ESTIMATING THE CARBON CONTENT OF RUSSIAN FORESTS; A COMPARISON OF PHYTOMASS/VOLUME AND ALLOMETRIC PROJECTIONS

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Abstract. As increased attention is being paid to the role Russian forests play in the global carbon budget, the desirability of being able to accurately and easily estimate the carbon content of the Russian forests is clear. In Russia timber volume has been estimated regularly and systematically as part of the former Soviet Union's forest inventory system. To determine the accuracy of using a volumetric approach to determining forest carbon pools, we developed allometric equations for the dominant trees (5 taxa) of two regions (Vologda and Volgograd) of Russia. Using these allometric equations and the phytomass/volume ratios previously developed to exploit the volume inventory data, we compared the forest carbon content of 51 forest stands of varying ages, composition and structure estimated using the two approaches.

Carbon estimates for the Vologda region were on average 8% (±4% 95% CI) greater using the volume approach than the allometric approach, and 4% greater (± 4%) in the Volgograd region. The greatest difference was for pine dominated stands (-15%) and the least for birch dominated stands (+1%). We also compared the carbon estimated for the 26 Vologda stands utilizing allometric equations developed for the same genera growing in similar forest types in North America. The North American allometric equations predicted slightly higher carbon content on average as compared to the Russian derived equations (2% ± 4).

The data presented suggest that using volumetrically derived carbon estimates provide reasonably accurate estimates of forest carbon.

Key Words: Betula, carbon content, boreal forest, forest biomass, phytomass/volume ratios, Picea, Populus, Russia, timber volume

1. Introduction

Growing evidence of global climate change (Houghton *et al.*, 1996) has increased efforts to utilize forest management as a mechanism for sequestering carbon. Our ability to utilize forestry as a mitigation measure for increasing anthropogenic emissions of carbon dioxide is largely dependent on our ability to accurately predict changes in carbon storage (Brown *et al.*, 1996). The carbon accounting necessary for determining the impacts of any single management decision on carbon storage can be involved and complex. Yet if forestry is to become a viable

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mitigation option it is essential we identify simple and accurate techniques for assessing carbon changes in terrestrial ecosystems.

Though foresters have been making estimates of forest productivity for well over a century, those estimates have been largely in terms of timber volume (UN/FAO, 1995). Projects that increase merchantable timber and the economic value of a forest do not necessarily increase the carbon content of the forest. In order to utilize the vast knowledge available on the impacts of forest practices on timber volume to determine changes in carbon content of these same forests, we need to be able to easily convert from well established timber volume parameters to ecosystem carbon. (Schroeder *et al.*, 1997).

On a regional basis the conversion of timber volume to carbon is different than on a specific project basis. In regional estimates we are trying to determine standing stocks over large areas, thus we are utilizing carbon values of average stand characteristics for large regions. In individual offset projects increased carbon sequestration is claimed as a result of a management policy change. If these project-specific estimates are biased, or skewed, they may not result in additional sequestered carbon. In order to ensure that project-based carbon benefits are realized, it is essential that the methodological limitations to measuring carbon in forestry projects is well understood.

If volume-based approaches provide reliable estimates of carbon changes it would enhance the usefulness of forestry-based carbon off-set projects. Since the accuracy of allometric approaches is well established (Siccama *et al.*, 1994) a comparison of volumetric- and allometric-based approaches is the most direct way to determine the suitability of volumetric approaches. The relationship of carbon content to volume of an individual tree is often non-linear, thus, it is not intuitively obvious whether volume estimates of stand carbon will be consistent or accurate across forest stands. By contrast allometrically derived carbon estimates incorporate genotypically determined relationships between tree diameter (diameter at breast height- dbh) and tree height, and tree weight and carbon content. By using stand inventory data, dbh and height, and allometric equations for the species of interest, it is possible to accurately determine tree biomass. Such an approach however requires a level of information that will not be readily available to all carbon off-set projects. Regrettably, regional compilations of allometric weight equations for forest tree species (see Tritton and Hornbeck, 1982) are not universally available.

We compared the volume and allometrically derived carbon estimates of 51 Russian forests with a wide range of ages. The sites were from the Vologda region, an area of boreal forest and the Volgograd region, representing the transition between temperate forests and steppe grasslands. Russia provides an ideal setting for comparing these two approaches since large data sets, collected from across the country, include tree volume, tree weights, and stand characteristics. A system of phytomass/volume ratios was developed to convert timber volume to stand carbon (Isaev *et al.*, 1993 and 1995). These tables represent a very efficient means of estimating carbon changes in forest biomass resulting from forestry off-set projects if they can be shown to provide a good estimate of forest carbon. The study described below evaluates the differences in estimates of forest carbon derived from allometric and volume approaches.

To reduce the costs of carrying out forest mitigation projects there will be an incentive to use existing allometric equations developed outside the project region to estimate forest carbon. The applicability of using generalized allometric equations was evaluated by comparing estimates generated utilizing North American allometric equations with the locally derived Russian equations developed in this study.

2. Methods

The Vologda region (58-61°N, 35-47°E) is characterized by little topographic relief (<5°), a mixture of moderately and poorly drained podzols (spodosols), and boreal vegetation dominated by *Picea abies, Pinus slyvestris, Betula sp.*, and *Populus tremula* L. The forests of the Volgograd region (50°N) by contrast are dominated by plantations of *Pinus sylvestris.* Representative stand data were selected from information in the Russian National Forest Inventory for forests with species compositions representative of the dominant vegetation of the two regions of interest. Fifty-one stands with a wide range of ages were selected (20 - 155 years). The Vologda plot data were collected in 1988, and the Volgagrad data in 1995.

Construction of the allometric equations utilized data from individual trees and shrubs (dry weights and heights) collected from 1970 to 1995 in the Vologda, Novgorod, Yaroslavl, Tver, Vladimir and Komi regions (55-62°N, 33-50°E). Construction of the allometric equations for *Pinus sylvestris* L. (south) utilized data from the Samara and Uljanovsk regions (53°N, 48-50°E) (Vompersky, 1982; Vompersky, Utkin, 1986, 1988; Smirnov, 1971; Dylis, Nosova, 1977).

2.1 DEVELOPMENT OF ALLOMETRIC EQUATIONS

One thousand individual trees of the five dominant species found in the Vologda and Volgograd (*Pinus* south) regions were destructively sampled. These trees were selected after all trees within a plot were inventoried and divided into diameter classes. They were selected proportionally to the size classes found in the forest plots. The size class distributions among the samples tress were: 0-5 cm dbh - 20%; 5-10 cm dbh - 25%; 10-15 cm dbh - 20%; 15-20 cm dbh 15%; 20-25 cm dbh - 10%; >25 cm dbh - 15%. An additional 350 trees and shrubs with a height of less than 12 m were also sampled. All trees were cut in late summer, prior to leaf fall. Trees were divided into four parts for development of the allometric equations; stem, branches, leaves, and roots.

The bole of each tree was cut into 1 m lengths (2 m for oldest trees) which were weighed in the field and a disk cut and dried (105°C) for wet/dry weight conversion. Branches from each 1 m section of stem were bundled and weighed in the field. A representative subsample was returned to the laboratory where leaves were separated from the branches and dried. Wet/dried weight conversions were applied to the field weight. Roots were sampled two ways; using small amounts of explosives placed under a stump and manual excavation. With both approaches the roots were subsampled, washed, and dried. Blasting resulted in 80% of the root mass in comparison to manual extraction. A belowground/aboveground biomass ratio of 0.21 was used to estimate the root biomass of Volgograd *Pinus sylvestris* stands, as no root weights were collected in that region.

Allometric equations were developed for the trees of interest using two equations:

$$W = aD^2H^b$$

$$W = aD^bH^c$$

where; W is kg dry weight (105°C) of the whole tree, or component of the tree (stem, branches, foliage, crown (branches + foliage), aboveground total, roots, total); D is dbh in cm; H is height in m; and a,b,c, are coefficients. For shrubs and small tress ($<$ 12 m in height) a simpler equation was used;

$$W = aH^b$$

where W is the dry weight of the aboveground total and foliage.

On each plot the heights of 10-12 trees were measured and allometric equations relating tree height to dbh developed. These plot specific height predictions were used to estimate the height of each tree, which in turn was used as one of the independent variables for the determination of biomass.

Regression analysis was conducted using the nonlinear approximation procedure (SYSTAT).

2.2 CALCULATION OF CARBON CONTENTS

The carbon content of allometrically derived living biomass was assumed to be 50% for woody fractions and 45% for foliage (Isaev *et al.*, 1993 and 1995). Dead tree biomass was assumed to be 70% of that predicted using the appropriate allometric equation, with 53% of that mass carbon. For shrubs and small tress belowground biomass was assumed to be 30% of aboveground woody phytomass (total aboveground biomass minus leaves) for *Picea* and *Juniperus* and 20% of all other taxa. No consideration was given to non-woody species.

Volume-based estimates of carbon content of forest stands involved the application of zonal and regional species phytomass/volume ratios (Isaev *et al.*, 1993 and 1995), evaluated using the forest phytomass and productivity database available in Russia (Utkin *et al.*, 1994). These ratios are constructed by calculating the weight of representative stands and then taking the average phytomass/volume ratio by stand age and dominant species. These ratios require knowledge of stand age ±5 y and the dominant tree species. From a look-up table one identifies the appropriate phytomass/volume coefficient and multiplies it by the established stand volume. These phytomass/volume ratios utilize the same carbon/dry weight percentages as was used in the allometric calculations.

2.3 COMPARISON OF NORTH AMERICAN AND RUSSIAN ALLOMETRIC EQUATIONS

To see if it is necessary to develop local allometric equations to accurately estimate forest carbon, North American-derived allometric equations were used to estimate the aboveground biomass of the 26 Vologda forest stands. The equations employed utilized parabolic volume as the independent variable and aboveground biomass as the dependent variable. Two sets of equations were employed, one of generalized regional equations and the second composed of four species specific equations for the same genera as those found in the Russian forests of interest (Tritton and Hornbeck, 1982; Siccama *et al.*, 1994). All of the equations were developed in the New England region of the United States that has a similar climate to that of Vologda. The aboveground biomass equations utilized were as follows:

USA 1 (Monteith 1979 as reported by Tritton and Hornbeck, 1982)

conifers

$$W(kg) = 1.5773 + 0.1304\ D(mm) - 1.2192\ H(m) + 0.0001774\ D^2H$$

hardwoods

$$W(kg) = 0.3167 + 0.04666\ D(mm) - 0.2082\ H(m) + 0.0002549\ D^2H$$

USA 2

Picea (Siccama *et al*,. 1994)

$$\log_{10}W(g) = 0.8219 + 0.7966\log_{10}(3.14(D(cm)/2)/2)H(cm))$$

Betula (Siccama *et al.* 1994)

$$\log_{10}W(g) = 0.0974 + 0.9615\log_{10}(3.14(D(cm)/2)/2)H(cm))$$

Populus (Monteith 1979 as reported by Tritton and Hornbeck, 1982)

$$W(kg) = 3.8124 + 0.09632\ D(mm) - 1.3154\ H(m) + 0.0002079\ D^2H$$

Pinus (Monteith 1979 as reported by Tritton and Hornbeck, 1982)

$$W(kg) = 0.5209 + 0.07434\ D(mm) - 0.5439\ H(m) + 0.0001516\ D^2H.$$

3. Results

Allometric equations developed to predict total biomass for five taxa from Vologda and aboveground biomass for one taxon for Volgograd have adjusted R^2s of > 0.97 (Table 1). Predicting the weight of some component parts is somewhat less reliable with the adjusted R^2s dipping as low as 0.77. Even estimates of root biomass were very consistent, with adjusted R^2s > 0.95 (Table 1). There was more variability in the relationship of height to aboveground and/or total biomass of the 14 taxa of shrubs and small trees examined, adjusted R^2s of 0.37-1.00 (Table 2).

Among the Vologda stands age varied from 26-155 years, while mean tree height (14-31 m) and mean tree diameter (10-33 cm) varied as well (Table 3). The relationship of tree height and tree diameter was very consistent within each plot, but showed some inter-plot variability (Table 4). Total living tree density varied from 3018 to 487 trees ha^{-1}, varying predictably with stand age and dominant species. Dead tree density varied less predictably with stand age (Table 3).

Biomass of the 26 Vologda stands averaged 101 Mg-C ha^{-1} (Table 5). Among the sites biomass varied widely as would be expected from forest stands of such a wide age-range. Dead trees and shrubs and regeneration on average accounted for about 2% of the total carbon in the stands (Table 5). Shrubs and regeneration never exceeded 3% of total forest carbon excluding soils (Table 5; plot 21) and dead standing trees never exceeded 9% of total stand carbon excluding soils (Table 5; plot 26). Sixty-nine percent of biomass was in the stems and 18% in the roots; the remaining 13% were in branches and foliage (Table 5).

Forest carbon estimated volumetrically was higher than the allometric estimate in all but four hardwood dominated plots (Table 5). The mean difference between the allometric and volume based estimates for the 26 Vologda stands was 8.2% with a 95% confidence interval of 4.2%. The range of differences between the two methods was -28% to +13%. The variation between the two estimates was correlated with dominant tree species. Allometrically derived carbon estimates were actually higher on average for the seven birch dominated plots (+1%), and lower for the other three species; spruce (-10.8%), pine (-15.0%), aspen (-9.3%).

Comparison of the biomass predicted using the North American and Russian allometric equations showed few difference for the 26 Vologda plots (Table 6). The USA 2 equations developed for congeners of the tree species present on the plots resulted in no significant difference in the biomass estimates (1.7%) from those using the Russian derived equations. The generalized North American equations did yield a small but significant difference (5.6%) when compared to the Russian equation based estimates. The differences were not uniform among the plots. The birch dominated plots had 12% more biomass using the North American species level equations (USA 2) relative to the Russian equations. In contrast the spruce dominated plots had the same biomass on average using North American and Russian equations (0.35% difference). The pine plots were 5% different and the aspen plots 4%.

The 25 Volgograd plots varied in age from 20-89 years-old, in canopy height from 9-22 m and tree density of 2280-412 trees ha^{-1} (Table 7). Total biomass averaged 65.6 Mg-C ha^{-1} (Table 8). Dead trees, shrubs and regeneration contain insignificant amounts of carbon relative to the living biomass. Comparison of allometric and volumetric carbon estimates for the 25 forest stands in Volgograd are very similar, differing by 4.4% (Table 9). A comparison among plots indicated relatively low variability (2.9% 95% CI), yet use of zonal versus regional carbon/volume coefficients made a large difference (9.5%). The more specific volume/carbon coefficients provided a result closer to the estimate generated through the allometric equations.

Table 1. Allometric relationships of four dominant Russian forest tree genera were developed using non-linear regression analysis of 890 sample trees. Diameter at breast height (D) in cm and height (H) in m were used as independent variables and weight of biomass fraction in kg dry weight as the dependent variable (Biomass = $a(D^2H)^b$ or Biomass = aD^bH^c). All data were collected during the growing season. All sample trees were collected in a latitude range of 55-62°N, except those included in Pinus (south) which was from 53 °N .

Dependent Variable by species and tree component	d range cm	n	Regression equations								
			$a(D^2H)^b$				aD^bH^c				
kg dry weight			a	b	adjusted R^2	standard error (kg)	a	b	c	adjusted R^2	standard error (kg)
Picea abies Karst.											
Stem	0.5-52	236	0.0420	0.8958	0.982	22	0.0442	1.8092	0.8618	0.982	22
Branches	0.5-52	231	0.0022	1.0087	0.925	8	0.0203	2.6514	-0.3337	0.949	7
Foliage	0.5-52	231	0.0233	0.7211	0.879	5	0.0803	2.0941	-0.3486	0.905	5
Crown (branches+foliage)	0.5-52	230	0.0105	0.9010	0.921	12	0.0699	2.4712	-0.3868	0.948	10
Aboveground	0.5-52	222	0.0533	0.8955	0.981	29	0.0842	1.9443	0.5941	0.982	28
Roots	1-32	62	0.0239	0.8408	0.924	9	0.0386	2.5377	-0.1832	0.955	7
Total	1-32	48	0.1237	0.8332	0.986	19	0.1449	1.8246	0.6231	0.988	18
Pinus sylvestris L.											
Stem	1-34	315	0.0304	0.9231	0.972	13	0.0219	1.5923	1.2943	0.979	11
Branches	1-34	315	0.0047	0.8959	0.775	5	0.0165	2.7352	-0.5104	0.864	4
Foliage	1-34	315	0.0226	0.6249	0.695	2	0.0639	2.0764	-0.5824	0.793	2
Crown (branches+foliage)	1-34	315	0.0139	0.8143	0.774	6	0.0465	2.5379	-0.5367	0.867	5
Aboveground	1-34	315	0.0410	0.9076	0.976	13	0.0374	1.7459	1.0096	0.976	13
Roots	1-32	40	0.0144	0.8569	0.976	2	0.0060	1.4615	1.4390	0.979	2
Total	1-32	40	0.1036	0.8332	0.973	15	0.0427	1.4040	1.4288	0.976	14
Pinus sylvestris L.(south)											
Stem	2-39	80	0.0218	0.9652	0.988	11	0.0101	1.6941	1.4530	0.990	10
Branches	2-39	80	0.0002	1.2298	0.921	4	0.0080	3.4932	-1.0175	0.957	3
Foliage	2-39	80	0.0043	0.8164	0.875	2	0.0329	2.4914	-0.7262	0.931	1
Crown (branches+foliage)	2-39	80	0.0010	1.1028	0.929	5	0.0224	3.1758	-0.9079	0.970	3
Aboveground	2-39	80	0.0217	0.9817	0.989	12	0.0191	1.9249	1.0613	0.989	12

Table 1 (continued). Allometric relationships of four dominant Russian forest tree genera were developed using non-linear regression analysis of 890 sample trees. Diameter at breast height (D) in cm and height (H) in m were used as independent variables and weight of biomass fraction in kg dry weight as the dependent variable (Biomass = $a(D^2H)^b$ or Biomass = aD^bH^c). All data were collected during the growing season. All sample trees were collected in a latitude range of 55-62°N, except those included in Pinus (south) which was from 53 °N .

Dependent Variable by	d range	n	Regression equations								
species and tree component	cm		$a(D^2H)^b$				aD^bH^c				
kg dry weight			a	b	adjusted R^2	standard error (kg)	a	b	c	adjusted R^2	standard error (kg)
Betula pendula Roth. & *B. pubescens* Ehrh.											
Stem	0.2-72	217	0.5621	0.6323	0.901	37	0.0038	0.9349	2.5439	0.949	27
Branches	0.2-72	216	0.0257	0.7621	0.789	11	0.0008	1.3637	2.0000	0.799	10
Foliage	0.2-72	216	0.0200	0.5887	0.813	1	0.0167	1.1625	0.5615	0.313	1
Crown (branches+foliage)	0.2-72	216	0.0358	0.7422	0.798	12	0.0018	1.3372	1.3351	0.307	11
Aboveground	0.2-72	216	0.5443	0.6527	0.889	48	0.0054	1.0221	2.3905	0.926	39
Roots	1-19	21	0.0387	0.7281	0.950	2	0.0607	2.6748	-0.5610	0.995	1
Total	1-19	21	0.0557	0.9031	0.988	5	0.0562	2.3501	0.3932	0.993	4
Populus tremula L.											
Stem	1-35	142	0.0179	0.9850	0.994	7	0.0046	1.7325	1.5526	0.995	6
Branches	1-35	142	0.0015	1.0439	0.907	4	0.0140	2.4855	-0.0675	0.911	4
Foliage	1-35	142	0.0069	0.6869	0.827	1	0.0411	1.8706	-0.3812	0.336	1
Crown (branches+foliage)	1-35	142	0.0029	0.9893	0.901	5	0.0312	2.4247	-0.2127	0.905	5
Aboveground	1-35	142	0.0208	0.9856	0.994	8	0.0102	1.8450	1.3386	0.994	8
Roots	1-12	12	0.0145	0.8749	0.977	1	0.0307	2.4427	-0.0708	0.998	0.2
Total	1-12	12	0.0968	0.8070	0.987	2	0.1462	1.9715	0.3096	0.993	1

Table 2. Allometric relationships of 12 genera of common unerstory trees and shrubs in the southern boreal forests (55-62°N) of Russia were developed using non-linear regression analysis. *Pinus* (south) is from a latitude of 53 °N. Height (h) in m was used as the independent variable and weight of biomass fraction in kg dry weight as the dependent variable in the equation, Biomass = a H^b. *Pinus, Betula* and *Populus* sample trees were from regenerating forests stands with no overstory (some of the sample trees were used in development of both forest tree and understory regressions), with all other samples collected from closed canopy forests.

Species	Biomass fraction kg dry weight	Height range m	n	a	b	adjusted R^2	standard error (kg)
Picea abies Karst.	Stem	0.8-11.5	59	0.0858	2.0326	0.936	0.3
	Branches	0.8-11.5	59	0.1352	1.4244	0.579	0.5
	Foliage	0.8-11.5	59	0.1134	1.5018	0.604	0.3
	Aboveground woody	0.8-11.5	59	0.2081	1.7756	0.839	0.7
	Aboveground total	0.8-11.5	59	0.3173	1.7011	0.810	1.1
Pinus sylvestris L.	Stem	2.0-10.0	53	0.0866	1.7812	0.586	1.0
	Aboveground woody	2.0-10.0	53	0.1410	1.5935	0.521	1.2
	Aboveground total	2.0-10.0	53	0.2169	1.4172	0.449	1.3
	Roots	2.2-7.1	14	0.0030	2.6807	0.542	0.2
	Total	2.2-7.1	14	0.0802	1.9142	0.435	1.3
Pinus sylvestris L.(south)	Stem	2.6-7.1	10	0.2161	1.3058	0.698	0.5
	Aboveground woody	2.6-7.1	10	0.3735	1.0801	0.581	0.6
	Aboveground total	2.6-7.1	10	0.6448	0.8595	0.430	0.9
Betula pendula Roth. & *Betula pubescens* Ehrh.	Stem	1.5-11.9	99	0.0264	2.2684	0.804	0.5
	Aboveground woody	1.5-11.9	98	0.0388	2.1373	0.754	0.7
	Aboveground total	1.5-11.9	98	0.0489	2.0529	0.788	0.8
	Roots	3.1-10.8	9	0.0356	1.4149	0.205	0.4
	Total	3.1-10.8	9	0.1561	1.6129	0.377	0.7
Populus tremula L.	Stem	2.7-9.0	40	0.0135	2.5486	0.659	0.6
	Aboveground woody	2.7-9.0	40	0.0204	2.4008	0.561	0.9
	Aboveground total	2.7-9.0	40	0.0264	2.2978	0.521	0.9
	Roots	2.7-8.1	6	0.0747	1.2262	0.309	0.5
	Total	2.7-8.1	6	0.3162	1.2762	0.335	2.2
Corylus avellana Mill.	Aboveground woody	0.2-4.5	31	0.0665	1.8775	0.911	0.1
	Foliage	0.2-4.5	31	0.0114	1.3714	0.888	0.01
	Aboveground total	0.2-4.5	31	0.0768	1.8329	0.920	0.1
Lonicera xylosteum L.	Aboveground woody	0.2-1.3	11	0.0544	1.9326	0.929	0.01
	Foliage	0.2-1.3	11	0.0053	2.0581	0.883	0.001
	Aboveground total	0.2-1.3	11	0.0597	1.9419	0.930	0.01

Table 2 (continued). Allometric relationships of 12 genera of common unerstory trees and shrubs in the southern boreal forests (55-62°N) of Russia were developed using non-linear regression analysis. *Pinus* (south) is from a latitude of 53 °N. Height (h) in m was used as the independent variable and weight of biomass fraction in kg dry weight as the dependent variable in the equation, Biomass = a H^b. *Pinus*, *Betula* and *Populus* sample trees were from regenerating forests stands with no overstory (some of the sample trees were used in development of both forest tree and understory regressions), with all other samples collected from closed canopy forests.

Species	Biomass fraction kg dry weight	Height range m	n	a	b	adjusted R^2	standard error (kg)
Rhamnus sp.	Aboveground woody	0.1-3.2	9	0.0137	1.4805	0.983	0.003
	Foliage	0.1-3.2	9	0.0020	1.2856	0.923	0.001
	Aboveground total	0.1-3.2	9	0.0157	1.4600	0.983	0.003
Euonymus verrucosa Scop.	Aboveground woody	0.1-1.3	8	0.0179	2.8026	0.951	0.003
	Foliage	0.1-1.3	8	0.0014	1.0499	0.691	0.000
	Aboveground total	0.1-1.3	8	0.0195	2.6069	0.954	0.003
Viburnum opulus L.	Aboveground woody	0.2-2.0	5	0.0240	2.7603	1.000	0.000
	Foliage	0.2-2.0	5	0.0048	1.9840	1.000	0.000
	Aboveground total	0.2-2.0	5	0.0294	2.6318	1.000	0.000
Sorbus aucuparia L.	Aboveground woody	0.2-6.7	13	0.0521	1.6344	0.889	0.1
	Foliage	0.2-6.7	13	0.0065	1.6122	0.910	0.01
	Aboveground total	0.2-6.7	13	0.0586	1.6318	0.911	0.1
Padus sp.	Aboveground woody	2.1-8.9	14	0.0145	2.7835	0.832	0.5
	Foliage	2.1-8.9	14	0.0035	1.9469	0.707	0.03
	Aboveground total	2.1-8.9	14	0.0168	2.7304	0.829	0.5
Juniperus excelsa M.B.	Aboveground woody	0.8-1.4	6	0.2874	1.1713	0.869	0.03
	Foliage	0.8-1.4	6	0.1442	0.7049	0.919	0.01
	Aboveground total	0.8-1.4	6	0.4316	1.0244	0.890	0.04

Table 3. Stand characteristics of 26 forest plots in the Vologda region of Russia. Stand age represents the mean age of the dominant canopy trees. Site index and tree volume were determined using standard Russian forestry methods based on: dominant species, stand age, mean height and mean diameter. Minimum tree size inventoried was 6 cm in 15 plots, in the other 11 plots it varied from 2-10 cm.

Plot #	Stand age yr	Dominant tree species	Plot size ha	Mean tree height m	Mean tree diameter cm	Site index	Tree volume m^3 ha^{-1}	Tree density trees ha^{-1}					
								Picea	*Pinus*	*Betula*	*Populus*	total living	total dead
1	26	aspen	0.18	13.8	10	1a	112	0	0	183	1828	2011	0
2	35	aspen	0.11	16	12	1	246	0	0	1045	1973	3018	327
3	40	birch	0.18	19	14	1a	275	0	0	1250	567	1817	183
4	40	birch	0.25	17	14	2	158	160	56	884	248	1348	0
5	43	birch	0.2	19.3	14	1	224	80	0	1140	275	1495	65
6	45	birch	0.184	24	18	1a	286	0	0	1098	158	1255	27
7	50	birch	0.2	22	20	1	402	0	0	1015	410	1425	65
8	50	spruce	0.14	23.5	13	3	279	1571	150	0	0	1721	43
9	50	birch	0.263	24	20	1	403	0	0	844	255	1099	8
10	60	pine	0.28	23	20	1	398	214	725	229	211	1379	129
11	60	aspen	0.275	27	-	1	454	633	0	251	749	1633	33
12	60	spruce	0.264	20	21	1	323	777	11	19	110	917	4
13	62	birch	0.25	17	15	3	184	100	0	1204	0	1304	84
14	65	spruce	0.33	25	23	2	321	645	30	52	42	770	18
15	65	spruce	0.225	-	-	2	267	889	4	129	53	1076	22
16	65	pine	0.5	26	24	1	276	0	468	102	0	570	16
17	70	spruce	0.23	18	18	3	230	996	30	0	0	1026	0
18	72	pine	0.2	20	18	2	311	10	1235	55	0	1300	220
19	75	spruce	0.33	22.3	21	2	359	624	133	109	6	873	12
20	77	aspen	0.7	31.4	33	1a	493	69	0	69	350	487	14
21	80	pine	0.5	14.5	18	4	149	186	466	268	0	920	0
22	87	spruce	0.35	22	23	3	371	654	0	203	0	857	46
23	107	spruce	0.54	21	26	3	300	281	0	115	102	498	9
24	115	pine	0.4	15.5	21	5	145	83	503	0	0	585	13
25	130	spruce	0.325	24.8	24	3	451	631	58	175	55	920	62
26	155	spruce	0.25	19.4	18	2	221.5	808	24	152	0	984	244

Table 4. Relationships of height (h) in m and diameter at breast height (D) in cm of *Picea abies* trees in five sample plots in the Vologda region of Russia (60°N).

Diameter range (cm)	plot number	r	Regression equations $h = a\,d + b\,d^2$			$h = a\,d^b$		
			a	b	adjusted R^2	a	b	adjusted R^2
8-41	12	24	1.20977	-0.01443	0.996	3.09657	0.58813	0.995
8-46	17	23	1.10051	-0.01292	0.990	2.73563	0.59225	0.986
12-43	22	26	1.32553	-0.01736	0.996	4.90677	0.45528	0.993
8-48	23	23	1.28463	-0.01707	0.996	6.08259	0.37203	0.996
10-43	25	25	1.34669	-0.01561	0.996	3.58145	0.57362	0.995

Table 5. Biomass and carbon content of the vegetation of the 26 forest stands in the Vologda region of Russia. Allometrically derived estimates of stand carbon contents were compared with those determined using regional carbon/volume coefficients. Percentage differences between allometric and volume derived living tree carbon were calculated using the following equation: (allometric carbon - volume carbon) / allometric carbon.

		Allometric Approach													Volume Approach		
		biomass (Mg dry weight ha^{-1})							carbon (Mg C ha^{-1})								
Plot #	Age yr	stems	branches	roots	foliage	total in trees	shrubs and regeneration	stand total	living trees	dead trees	total in trees	shrubs and regeneration	stand total	C/volume coefficient Mg-C m^{-3}	carbon in living trees Mg-C ha^{-1}	Allometric vs volume carbon (%)
1	26	52	7	17	2	78	0	78	39	0	39	0	39	0.442	50	-27.9
2	35	134	17	32	4	188	0.7	189	94	3.5	97	0.3	98	0.416	102	-9.1
3	40	154	21	30	4	209	2.5	211	104	4	108	1.2	109	0.392	108	-3.4
4	40	91	12	18	3	123	0.1	123	62	0	62	0.1	62	0.392	62	-0.7
5	43	136	19	25	4	184	0.8	185	92	0.9	93	0.4	93	0.392	88	4.4
6	45	173	25	31	4	233	0	233	116	0.8	117	0	117	0.392	112	3.6
7	50	202	29	42	5	278	0	278	139	1.3	140	0	140	0.366	147	-6.1
8	50	110	15	36	12	173	0.4	173	86	0.6	86	0.2	87	0.334	93	-8.8
9	50	202	31	41	5	278	0	278	139	0.6	139	0	139	0.366	148	-6.3
10	60	179	24	44	8	254	4	258	127	2.1	129	2	131	0.346	138	-8.7
11	60	220	32	62	11	325	1.2	326	162	0.4	162	0.6	163	0.309	140	13.4
12	60	132	21	43	13	208	0.4	209	103	1.2	105	0.2	105	0.353	114	-10.2
13	62	121	17	20	4	160	0.2	161	80	2.7	83	0.1	83	0.367	68	15.5
14	65	134	21	42	12	208	0	208	103	0.6	104	0	104	0.353	113	-9.5
15	65	120	18	37	11	186	4.4	191	93	1.6	94	2.2	96	0.353	94	-1.7
16	65	116	14	27	5	162	3.6	165	81	0.6	81	1.8	83	0.346	96	-18.6
17	70	95	14	32	10	152	0.8	153	75	0	75	0.4	76	0.353	81	-7.7
18	72	128	15	33	7	183	2.7	185	91	2.4	93	1.3	95	0.346	108	-18.3
19	75	152	22	45	12	232	0.2	232	115	0.3	116	0.1	116	0.353	127	-9.7
20	77	213	33	54	5	305	0.4	305	152	1.3	153	0.2	154	0.35	173	-13.6
21	80	71	9	18	4	102	3.2	105	51	0	51	1.6	52	0.346	52	-1.7
22	87	160	25	48	14	246	0.2	247	123	3.3	126	0.1	126	0.369	137	-11.9
23	107	118	19	33	7	177	1.4	179	88	1	89	0.7	90	0.369	111	-25.5
24	115	54	7	15	3	79	3.6	82	39	0.6	40	1.7	42	0.346	50	-27.7
25	130	185	29	54	14	282	1.8	284	140	1.9	142	0.9	143	0.369	167	-18.8
26	155	102	15	31	9	157	0	157	78	7.4	85	0	85	0.369	82	-5
Mean	69	137	20	35	7	198	1.3	200	99	1.5	100	0.6	101	0.365	106	-8.2
SD	30	46	7	12	4	65	1.5	65	33	1.7	33	0.7	33		35	10.9
95% CI	12	18	3	5	2	25	0.6	25	13	0.6	13	0.3	13		13	4.2

Table 6. Aboveground mass of trees of the 26 forest stands in the Vologda regions of Russia, estimated using Russian (RUS) and two American (US1 and US2) sets of regression equations. Percentage differences between estimations were calculated using the equations (RUS mass - US mass) / RUS mass for RUS vs USA1 and RUS vs USA2 and (USA1 mass - USA2 mass) / USA1 mass for USA1 vs USA2.

Plot #	Age (yr)	Dominant tree species	Aboveground mass of trees Mg-dry weight ha^{-1}			Percentage difference in estimations (%)		
			RUS	USA1	USA2	RUS vs USA1	RUS vs USA2	USA1 vs USA2
1	26	aspen	61	80	57	-30.4	6.7	28.4
2	35	aspen	156	168	145	-7.8	7.3	14.0
3	40	birch	178	187	187	-4.5	-4.7	-0.2
4	40	birch	106	99	105	6.6	0.3	-6.7
5	43	birch	159	152	166	4.2	-4.4	-9.0
6	45	birch	202	220	239	-9.1	-18.6	-8.7
7	50	birch	236	282	274	-19.4	-16.3	2.6
8	50	spruce	136	120	136	12.2	0.4	-13.4
9	50	birch	238	305	312	-28.6	-31.5	-2.3
10	60	pine	210	237	222	-12.7	-5.5	6.4
11	60	aspen	263	274	219	-4.2	16.9	20.2
12	60	spruce	165	161	151	2.4	8.5	6.2
13	62	birch	141	129	150	8.2	-6.9	-16.4
14	65	spruce	167	174	164	-4.3	1.8	5.9
15	65	spruce	149	143	152	4.0	-1.7	-5.9
16	65	pine	134	146	132	-8.8	1.9	9.8
17	70	spruce	120	112	113	6.3	5.6	-0.8
18	72	pine	150	149	132	0.2	12.0	11.8
19	75	spruce	187	186	185	0.5	1.0	0.6
20	77	aspen	251	351	291	-39.7	-15.7	17.2
21	80	pine	84	80	76	4.7	9.6	5.1
22	87	spruce	199	197	196	1.0	1.1	0.1
23	107	spruce	144	172	160	-19.0	-10.7	7.0
24	115	pine	64	68	59	-6.0	7.9	13.1
25	130	spruce	228	242	238	-6.0	-4.5	1.4
26	155	spruce	126	121	132	3.8	-5.0	-9.1
Mean			164	175	169	-5.6	-1.7	3.0
SD			61	68	66	12.8	10.7	10.7
95% CI			263	28	26	4.9	4.1	4.1

Table 7. Stand characteristics of 25 pine (*Pinus sylvestris*) forest plots in the Volgograd region of Russia. Stand age represents the mean age of the dominant canopy trees. Site index and tree volume were determined using standard Russian forestry methods based on: dominant species, stand age, mean height and mean diameter. Minimum tree size inventoried was 6 cm in 8 plots, in the other 17 plots it varied from 2-16 cm.

Plot #	Stand age yr	Plot size ha	Mean tree height m	Mean tree diameter cm	Site index	Tree volume $m^3 ha^{-1}$	Tree density trees ha^{-1}	
							growing	dead
1	20	0.2	9.2	10.4	1	79	2010	0
2	22	0.1	9.2	10.6	1	89	2110	0
3	26	0.2	11.3	8.8	1	68	1640	50
4	31	0.25	10	12	3	66	988	0
5	31	0.125	13.4	14.2	1	219	1992	24
6	31	0.37	12.3	17.6	2	111	686	0
7	32	0.24	12.8	20.9	1	262	1100	75
8	32	0.15	11	14	2	186	1987	7
9	32	0.12	11.5	15	2	92	858	0
10	32	0.37	13	18.9	1	149	786	32
11	33	0.45	14.3	14.6	1	160	1280	47
12	33	0.2	14	15.4	1	184	1350	15
13	41	0.15	13	14	2	239	2280	47
14	42	0.1	16.9	13.9	2	294	2260	510
15	55	0.25	16.1	22	2	245	812	4
16	62	0.4	17	21.2	3	259	865	23
17	66	0.5	22	27.9	0	257	412	0
18	68	0.2	15.5	18	2	230	1400	0
19	74	0.4	25	29	1	530	705	3
20	77	0.32	19.4	21.6	3	295	788	0
21	78	0.5	22	24	2	494	1098	12
22	82	0.4	16.5	21.4	4	216	773	45
23	87	0.48	20.3	28.7	3	308	490	0
24	88	0.5	14.8	24.3	4	147	412	2
25	89	0.4	21.9	24.2	3	444	930	10

Table 8. Allometrically derived biomass and carbon content of the vegetation of the 25 pine forest stands in the Volgograd region of Russia.

Plot #	Age	Biomass Mg -dry weight ha^{-1}							Carbon Mg-C ha^{-1}				
	yr	stems	branches	roots	foliage	total in trees	shrubs and regeneration	stand total	living trees	dead trees	total in trees	shrubs and regeneration	stand total
1	20	35	2	8	2	47	0	47	23	0	23	0	23
2	22	39	2	9	3	52	0	52	26	0	26	0	26
3	26	27	2	6	2	36	0	36	18	0	18	0	18
4	31	25	2	6	2	33	0	33	17	0	17	0	17
5	31	89	7	20	5	121	0	121	60	0	61	0	61
6	31	42	4	10	2	58	0	58	29	0	29	0	29
7	32	100	9	23	5	137	0	137	68	0	69	0	69
8	32	72	5	16	4	98	0	98	49	0	49	0	49
9	32	38	3	9	2	51	0	51	26	0	26	0	26
10	32	59	5	14	3	82	0	82	41	0	41	0	41
11	33	64	5	14	4	87	1	87	43	0	44	0	44
12	33	77	6	17	4	105	0	105	52	0	52	0	52
13	41	99	8	23	6	135	0	135	67	0	68	0	68
14	42	125	11	28	7	171	0	171	85	4	89	0	89
15	55	101	10	23	5	139	0	139	70	0	70	0	70
16	62	107	11	25	5	148	0	148	74	0	74	0	74
17	66	109	14	26	5	154	0	154	77	0	77	0	77
18	68	119	11	27	6	163	0	163	81	0	81	0	81
19	74	232	31	55	10	328	0	328	163	0	163	0	163
20	77	126	14	29	6	176	0	176	87	0	87	0	87
21	78	216	25	51	10	302	0	302	151	0	151	0	151
22	82	89	9	21	5	123	3	126	62	1	63	1	64
23	87	128	16	30	6	181	0	181	90	0	90	0	90
24	88	59	6	14	3	82	0	82	41	0	41	0	41
25	89	190	23	45	9	266	0	266	133	0	133	0	133
Mean	51	95	10	22	5	131	0	131	65	0	66	0	66
SD	24	55	8	13	2	78	1	78	39	1	39	0	39
95% CI	9	21	3	5	1	30	0	30	15	0	15	0	15

Table 9. Stand carbon content of the 26 pine forest stands in the Volgograd region of Russia. Allometrically derived estimates of stand carbon contents were compared with those determined using zonal and regional carbon/volume coefficients. Percentage differences between allometric and volume derived living tree carbon were calculated using the following equation: (allometric carbon - volume carbon) / allometric carbon.

Plot #	Age	Allometric	Volume Approach					
	yr	Approach	*zonal*			*regional*		
		carbon in living trees Mg-C ha^{-1}	C/volume coefficient Mg-C m^{-3}	carbon in living trees Mg-C ha^{-1}	allometric vs volume carbon %	C/volume coefficient Mg-C m^{-3}	carbon in living trees Mg-C ha^{-1}	allometric vs volume carbon %
1	20	23	0.348	28	-4.3	0.296	23	-1.0
2	22	26	0.348	31	-4.8	0.296	26	-1.2
3	26	18	0.348	24	-5.9	0.296	20	-13.3
4	31	17	0.348	23	-6.4	0.296	20	-18.5
5	31	60	0.348	76	-15.7	0.296	65	-7.5
6	31	29	0.348	39	-10.0	0.296	33	-15.0
7	32	68	0.348	91	-22.5	0.296	78	-13.4
8	32	49	0.348	65	-15.7	0.296	55	-12.7
9	32	26	0.348	32	-6.5	0.296	27	-7.2
10	32	41	0.348	52	-11.1	0.296	44	-8.6
11	33	43	0.348	56	-12.4	0.296	48	-9.9
12	33	52	0.348	64	-11.9	0.296	55	-4.7
13	41	67	0.334	80	-12.5	0.303	72	-7.4
14	42	85	0.334	98	-13.1	0.303	89	-4.5
15	55	70	0.334	82	-12.4	0.303	74	-6.8
16	62	74	0.353	91	-17.8	0.300	78	-5.6
17	66	77	0.353	91	-14.2	0.300	77	-0.7
18	68	81	0.353	81	0.1	0.300	69	15.1
19	74	163	0.353	187	-23.7	0.300	159	2.6
20	77	87	0.353	104	-16.6	0.300	89	-1.2
21	78	151	0.353	174	-23.6	0.300	148	1.7
22	82	62	0.369	80	-18.1	0.282	61	1.2
23	87	90	0.369	114	-23.6	0.282	87	3.6
24	88	41	0.369	54	-13.7	0.282	42	-2.0
25	89	133	0.369	164	-31.4	0.282	125	5.6
Mean	51	65	0.351	79	-13.9	0.296	67	-4.4
SD	24	39		45	7.3		37	7.5
95% CI	9	15		17	2.8		14	2.9

4. Discussion

There is no comprehensive inventory of applicable forest allometric or biomass data, but where such data exist they can be profitably exploited. If forestry mitigation projects are adopted as a prescribed tool under the Framework Convention on Climate Change, it would be highly profitable to undertake a systematic inventory of the relevant allometric equations and weight data available for the forests of the world.

The consistent form and high degree of constancy among the allometric equations developed indicates that allometric approaches to estimating tree weight are straight forward and effective. The very high adjusted R^2s are comparable to those found for species where the equations have been demonstrated to accurately predict forest biomass (Siccama *et al.*, 1994). The equations that were developed as part of this study are consistent in all respects with those reported for North American species.

The forest stands studied in Vologda and Volgograd represented a good cross section of the regions' forests. The variation in average tree size and density provided a very robust comparison of the volumetric versus allometric approaches to estimating forest carbon. The five to ten-fold difference in carbon among stands within the two regions is a reminder that project based carbon estimates require reliable stand information. Regional stand averages have a high degree of uncertainty due to the natural variation in growing conditions, disturbance histories and stochastic factors such as seed sources and pest outbreaks. Generalized approaches to calculating changes in forest management impacts on carbon storage are of limited use if not tied to stand specific data.

The variation between the two carbon estimates was largely related to species composition within the stands. If one project involves birch stands, for which there was no net measurable difference (1%) between estimates using the two methods, and another involves pine stands, for which there was a rather large difference (15%), then the absolute accuracy will be considerably different depending on the method employed. For site specific forestry mitigation projects it is important to know tree heights and species composition and size distributions for the project forests. Further confirmation of the dry weight/carbon ratio would be very useful. Such additional data would allow more accurate estimates of the uncertainty that this conversion introduces.

As trees grow the bole to branch ratio does not vary consistently among species. This shifting ratio can lead to errors in volume based carbon estimates. Further complicating the consistency of the volume estimates among stands is the use of a single phytomass/volume conversion factor for estimating the carbon content of each stand. This single factor approach means differences in species composition within stands are not reflected in the carbon estimates, increasing the inaccuracy of this approach.

Does it matter whether an allometric or volumetric approach is employed when calculating the carbon that might be creditable to a forestry offset project? The results of our study indicate that it makes a moderate difference in some cases. The volumetric approach to estimating carbon proved a viable method, though the degree of consistency differed among species. The volumetric approach utilized in this study employs age specific conversion factors which greatly reduce the inaccuracy of the volumetric approach. If a single average conversion factor were employed it would add an additional 5-10 % inaccuracy to the carbon estimates.

We would recommend allometric equations as the preferred method of determining project level carbon. When volumetric approaches are employed there needs to be some form of discounting applied, as it is not possible to determine *a priori* the direction of any inaccuracies. This discounting need not be large, 5-10%, but it would help to protect against exploitation of the added uncertainty volumetric approaches introduce.

The North American derived allometric equations proved reliable, but were subject to species level variations in consistency. Until we develop more case studies like the one reported here, it will be very difficult to design a simple and fair set of rules for crediting sequestered carbon in forestry projects. We need a set of rules that meet the goal of insuring no net over reporting of carbon sequestered, while not imposing overly harsh penalties for uncertainty. The differences in carbon estimated using the methods reported here are not great ($\geq$15%). These results are very supportive of the feasibility of developing robust and universal rules for cost effective forestry mitigation projects.

5. Conclusions

- Volumetrically and allometrically derived carbon estimates of 51 Russian Forests were very similar.
- The error associated with volumetrically derived carbon estimates varied with species composition. For some species there was no apparent difference between volumetric and allometric estimates, but for others it averaged 15%. The systematic nature of potential errors has to be considered.
- The results suggest that it is appropriate to utilize allometric equations developed for one species for estimating the carbon content of another species growing in a different region, as long as they are for phenotypically similar.
- Both volumetric and allometeric approaches for estimating forest carbon are useful. For regional based studies of forest carbon volumetric approaches are preferred, because they are easy to use. For stand based estimates of forest carbon allometric approaches provide greater reliability.
- Results were very similar across the two Russian regions examined, suggesting the broad applicability of our results.

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