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A PRELIMINARY CROWN BIOMASS TABLE FOR EVEN-AGED *Picea abies* STANDS IN SWITZERLAND

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The assessment of biomass and biomass changes due to environmental influences requires not only stem or merchantable mass, but also branches and needles. They have been of relatively little importance to forest managers to date, but their inclusion in models can make the resulting predictions more precise. A hybrid method is described to derive regressions for site quality, needle and branch biomass for individual Picea abies trees. By using Swiss stand table data on tree density distributions, a traditional yield table for branch and needle biomass is computed, and from these, regressions are derived which use only age and site quality as independent variables. Three tables for typical site qualities are given. The tabulated regressions include pseudo- probability values, coefficients of determination and estimated standard error for the overall models. These biomass fractions comprise a varying fraction of the tree, being important at low ages and much less so at later ages.

Introduction

There are two main directions to forest biomass structure research: ecological, related to the organic matter and energy cycling in the forest ecosystem, and forest biomass estimation for utilization purposes. Traditional stem volume yield tables have played a major role in the latter approach, but there is no comparable information on the temporal development of other parts of a tree, namely the branches, foliage and different categories of roots. Studies of carbon cycling are shifting to the global level, and there are a number of both national and international programmes related to carbon uptake by plants (Kurz et al., 1992; Kraeuchi, 1993; Nabuurs and Mohren, 1993). The development of methods to estimate the C pool and its annual turnover in forest biomass, involving about 70 per cent of the terrestrial carbon (Global BIOME Program, 1991), is therefore of interest. At present, the range of turnover estimates is extremely large, varying from 1 to 10 Gt a^{-1} on the global level (Global BIOME Program, 1991.; Kraeuchi, 1993), and for the territory of the former Soviet Union between 200 Mt a^{-1} (Zavarzin, 1992; Isaev et al., 1993) and 4360 Mt a^{-1} (Kolchugina and Vinson, 1993). These discrepancies indicate a major need for the improvement of methods to estimate forest biomass and carbon budgets in terrestrial ecosystems.

Early descriptions of forest productivity include harvest biomass data per hectare together with stand indices (e.g. mean height, site index, age, stand density). There is a wealth of compilations of biomass for different forest stands (Rodin and Bazilevich, 1967; Madgwick, 1970; Utkin, 1970; Pozdnyakov, 1975; Stanek and State, 1978; Gholz et al., 1979; Reichle, 1981; Cannell, 1982; Valentine et al., 1984; Alaback, 1986, 1987; Wharton and Cunia, 1987; Palumets, 1991). Attempts to describe the multivariate structure of forest biomass variability have been made, resulting in linear regression equations of the form $lnw_i=L(A,dbh,h,Z)$ (Usoltsev, 1983), or $(W_i/V)=L(A,V,S)$ (Onuchin and Borisov, 1984). (Symbols are listed at the end of the paper). The latter model has been used in forest biomass inventory, and acceptable results for total crown biomass have been achieved (Usoltsev, 1995). For other components, such as foliage and roots, it has been observed that the model can be improved by using N and D_m instead of V (Usoltsev, 1988b; Usoltsev and Hoffmann, 1997). Consequently, regression equations of the form:

$$ln(W_i/V)=L(A, S, D_m, N), \quad (1.1)$$

have been proposed (Usoltsev 1988a,b, 1995). A more recent method to estimate crown biomass exploits the pipe model (popularized by Shinozaki et al., 1964a,b) using the stem diameter just below the start of the crown dbc (White, 1993). Its use is the subject of another paper (Usoltsev et al., 1997).

A large number of stand volume and yield tables has accumulated during the last 150 years of development of forest mensuration. Today, because of changing environmental conditions, less time-consuming methods for the estimation of analogous data for the other biomass compartments need to be adopted. In this paper, a method for combining traditional forest mensuration tables and models designed for stem volume with harvest biomass data is proposed. Unfortunately, root biomass could not be included, because there were no data available.

Yet another approach to describe the distribution of biomass within a tree is the process model approach. Here, physiological and other processes which determine forest production are formulated and combined into a model.

Landsberg (1986) gives a basic set of equations governing weather influence, stand structure and microclimate, carbon balance of leaves of trees, nutrient dynamics and tree growth, and water relations, from the physiological point of view. Dixon (1990) discusses the main physiological processes from the modeler's point of view. Hierarchical and compartmentalized process models have been developed (e.g. Mitchell, 1975; Blake and Hoogenboom, 1988; Ford and Kiester, 1990; Bassow et al., 1990; Isebrands et al., 1990; Sievaenen, 1993). Data for input consist of starting values of state variables, and of coefficients for the model equations which are estimated from process data, using mostly regression. This approach is not followed any further here, because stand tables cannot furnish these data.

Materials and methods

There are at least three major approaches of linking forest biomass data with yield table data. The first involves the use of recursive systems of regression equations (Amateis et al., 1984; Borders and Bailey, 1986; Borders, 1989; Usoltsev, 1988a, 1989, 1990), where the dependent variable of one of the equations becomes the independent variable in the others. Such a recursive system can be constructed by augmenting equation (1.1) by the linear regressions:

$V = L\,(A, S)$

$N = L\,(A, S)$ (1.2)

$D_m = L\,(A, S)$

and

$S = L\,(A, H_m)$.

S is used instead of mean height because of its wider use in yield tables and better predictive value.

Equations (1.1) to (1.3) were applied to aspen, birch, and stands of *Pinus sylvestris* L. In Northern Kazakhstan (Usoltsev, 1988b, 1989, 1990) and to stands of *Picea abies* and *Pinus sylvestris* in the Middle Urals (Usoltsev et al., 1994) where the qualities (1.2) and (1.3) were taken partly in analytical and partly in tabular form from yield tables. This approach rests on the assumption that stands with the same mean height, age, site index, mean diameter, tree density and stem volume agree in their distribution of biomass components.

The second approach is oriented to individual trees. It was suggested by Makarenko and Malenko (1984), and their biomass equations are of the form:

$w^{1/3} = L\,(S, D_m, dbh, h)$. (2)

Makarenko et al. (1980) compiled yield tables for *Pinus sylvestris* stands in each of three regions of Northern Kazakhstan and described mathematically the age dynamics of the tree diameter distribution, also giving graphs of *h* vs. *dbh*.. Makarenko and Malenko (1984) constructed stand biomass tables by using (2) and the graphs of *h* vs. *dbh*. The precision of these tables is roughly the same as that of the first approach, since it is assumed that two stands have the same biomass distribution if they have the same diameter distribution. This, however, is rather rare (Semechkina, 1978).

The third approach also uses biomass equations for individual trees, but does not take into account tree diameter distribution. Naturally, these estimates are less exact than those of the first two approaches, but they require less harvest biomass data. Root biomass tables for pine stands in Northern Kazakhstan of different age classes and ecological conditions were constructed in this manner (Usoltsev et al., 1985; Usoltsev and Vanclay, 1993):

$$ln\ w_i = L(A, dbh, h). \quad (3)$$

To reach the stand level, equations (3) were modified as:

$$ln(W_i/N) = L\ (A, D_m, H_m) \quad (4.1)$$

and developed into a recursive system of equations ((4.1) and (4.2) taken together):

$$\begin{aligned} N &= L(A, S) \\ D_m &= L(A, S) \quad (4.2) \\ H_m &= L(A, S), \end{aligned}$$

where equations (4.2) were taken in a tabular expression from yield tables.

Results

Burger (1953) published biomass data for 189 Norway spruce trees, from 15 to 285 years old, harvested in even-aged stands with different ecological conditions. These data include tree height, age and social status , but not site index or tree volume. Therefore, elements from all three approaches were used to compile biomass tables derived from the Swiss yield tables for even-aged spruce stands ([Badoux], 1983). As an approximation to the missing site index, following the first approach, a regression equation in the form of (1.3) was derived from the yield table. Inspection of the graphs of $ln(S)$ vs. $ln(H_m)$

for constant A (see Figure 1) suggested the inclusion of terms up to the second order. Backwards stepwise regression was produced:

$$\ln S = L(A, H_m) =$$
$$=a_0+a_1(\ln A)^2+a_2(\ln H_m)^2+a_3(\ln A)(\ln H_m)+a_4(\ln A)^2(\ln H_m)+a_5(\ln A)(\ln H_m)^2+$$
$$+a_6(\ln A)^2(\ln H_m)^2. \quad (5)$$

Coefficients and goodness of fit are shown down.

Regression coefficients and goodness of fit for equation (5) for site quality. Pseudo-probabilities for all coefficients are < 0,00015

a_0	3,8172	a_2	0,1332	a_4	-0,06253	a_6	0,02527	R^2	0,997
a_1	-0,1353	a_3	0,2918	a_5	-0,1086	n	131	s.d.	0,0208

To eliminate the bias introduced by taking the logarithm of S, a_0 should be replaced by $a_0+(\text{s.d.})^2/2$, following Finney (1941) and Baskerville (1972). This device is also recommended for equations (6) and (7). Based on the second approach, but using age instead of S and D_m in (2), the following regression equations for branches and foliage dry mass were derived from Burger's data (тable 1).

$$\ln w_i = L(A, dbh, S) =$$
$$=a_0+a_1(\ln A)+a_2(\ln dbh)+a_3(\ln A)(\ln dbh)+a_4S+a_5(\ln S)+a_6(\ln v). \quad (6)$$

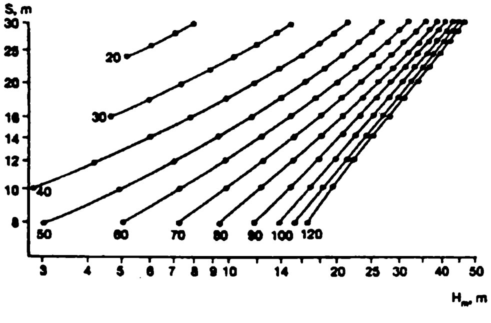

Fig. 1. Relationship between site index S and mean height H_m for different stand ages, labeled in years

$(\ln v)$ is not significant in $(\ln w_f)$, but if this term is included in $(\ln w_b)$ (see line 3 labeled $(\ln w_b)^*$ in Table 1), a slightly higher R^2 and a smaller s.d. are obtained than without this term. The use of v became possible by retrieving the volumes from the original data records , but they were recorded for only 97 sample trees. Stem volume v was not used in the subsequent computations for several reasons. First, too many of already scarce data would be lost without much gain. Second, sticking to the larger data set would tend to give

Table 1

Coefficients and goodness of fit for equations (6) for dry biomass (kg) of foliage and branches

Constants	$\ln w_f$	$\ln w$	$\ln w_b$
a_0	-0,8923	0,8939	9,8422
a_1	-0,6451	-2,2271	-3,3238
a_2	2,2608	-1,5053	-1,4918
a_3	-	0,7733	1,0899
a_4	-0,0460	-0,1737	-
a_5	-	3,1575	-
a_6	-	-	-0,4642
n	168	161	97
R^2	0,888	0,888	0,919
s.d	0,3760	0,3747	0,3124

Note. All a_i of foliage have $p<0{,}01$, those of branches have $p<0{,}00002$, except for $p(a_4)=0{,}025$, $p(a_5)=0{,}039$, all $p^*<0{,}008$, except for $p(a_2)^*<0{,}047$/

better general predictions , against fitting a smaller set more precisely. Thus Table 2 was derived by applying (6) and using the coefficients of the first two lines of Table 1 to each diameter class and subsequent summation. Borrowing from the third approach (4), S from (5) was used, generating from these tabulated data the relationship:

$$\begin{gathered} \ln W_i = L(A, S) = a_0+a_1(\ln A)+a_2(\ln A)^2+a_3(\ln A)^3+a_4(\ln S)+a_5(\ln S)^2+a_6(\ln S)^3+ \\ +a_7(\ln A)(\ln S)+a_8(\ln A)(\ln S)^2+a_9(\ln A)^2(\ln S)+a_{10}(\ln A)^2(\ln S)^2+a_{11}(\ln A)^3(\ln S)+ \\ +a_{12}(\ln A)^3(\ln S)^2 \end{gathered} \tag{7}$$

for foliage and branches. The coefficients are given in Table 3. In addition to the measured data, artificial data were introduced, using $Wi = 1$, $A = 2$, at for every $S = 8, 10,...30$, to achieve reasonable extrapolation for ages less than the minimum age given in the yield table. Equations (7) should not be used

Table 2

Dry biomass (kg ha^{-1}) of foliage (first line) and of branches (second line), and tree density (ha^{1}) (third line, from yield table), according to site index, stand age, and diameter class (cm). Bias correction applied.

Site index=14

Age	Total	Diameter class (cm)												
		2	6	10	14	18	22	26	30	34	38	42	46	50
40	10480	27	1342	3387	5296	427	-	-	-	-	-	-	-	-
	14484	177	3166	5010	5761	369	-	-	-	-	-	-	-	-
	2894	*268*	*1093*	*869*	*635*	*29*	-	-	-	-	-	-	-	-
50	11200	3	565	1583	3828	3250	1766	205	-	-	-	-	-	-
	13282	17	1275	2448	4613	3252	1522	156	-	-	-	-	-	-
	1918	*38*	*531*	*469*	*530*	*255*	*88*	*7*	-	-	-	-	-	-
60	11461	-	180	968	1823	3751	2747	1796	216	-	-	-	-	-
	13074	-	391	1520	2389	4227	2744	1623	179	-	-	-	-	-
	1350	-	*190*	*316*	*284*	*331*	*154*	*69*	*6*	-	-	-	-	-
70	11420	-	27	494	1035	2452	3731	2521	1075	86	-	-	-	-
	13365	-	56	817	1455	3056	4222	2633	1047	79	-	-	-	-
	1003	-	*31*	*182*	*178*	*239*	*231*	*107*	*33*	*2*	-	-	-	-
80	11358	-	5	272	661	715	2549	3913	2479	714	51	-	-	-
	13871	-	10	461	989	973	3213	4631	2780	763	52	-	-	-
	770	-	*6*	*109*	*124*	*76*	*172*	*181*	*83*	*18*	*1*	-	-	-
90	11167	-	-	115	386	558	1318	2665	2963	2205	898	59	-	-
	14568	-	-	201	608	820	1828	3522	3758	2698	1064	68	-	-
	608	-	-	*50*	*78*	*64*	*96*	*133*	*107*	*60*	*19*	*1*	-	-
100	10969	-	-	43	125	587	860	1497	2406	2643	1854	886	68	-
	15509	-	-	77	207	923	1298	2185	3408	3650	2503	1171	88	-
	495	-	-	*20*	*27*	*72*	*67*	*80*	*93*	*77*	*42*	*16*	*1*	-
110	10621	-	-	-	56	353	664	898	1654	2453	2574	1457	511	-
	16417	-	-	-	98	590	1082	1432	2590	3779	3906	2183	757	-
	407	-	-	-	*13*	*46*	*55*	*51*	*68*	*76*	*62*	*28*	*8*	-
120	10246	-	-	-	-	217	536	632	897	1648	2237	2116	1451	511
	17360	-	-	-	-	385	938	1095	1538	2804	3779	3552	2421	848
	339	-	-	-	-	*30*	*47*	*38*	*39*	*54*	*57*	*43*	*24*	*7*

Site index=20-

Age	otal	Diameter class (cm)																	
		2	6	10	14	18	22	26	30	34	38	42	46	50	54	58	62	66	70
30	10865 16232 *2708*	52 649 *556*	782 2608 *697*	2393 4467 *672*	3779 4814 *496*	3860 3695 *287*	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
40	12256 16508 *1725*	- - -	336 1137 *361*	1402 2972 *474*	2095 3266 *331*	3519 4361 *315*	3059 357 *174*	1667 1477 *65*	177 138 *5*	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
50	12480 16092 *1167*	- - -	66 214 *82*	592 1311 *231*	1233 2130 *225*	1828 2621 *189*	3685 4553 *242*	3043 3323 *137*	1381 1357 *45*	652 583 *16*	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
60	12564 16514 *839*	- - -	- - -	294 675 *129*	653 1226 *134*	1109 1792 *129*	1394 1996 *103*	340 4067 *159*	393 3796 *117*	1557 1717 *43*	931 961 *20*	292 284 *5*	- - -	- - -	- - -	- - -	- - -	- - -	- - -
70	12375 17290 *630*	- - -	- - -	130 308 *63*	35 676 *76*	670 1196 *86*	723 1173 *59*	1180 1766 *66*	2619 3659 *106*	348 4141 *96*	2319 2892 *55*	1057 1257 *20*	195 222 *3*	- - -	- - -	- - -	- - -	- - -	- - -
80	12040 18459 *486*	- - -	- - -	43 106 *23*	125 269 *31*	343 668 *48*	573 1036 *51*	755 1280 *46*	1609 2587 *71*	2527 3874 *84*	2669 3924 *69*	1843 2609 *38*	1192 1630 *20*	360 477 *5*	- - -	- - -	- - -	- - -	- - -
90	11801 19988 *388*	- - -	- - -	- - -	86 195 *23*	179 376 *27*	438 870 *42*	517 979 *34*	861 1566 *41*	1478 2592 *53*	2008 3412 *56*	2113 3489 *47*	1822 2932 *33*	1334 2095 *20*	873 1341 *11*	93 140 *1*	- - -	- - -	- - -
100	11582 21876 *318*	- - -	- - -	- - -	42 100 *12*	87 195 *14*	175 379 *18*	483 1010 *34*	530 1076 *27*	808 1598 *31*	1306 2527 *39*	1848 3503 *44*	2012 3743 *39*	1869 3418 *30*	1334 2402 *18*	784 1391 *9*	304 532 *3*	- -	- - -
110	11205 23724 *263*	- - -	- - -	- - -	13 33 *4*	41 98 *7*	73 171 *8*	294 672 *22*	388 870 *21*	514 1136 *21*	913 1987 *29*	1461 3138 *37*	1698 3603 *35*	1640 3442 *28*	1534 3186 *22*	1229 2530 *15*	857 1749 *9*	549 1110 *5*	- - -
120	10810 25705 *221*	- - -	- - -	- - -	- - -	11 28 *2*	43 109 *5*	189 470 *15*	314 772 *18*	301 734 *13*	506 1226 *17*	822 1977 *22*	1238 2962 *27*	1717 4085 *31*	1714 4057 *26*	1627 3834 *21*	1261 2959 *14*	830 1940 *8*	237 552 *2*

(c) Site index =26

Age	Total	Diameter class (cm)																					
		2	6	10	14	18	22	26	30	34	38	42	46	50	54	58	62	66	70	74	78	82	86
20	10251	100	1306	1930	2028	3009	1878	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	17352	2023	5385	3795	2648	2524	1177	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	3400	*1082*	*1181*	*550*	*270*	*227*	*90*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	12070	6	370	1227	2145	1949	3373	2179	777	43	-	-	-	-	-	-	-	-	-	-	-	-	-
	14362	86	1410	2614	3119	2130	2935	1569	476	23	-	-	-	-	-	-	-	-	-	-	-	-	-
	1870	*91*	*435*	*454*	*371*	*191*	*210*	*93*	*24*	*1*	-	-	-	-	-	-	-	-	-	-	-	-	-
40	12515	-	20	516	1253	2238	1868	2803	2394	964	459	-	-	-	-	-	-	-	-	-	-	-	-
	13957	-	71	1165	2080	2951	2051	2642	1980	711	306	-	-	-	-	-	-	-	-	-	-	-	-
	1193	-	*28*	*230*	*261*	*264*	*140*	*144*	*89*	*27*	*10*	-	-	-	-	-	-	-	-	-	-	-	-
50	12484	-	-	136	453	1050	1548	2073	2609	2071	1351	947	245	-	-	-	-	-	-	-	-	-	-
	14043	-	-	321	833	1602	2036	2409	2726	1973	1185	771	186	-	-	-	-	-	-	-	-	-	-
	815	-	-	*70*	*109*	*143*	*134*	*123*	*112*	*67*	*34*	*19*	*4*	-	-	-	-	-	-	-	-	-	-
60	12258	-	-	33	170	411	822	1064	1636	2831	2332	1640	925	394	-	-	-	-	-	-	-	-	-
	14766	-	-	80	340	707	1252	1467	2070	3322	2561	1695	906	367	-	-	-	-	-	-	-	-	-
	587	-	-	*19*	*46*	*63*	*80*	*71*	*79*	*103*	*66*	*37*	*17*	*6*	-	-	-	-	-	-	-	-	-
70	11984	-	-	-	90	183	409	610	712	1567	2304	2367	1675	1012	637	416	-	-	-	-	-	-	-
	15896	-	-	-	194	348	706	972	1059	2195	3057	2994	2029	1177	714	451	-	-	-	-	-	-	-
	444	-	-	-	*27*	*31*	*44*	*45*	*38*	*63*	*72*	*59*	*34*	*17*	*9*	*5*	-	-	-	-	-	-	-
80	11764	-	-	-	43	98	171	448	413	548	1115	1656	2170	1856	1364	1069	710	102	-	-	-		-
	17402	-	-	-	98	202	328	809	706	894	1745	2495	3159	2618	1869	1426	924	130	-	-	-	-	-
	345	-	-	-	*14*	*18*	*20*	*36*	*24*	*24*	*38*	*45*	*48*	*34*	*21*	*14*	*8*	*1*	-	-	-	-	-
90	11214	-	-	-	-	60	95	242	383	508	626	682	1215	1670	1667	1415	1152	758	541	-	-	-	-
	18838	-	-	-	-	135	201	488	740	948	1132	1199	2081	2791	3052	2268	1811	1171	822	-	-	-	-
	276	-	-	-	-	*12*	*12*	*21*	*24*	*24*	*23*	*20*	*29*	*33*	*31*	*20*	*14*	*8*	*5*	-	-	-	-
100	10942	-	-	-	-	28	44	75	164	296	483	542	861	1324	1519	1521	1307	1151	809	688	129	-	-
	20951	-	-	-	-	68	102	168	354	625	994	1093	1705	2576	2910	2871	2434	2117	1470	1236	230	-	-
	226	-	-	-	-	*6*	*6*	*7*	*11*	*15*	*19*	*17*	*22*	*28*	*27*	*23*	*17*	*13*	*8*	*6*	*1*	-	-
110	10597	-	-	-	-	-	28	51	70	167	287	450	515	845	1058	1492	1301	1166	1046	863	850	408	-
	23148	-	-	-	-	-	69	123	167	393	664	1027	1164	1886	2339	3268	2825	2510	2236	1830	1791	854	-
	188	-	-	-	-	-	*4*	*5*	*5*	*9*	*12*	*15*	*14*	*19*	*20*	*24*	*18*	*14*	*11*	*8*	*7*	*3*	
120	10505	-	-	-	-	-	-	19	40	141	407	255	383	420	600	941	1367	1338	1169	1020	919	772	716
	26194	-	-	-	-	-	-	51	104	365	1048	653	975	1064	1512	2359	3414	3329	2897	2518	2261	1893	1751
	168	-	-	-	-	-	-	*2*	*3*	*8*	*18*	*9*	*11*	*10*	*12*	*16*	*20*	*17*	*13*	*10*	*8*	*6*	*5*

beyond ages A greater than 120 years, because the yield tables only give tree densities up to this age.

Discussion

A very precise representation of site quality has been derived in (5). By adding s.d.^{2}/2 to the constant term, bias can be corrected. It can now be used wherever age and mean height are available. Although the stand tables were generated by visually smoothing growth data, the residuals of (5) show a reasonably normal behavior, with only eight out of 131 deviating from normal at the tails.

The regressions (6) for branch and needle biomass of individual trees depend on *dbh*, age and site quality only. Following from the value of s.d. and because of the natural logarithm in (6), we get a *relative* error for predicting biomass of about 40 per cent. Thus, the entries of Table 2 should be seen as being precise to at most the first digit. They have not been rounded to one significant figure to avoid the introduction of another source of imprecision and to make it easier to assess their generation *vis-a-vis* future improvements. As can be seen from the tables, the foliage biomass for each site quality varies very little with age, showing a broad maximum in the middle of the age range. Within the range of prediction branch biomass drops to a minimum at about 50 years of age and rises from there with old age and site quality. The minimum of branch biomass with age varies with site quality and is highest for the medium site quality.

Although equation (6) suffers from a considerable lack of precision, it was decided to approximate the totals of Table 2 as precisely as these data permitted, arriving at equation (7) and Table 3, using age and site quality alone. Although Burger's data include trees older than 120, (7) cannot be used for ages above 120 years, because stand table density data are lacking.

This material is preliminary. First, Burger's data were taken from experimental and some *ad hoc* plots. During the last 70 years ecological conditions may have changed, and with them, site index (Keller, 1978; Sennov, 1983). Consequently, there is a need to gather new field data. Second, root biomass distribution are also needed. Third, an attempt to obtain more tree volumes for Burger's original data should be made.

Conclusions

For carbon balance calculations there is a particular need of forest biomass tables which comprise more than stem volume. In this paper it is shown how recursive regression analysis can combine forest inventory data with biomass harvest data. Careful analysis of functional relationships can lead to good empirical formulae.

Although only a relatively small data set has been available, the results suggest that it is possible to estimate the biomass of foliage and branches from stand inventory data. However, uncertainties remain, which need to be resolved by collecting more data on the biomass of particular forest components, such as branches, leaves and needles, and most urgently, on roots. There are seldom considered in national forest inventories, but current changes in the requirements of such inventories mean that in the future, more data may be collected that are relevant to biomass estimation and the whole issue of carbon sequestration in forest (table 3).

Table 3

Coefficients and goodness of fit of equation (7) for dry biomass of foliage and branches (t ha^{-1})

	$\ln Wf$	$\ln W_b$		$\ln Wf$	$\ln W_b$
a_0	7,0126	6,7973	a_8	0,3544	1,3199
a_1	-6,6481	-1,7212	a_9	-2,0172	-2,0897
a_2	3,2511	-	a_{10}	0,0484	0,2016
a_3	-0,3633	0,0535	a_{11}	0,1785	0,1201
a_4	-8,0522	-12,0978	a_{12}	-	$-7{,}802 * 10^{-6}$
a_5	1,7832	3,1221	n	130	130
a_6	-0,1890	-0,2793	R^2	1,000	1,000
a_7	6,8172	9,8377	s.d	0,0219	0,0400

Note. All a_i of foliage have $p<0{,}0002$, those of branches have $p<0{,}016$, except for $p(a_6)=0{,}079$, $p(a_{12})=0{,}145$.

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List of symbols

A age of tree (years)
a_i coefficients of regression equations
dbc stem diameter just below the start of the crown (cm)
dbh stem diameter at breast height (cm)
D_m mean diameter at breast height (cm) = $(\sum dbh_i)/n$, summed over the

stand

h tree height (m)

H_m stand mean height (m)

L polynomial of arguments in following brackets and of logarithms of these arguments

ln natural logarithm

n number of data points used in analysis

N tree density (ha^{-1})

p probability of regression coefficient

R^2 coefficient of determination of an estimated model

s.d. estimated standard deviation of residuals

S site index, i.e. height of 100 thickest trees (on 1 ha) at age 50 years (m)

v stem volume (dm^3)

V stem volume ($m^3\,ha^{-1}$)

w_i dry biomass (subscripts: *b* = branches, *f* = foliage) for a tree (kg)

W_i dry biomass (subscripts: *b* = branches, *f* = foliage) for a stand ($t\,ha^{-1}$)

Z stem density (ha^{-1}) divided by the stem density taken from a corresponding yield table

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