magnesium		
a	5.8145	1.8064	-10.0987	-2.9251	-6.2073
b	0.0030	0.0012	0.0038	0.0030	0.0110
r^2	0.8827	0.9201	0.7119	0.7125	0.9309
SEE%	23.88	21.17	90.02	63.39	25.52

Table 2c. Prediction equations based on $dbh^2 \cdot h$ for the nutrient content in grams of sugar maple

dbh = 5.2 - 20.9 cm; h = 7.3 - 18.0 m; n = 9

	Stem wood	Stem bark	Live branches	Twigs & leaves	Full tree
			Nitrogen		
a	-2.3939	7.6739	2.1499	3.5518	10.9533
b	0.0183	0.0106	0.0066	0.0117	0.0473
r^2	0.9810	0.9468	0.9585	0.8831	0.9885
SEE%	13.57	17.97	17.62	31.00	09.37
			Phosphorus		
a	0.4308	0.1973	0.2922	0.9562	1.9178
b	0.0012	0.0010	0.0007	0.0022	0.0051
r^2	0.8930	0.9029	0.8700	0.8499	0.9104
SEE%	29.03	28.85	31.87	34.40	26.15
			Potassium		
a	2.1810	7.7601	-3.9215	5.5961	11.6091
b	0.0169	0.0119	0.0088	0.0079	0.0454
r^2	0.8845	0.9091	0.8351	0.8717	0.9208
SEE%	32.44	24.42	48.51	29.19	25.34
			Calcium		
a	17.5356	37.8593	3.8847	6.4813	65.7578
b	0.0317	0.0698	0.0253	0.0086	0.1355
r^2	0.9213	0.8213	88.1888	0.9338	0.9161
SEE%	23.20	37.14	25.10	20.05	24.47
			Magnesium		
a	5.2427	0.9849	-0.2777	1.1070	7.0742
b	0.0039	0.0018	0.0018	0.0016	0.0091
r^2	0.7792	0.8867	0.8447	0.8911	0.8817
SEE%	34.64	28.42	42.18	26.74	27.36

Table 2d. Prediction equations based on $dbh^2 \cdot h$ for the nutrient content in grams of red maple

dbh = 5.9 - 20.3 cm; h = 9.9 - 16.6 m; n = 6

	Stem wood	Stem bark	Live branches	Twigs & leaves	Full tree
			Nitrogen		
a	5.4280	-2.7588	-13.2145	6.5365	-3.9853
b	0.0112	0.0125	0.0190	0.0170	0.0596
r^2	0.8836	0.8640	0.8091	0.9502	0.9951
SEE%	31.31	44.07	66.88	20.39	07.32
			Phosphorus		
a	0.90437	-0.1220	-1.9132	1.3837	0.3342
b	0.0009	0.0012	0.0027	0.0017	0.0065
r^2	0.9598	0.9946	0.7883	0.4217	0.8104
SEE%	14.98	07.81	71.63	91.58	48.37
			Potassium		
a	-6.2427	2.7539	-11.7351	5.0414	-10.2377
b	0.0259	0.0043	0.0167	0.0084	0.0533
r^2	0.9955	0.9511	0.8628	0.9161	0.9881
SEE%	07.54	18.68	55.13	25.18	12.02
			Calcium		
a	-5.9624	7.1510	-20.6750	10.1294	-9.4139
b	0.0332	0.0219	0.0350	0.0091	0.0992
r^2	0.9359	0.9748	0.6720	0.6722	0.9448
SEE%	28.58	14.60	91.30	50.25	25.54
			Magnesium		
a	-3.4682	-0.4544	-3.4685	1.2701	-6.1496
b	0.0078	0.0017	0.0044	0.0030	0.0170
r^2	0.9503	0.9620	0.6425	0.9051	0.9814
SEE%	27.93	22.43	07.21	28.45	16.21

Table 2e. Prediction equations based on $dbh^2 \cdot h$ for the nutrient content in grams of ironwood

dbh = 5.2 - 18.5 cm; h = 6.3 - 11.9 m; n = 5

	Stem wood	Stem bark	Live branches	Twigs & leaves	Full tree
			Nitrogen		
a	2.6913	3.7450	0.2867	2.8662	9.5606
b	0.0169	0.0065	0.0104	0.0254	0.0591
r^2	0.9724	0.9438	0.9890	0.9838	0.9935
SEE%	17.67	19.93	12.14	13.90	08.48
			Phosphorus		
a	0.9645	0.2323	0.1931	0.5167	0.8657
b	0.0015	0.0004	0.0008	0.0022	0.0049
r^2	0.9370	0.9257	0.9985	0.9709	0.9900
SEE%	20.51	22.59	03.85	17.25	09.16
			Potassium		
a	5.1251	1.9929	1.2849	0.8832	9.2599
b	0.0098	0.0020	0.0036	0.0131	0.0289
r^2	0.5036	0.6962	0.8161	0.9921	0.5826
SEE%	83.63	44.07	44.03	09.97	39.25
			Calcium		
a	10.6245	22.2245	10.1564	-25.2331	17.7724
b	0.0200	0.0176	0.0202	0.0642	0.1220
r^2	0.9497	0.4774	0.6795	0.8646	0.9923
SEE%	19.28	62.79	58.41	66.51	09.33
			Magnesium		
a	1.1228	0.2604	-0.1722	-0.6969	0.5186
b	0.0057	0.0011	0.0024	0.0063	0.0155
r^2	0.9863	0.9963	0.9700	0.9350	0.9851
SEE%	12.08	06.04	21.90	33.90	14.12

Table 2f. Prediction equations based on $dbh^2 \cdot h$ for the nutrient content in grams of red oak

dbh = 5.5 - 38.9 cm; h = 8.1 - 23.0 m; n = 15

	Stem wood	Stem bark	Live branches	Twigs & leaves	Full tree
			Nitrogen		
a	33.4554	41.7351	-76.3143	20.0612	18.8919
b	0.0152	0.0078	0.0185	0.0084	0.0499
r^2	0.0227	0.9355	0.8153	0.8183	0.9558
SEE%	20.24	15.18	58.05	32.57	17.15
			Phosphorus		
a	1.2630	1.8648	-6.1384	1.9992	-1.0549
b	0.0005	0.0005	0.0024	0.0007	0.0041
r^2	0.8773	0.8411	0.8241	0.8299	0.9098
SEE%	25.65	27.13	47.50	30.70	26.40
			Potassium		
a	56.1135	11.6658	-65.8078	7.4586	9.3854
b	0.0161	0.0048	0.0161	0.0048	0.0417
r^2	0.9309	0.7041	0.7476	0.7889	0.8953
SEE%	17.55	44.64	70.57	37.83	27.59
			Calcium		
a	24.4467	301.4893	-279.6794	-22.2658	23.9479
b	0.0084	0.0566	0.0628	0.0104	0.1382
r^2	0.8183	0.8813	0.8337	0.6702	0.9492
SEE%	31.44	21.22	56.58	69.41	18.74
			Magnesium		
a	-4.0035	5.0856	-11.9312	2.5527	-8.2826
b	0.0017	0.0009	0.0031	0.0010	0.0067
r^2	0.6314	0.7615	0.7425	0.8241	0.8427
SEE%	77.56	31.91	69.05	31.76	39.29

Table 3. Prediction equations based on dbh²·h for the nutrient content in grams of trembling aspen, red maple, sugar maple and ironwood combined

	Stem wood	Stem bark	Live branches	Twigs & leaves	Full tree
			Nitrogen		
a	15.7071	5.2650	11.4061	35.8025	68.1660
b	0.0080	0.0095	0.0067	0.0063	0.0305
r^2	0.8895	0.9624	0.8771	0.7980	0.9703
SEE%	39.30	25.60	42.79	40.85	18.99
			Phosphorus		
a	2.0182	0.1752	2.0324	5.3360	9.5629
b	0.0005	0.0012	0.0009	0.0005	0.0031
r^2	0.8128	0.8821	0.8009	0.5340	0.9150
SEE%	44.76	49.73	54.05	54.85	30.51
			Potassium		
a	1.8103	1.1689	6.4982	25.1635	34.6369
b	0.0164	0.0092	0.0065	0.0025	0.0346
r^2	0.8918	0.9638	0.8574	0.6056	0.9587
SEE%	47.58	26.44	50.21	49.86	25.58
			Calcium		
a	21.6035	15.4365	10.0885	37.1381	84.2518
b	0.0211	0.0475	0.0203	0.0034	0.0922
r^2	0.9683	0.8755	0.9363	0.4201	0.9438
SEE%	22.24	50.20	34.02	69.21	30.37
			Magnesium		
a	4.0975	-6.1894	-0.9622	6.6234	3.5558
b	0.0042	0.0044	0.0030	0.0010	0.0127
r^2	0.9205	0.8979	0.9357	0.7060	0.9778
SEE%	36.31	56.50	37.79	49.69	20.18

Table 4. Percentage distribution of each nutrient among components.

	Stem wood	Stem bark	Live branches	Twigs & leaves	Full tree
			Nitrogen		
Trembling aspen	19.3	21.0	22.0	37.7	100
White birch	29.8	19.7	21.6	28.9	100
Sugar maple	33.2	26.8	14.5	25.5	100
Red maple	22.8	19.7	24.0	33.5	100
Ironwood	28.4	17.8	14.0	39.8	100
Red oak	35.4	22.6	22.1	19.9	100
			Phosphorus		
Trembling aspen	13.4	22.9	31.8	31.9	100
White birch	24.5	14.8	25.9	34.8	100
Sugar maple	23.5	18.3	14.0	44.2	100
Red maple	19.0	17.4	29.9	33.7	100
Ironwood	39.2	10.0	13.6	37.2	100
Red oak	15.4	16.8	45.7	22.1	100
			Potassium		
Trembling aspen	34.4	21.1	19.9	24.6	100
White birch	32.7	13.7	25.3	28.3	100
Sugar maple	35.3	30.2	14.1	20.4	100
Red maple	45.8	10.4	23.8	20.0	100
Ironwood	42.6	12.7	13.0	31.8	100
Red oak	49.9	13.8	23.4	12.9	100
			Calcium		
Trembling aspen	20.9	45.7	19.4	14.0	100
White birch	20.0	38.8	31.3	9.9	100
Sugar maple	24.0	52.6	16.4	7.0	100
Red maple	32.4	25.7	28.4	13.5	100
Ironwood	26.0	39.0	25.6	9.4	100
Red oak	7.6	60.2	26.3	5.9	100
			Magnesium		
Trembling aspen	33.8	21.0	22.6	22.6	100
White birch	37.5	14.3	23.0	25.2	100
Sugar maple	50.8	18.3	13.8	17.1	100
Red maple	44.5	10.5	21.1	23.9	100
Ironwood	47.9	9.7	12.5	29.9	100
Red oak	22.4	23.1	33.7	20.8	100

Table 5. Impact of full-tree (FT) versus tree-length (TL) harvesting on nutrient removal in a mixed hardwood stand as predicted by the combined equations for trembling aspen, red maple, sugar maple, and ironwood.

Nutrient	Tree length harvesting (kg/ha)	Full tree harvesting (kg/ha)	Difference (FT-TL) (kg/ha)	Difference/ Tree length (%)
Nitrogen	99	209	110	111
Phosphorus	11	23	12	109
Potassium	132	210	78	59
Calcium	363	568	205	56
Magnesium	42	73	31	74