Coarse woody debris in forest regions of Russia

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Abstract: To assess regional stores of coarse woody debris (CWD) in seven major forest regions of Russia, we combined data collected as part of the routine forest inventory with measurements in 1044 sample plots and the results of density sampling of 922 dead trees. The stores of CWD in the western part of Russia (St. Petersburg, Central, Khanty-Mansi, and Novosibirsk regions) were on average lower (14–20 m^3/ha or 4.0–5.8 Mg/ha) than in the East Siberian and Far Eastern regions (40–51 m^3/ha or 11.0–14.4 Mg/ha). The difference in CWD stores was particularly large between young forests in two western regions (2.4 Mg/ha in St. Petersburg and 3.4 Mg/ha in the Central region) and in the east (20.4–24.4 Mg/ha). This difference is associated with the prevailing disturbance type: clear-cut harvest in western Russia and natural disturbances in the east. Analysis of variance in CWD stores indicates that region, dominant species, forest age group, productivity class, and interactions of these factors explain 87–88% of the total variance and the strongest effects are for age group and region. Lower stores of CWD within the intensively managed forest regions suggest that further expansion of forest use in many regions of Russia may reduce regional stores of CWD and carbon.

Résumé : Les auteurs ont combiné des données collectées dans le cadre de l'inventaire forestier régulier avec des mesures prises dans 1044 places-échantillons et les résultats d'un échantillonnage par densité de 922 arbres morts pour évaluer les stocks régionaux de débris ligneux grossiers dans sept régions forestières d'importance en Russie. Les stocks de débris ligneux grossiers étaient en moyenne plus faibles (14–20 m^3/ha ou 4,0–5,8 Mg/ha) dans la partie ouest de la Russie (les régions de Saint-Petersbourg, Centrale, de Khanty-Mansi et de Novosibirsk) que dans les régions de la Sibérie orientale et de l'extrême Est (40–51 m^3/ha ou 11,0–14,4 Mg/ha). La différence dans les stocks de débris ligneux grossiers était particulièrement importante entre les jeunes forêts de deux régions occidentales (2,4 Mg/ha dans la région de Saint-Petersbourg et 3,4 Mg/ha dans la région Centrale) et celles des régions orientales (20,4–24,4 Mg/ha). Cette différence est associée aux principaux types de perturbations : la coupe à blanc dans l'ouest de la Russie et les perturbations naturelles dans l'est. L'analyse de variance des stocks de débris ligneux grossiers montre que la région, les espèces dominantes, le groupe d'âge des forêts, la classe de productivité et les interactions entre ces facteurs expliquent 87–88% de la variation totale et que les facteurs les plus importants sont le groupe d'âge et la région. Le fait que les stocks de débris ligneux grossiers soient plus faibles dans les régions où la forêt est sous aménagement intensif indique qu'une utilisation plus intensive de la forêt dans plusieurs régions de la Russie risque d'entraîner une réduction des stocks régionaux de débris ligneux grossiers et de carbone.

[Traduit par la Rédaction]

Introduction

Studies of dead wood, including logs and snags, increased dramatically in the last two decades following the recognition of the importance of coarse woody debris (CWD) in ecosystem functioning (Harmon et al. 1986). Recent studies in many boreal and temperate regions have examined the role of CWD in maintaining biodiversity (e.g., Ohlson et al. 1997; Esseen et al. 1997), measured decomposition rates of many important tree species (e.g., Frangi et al. 1997; Naesset 1999), evaluated the role of CWD in carbon and nutrient cycles (Hyvonen et al. 2000; Takahasi et al. 2000; Krankina et al. 1999) and analyzed the amount, structure, and dynamics of dead wood in natural and managed forests (e.g., Green and Peterken 1997; Siitonen et al. 2000). This improved understanding of the long-term effects of forest management on the amount and characteristics of CWD has lead to some changes in management operations with the intent of maintaining higher stores of CWD and promoting CWD structure similar to that found in unmanaged forests (e.g., Franklin et al. 1997; Graham et al. 1994).

Advances in CWD research and a growing appreciation of its role in carbon cycling made CWD an essential component in studies of carbon cycling and development of measures to address the global climate change (IPCC 2000). To measure the effect of land-use change and forestry on carbon stores as required by the Kyoto protocol (IPCC 2000), it is necessary to quantify the stores of carbon in CWD at regional and national scales. This task is likely to present a major challenge because comprehensive large-scale assessments of CWD remain very rare (Fridman and Walheim

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2000). A recent review of available data on CWD stores and decomposition rates indicates that global stores of carbon in CWD may range between 114 and 157 Pg, depending on estimation procedures (Harmon et al. 2001). Reducing the uncertainty in estimates of CWD can substantially improve the accuracy of regional, national, and global estimates of carbon pools and fluxes in terrestrial ecosystems. A better understanding of CWD distribution among forest types and regions may also influence the selection of management strategies to increase carbon stores on forest lands.

CWD stores in forest regions are difficult to assess because they vary significantly over succession and do not necessarily parallel the dynamics of live biomass. The amount of CWD is strongly influenced by disturbance (natural and (or) anthropogenic) and characteristics of the previous generation of trees on a given site (Harmon et al. 1986; Clark et al. 1998). Published studies of CWD in several major forest regions focused on successional changes of CWD within certain forest types (e.g., Delong and Kessler 2000; Spies et al. 1988; Clark et al. 1998; Spetich et al. 1999) and on the effect of different types of forest management on CWD amount and composition (Harmon et al. 1990; Krankina and Harmon 1995; Green and Peterken 1997; Linder and Ostlund 1998; Siitonen et al. 2000). However, these results do not easily lend themselves to extrapolation across the entire mosaic of forest landscapes in a region, because the amount and distribution of CWD is controlled by complex interactions between disturbance history, structural attributes and decomposition rates of different trees, site productivity, and other factors. So far, the only national-scale inventory of CWD based on systematic sampling has been performed in Sweden (Fridman and Walheim 2000).

Recent CWD studies in Russia examined primarily the western part of the country. Published results indicate that the store of CWD in northwestern Russia ranges from 1.7–2.4 Mg/ha in young forest stands, to 5.9–7.0 Mg/ha in middle-aged, and to 9.3–11.1 Mg/ha in mature and older forests (Krankina et al. 1995). A model based on tree mortality inputs and decomposition rates projected higher stores of CWD (14–42 Mg/ha in mature forests) for the St. Petersburg region (Tarasov 1999). Measurements in old-growth spruce forests found a wide range of CWD stores from 6.6 to 102 Mg/ha (Shorohova 2000). These results have yet to be incorporated into large-scale assessments of carbon stores in Russian forests. Past national assessments either ignored CWD (Kobak 1988; Melillo et al. 1988; Isaev et al. 1993) or estimated it as a constant proportion relative to live biomass (Kolchugina and Vinson 1993; Krankina and Dixon 1994) or calculated it from growth tables using assumed decomposition parameters (Alexeyev and Birdsey 1998). These methods were applied because the data needed to address the subject more adequately were lacking. The uncertainty in existing estimates of carbon stores in CWD and litter has been identified as one of the major sources of discrepancies in the assessments of carbon pools and fluxes in Russian forests (Alexeyev and Birdsey 1998; Moiseev et al. 2000).

Given the paucity of field measurements of CWD in Russia, it is critical to use existing data to the fullest extent possible and to develop methods of estimation based on other more readily available characteristics of forest stands, such as live wood volume, tree species composition, and age (Krankina et al. 1998). The Russian forest inventory system collects a wealth of stand-level data on forest lands including some information on CWD volume (Kukuev et al. 1997). Although these data provide only a partial measurement of CWD, it is a valuable data resource that covers a large proportion of the entire forest area of Russia and can provide a basis for regional estimates of CWD. This study used stand-level databases and regional summaries of forest inventory data to estimate the stores of CWD in several major forest regions of Russia and to examine the variation of CWD stores depending on the region, forest age, dominant species, and site productivity. The estimation methods that were developed can be applied to forest inventories in other regions of the Russian Federation.

Methods

General approach

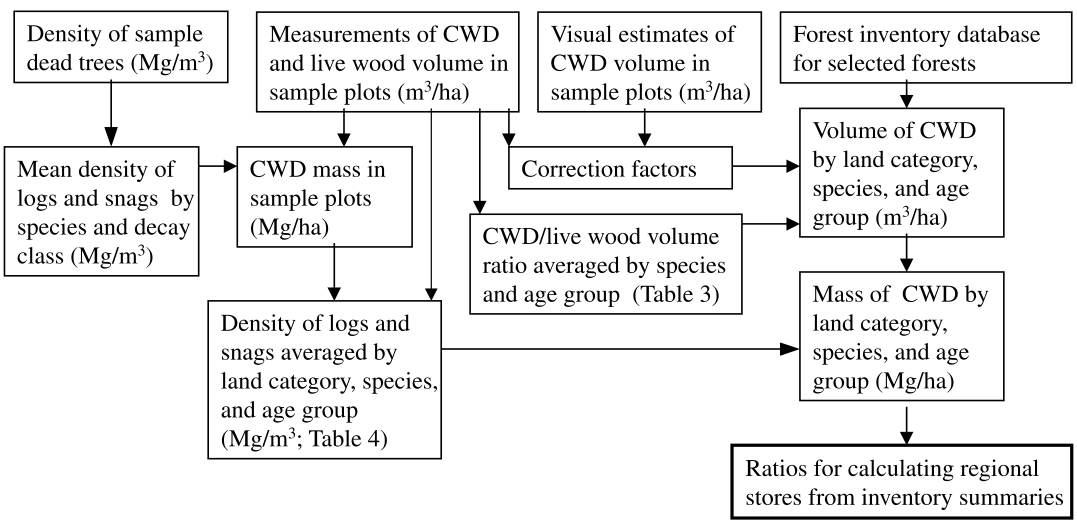
Methods and techniques for estimating CWD stores were designed to complement the existing system of forest inventory in Russia. Volume and mass of CWD was estimated for seven regions representing the variety of natural conditions and management history across the forest zone of Russia (Fig. 1). The availability of recent forest inventory data constrained the selection of regions (Kukuev et al. 1997). Regional stores of CWD were estimated from regional summaries of forest inventories using a set of ratios and means. To derive them a system of data analysis was developed (Fig. 2) that integrated three different types of field data: (*i*) measurements of the bulk density of CWD on sample trees (Table 1); (*ii*) CWD and live tree inventories in sample plots; and (*iii*) primary (stand-level) forest inventory data for selected forests in each region (Table 2).

Sample trees

The bulk density of wood and bark was measured for 922 sample trees representing major tree species in all the regions examined (Table 1). Sample trees were selected from five decay classes that covered all stages of decomposition from nearly sound wood (decay class 1) to soft and friable material (decay class 5). The visual characteristics of decomposition classes (e.g., extent of bark loss, moss cover) were recorded to facilitate the identification of decomposition classes during CWD inventory in plots. Samples were taken from four cross sections 2–5 cm thick located systematically along the length of each log or snag examined. The first cross section was taken at 1.37 m from the root collar, the last was taken as close as possible to the top, and the remaining two cross sections were located to maintain equal distance between all cross sections. The volume of wood and bark in each cross section was calculated from appropriate diameter and thickness measurements. For each cross section, the density of wood and bark was computed separately as dry mass divided by green (i.e., fresh) volume. The mass of each sampled log or snag was calculated as a weighted mean based on sample densities and wood and bark volumes in each section (Krankina and Harmon 1995). The mean density of each sample tree was calculated as a ratio of its total mass to volume. The sample trees were then grouped by species and decay class within each region, and mean densities were calculated for each grouping. These mean

Fig. 1. Map of forest regions where CWD stores were estimated: (1) St. Petersburg oblast; (2) Central region (see footnote to Table 1 for complete list of administrative units); (3) Khanty-Mansi okrug; (4) Novosibirsk oblast; (5) Krasnoyarsk krai; (6) Irkutsk oblast; (7) Khabarovsk krai.

Fig. 2. Data and calculation flow chart for generating variables to be used for estimation of CWD stores from regional summaries of forest inventories.



densities were used to compute masses of each CWD piece recorded in sample plots (Fig. 2).

Sample plots

CWD was measured in 1044 sample plots ranging in size from 0.1 to 1.0 ha. These plots represented the major dominant tree species and different successional stages (recently disturbed forests and young to old-growth forest stands) in all seven regions examined (Table 1). We used existing permanent plots installed for various research projects, training plots set up by forest inventory crews, and temporary plots set up by the authors in forest stand categories that remained underrepresented by available plots. Dead wood in plots was inventoried using the same five decay classes, which were defined by descriptions and measurements of sample trees. Measurements in plots included the end diameters, the middle diameter, and length of each piece of dead wood >10 cm in diameter and >1 m in length. All forms of CWD were inventoried including snags (standing dead), logs (dead and downed), and stumps (cut by harvest). The mass of each piece was calculated by multiplying the computed volume by the average bulk density of CWD for a given species and decay class. A description of the decay class system, CWD inventory methods, and results of plot measurements in northwestern Russia have been published elsewhere (Krankina and Harmon 1995; Harmon and Sexton 1996; Krankina et al. 1999).

Plot measurements were grouped by dominant tree species and age of live trees. Plots in recently disturbed forest stands including clearcuts and windthrow areas were examined sep-

Table 1. Field data overview: sampling of CWD density and inventory of sample plots.

		CWD density		CWD and live wood volume inventory	
Region	Administrative units	Species	No. of sample trees	Age group	No. of sample plots[a]
Northwest	St. Petersburg oblast	*Pinus sylvestris*	55	Young	43
		Picea abies	30	Middle age	211
		Betula pendula	28	Mature and older	125
		Populus tremula	12		
Central[b]		*Populus tremula*	20	Young	15
				Middle age	38
				Mature and older	30
West Siberia	Khanty-Mansi okrug; Novosibirsk oblast	*Abies sibirica*	20	Young	3
		Betula pendula	35	Middle age	19
		Pinus sylvestris	20	Mature and older	185
East Siberia	Krasnoyarsk krai; Irkutsk oblast	*Abies sibirica*	23	Young	12
		Betula pendula	99	Middle age	66
		Larix sibirica	113	Mature and older	161
		Picea obovata	63		
		Pinus sibirica	57		
		Pinus sylvestris	130		
Far East	Khabarovsk krai	*Betula costata*	30	Young	5
		Betula pendula	28	Middle age	30
		Larix dahurica	63	Mature and older	101
		Picea ajanensis	67		
		Pinus koraiensis	49		
Total			922		1044

[a]An additional 20 plots were set up in disturbed forests (including burned stands, windthrow areas, and clearcuts) across all regions.
[b]The Central region includes the following administrative units: Briansk oblast, Vladimir oblast, Ivanov oblast, Tver oblast, Kaluga oblast, Kostroma oblast, Moscow oblast, Oriol oblast, Riazan oblast, Smolensk oblast, Tula oblast, Yaroslav oblast, Nizhnii Novgorod oblast, Kirov oblast, Mari El Republic, Mordovia Republic, and Chuvashia Republic.

arately. Plots were assigned to one of three groups depending on the dominant species: conifers (excluding larch), larch, and hardwoods. Three age groups were defined according to the system adopted by the Russian forest inventory, where the young group included conifers ≤40 years old and hardwoods ≤20 years old, the middle-age group included conifers 41–80 years old and hardwoods 21–60 years old, and the group of mature and old forests included all remaining plots. It was essential to align the plot groupings with the system of forest categories used in the Russian forest inventory so that the results of plot data processing could be applied to forest inventory databases.

The measured volumes of logs and snags in each plot were compared with visual estimates reported in the forest inventory database. Correction factors (measured volume divided by visually estimated volume) were calculated separately for logs and snags in plots for which the visual estimates of log or snag volumes existed in the forest inventory database. These factors were used to develop a graduated scale of correction factors for logs ranging from 3.58 for visually estimated volume of ≤10 m^3 to 1.0 for visual estimates of ≥90 m^3. In two western regions the value of the correction factor for snags (0.942 ± 0.151; mean ± SE) was not significantly different from 1, implying that the volume of snags reported in forest inventory database did not require correction. For other regions a graduated scale of correction factors for snags was developed ranging from 1.48 for visually estimated volume of ≤10 m^3 to 1.0 for visual estimates of ≥60 m^3.

In plots where the visual estimates of log and (or) snag volumes were missing in the forest inventory database, the measured volumes were used to calculate the ratio of CWD (log or snag) volume to wood volume of live trees. These ratios were averaged by species and age group (Table 3) and used to calculate the volume of CWD for all those forest stands in the forest inventory database where the volume of logs or snags or both were not reported. The ratio varied widely in young forests, and this precluded the calculation of a meaningful number. We attributed this to the fact that dead wood found in young forest stands had been transferred from the previous (pre-disturbance) generation of trees, and consequently, the amount of CWD did not correlate with the current volume of young trees in plots. For young forests, the mean volumes of logs and snags per unit area were used to substitute for the missing volumes of logs and snags in the inventory database (Table 3).

The average bulk density of logs and snags was calculated for all 1044 sample plots by dividing the total mass of logs and snags in each plot by their respective volumes. In each region, mean values of CWD density were computed sepa-

Table 2. Field data overview: stand-level forest inventory databases.

Region	No. of forests[a]	Total area of inventoried forest (ha, $\times 10^6$)	No. of stand records ($\times 10^3$)	Categories of forest lands (% of total area of inventoried forest in region): Burned and dead	Clearcuts and young plantations	Area where CWD is reported
St. Petersburg	7	1.0	200	0.3	5.4	9
Central	5	2.9	54	0.02	5.2	8
Khanty-Mansi	4	2.1	117	1.4	0.02	14
Novosibirsk	2	0.2	28	0.1	2.1	6
Krasnoyarsk	5	4.7	159	1.8	0.9	19
Irkutsk	7	3.7	149	2.6	1.3	24
Khabarovsk	7	2.6	94	2.1	2.4	32
Total	37	17.2	801			

[a]The forest or Forest Management Enterprise (also known as a leskhoz) is the basic unit in Russian forestry (Kukuev et al. 1997), somewhat similar to the National Forest in the U.S.A.

Table 3. Parameters for estimating CWD volume in forest stands with no CWD reported in the forest inventory database: volume of dead wood in young forests and CWD/live wood volume ratio in middle aged and older forests (mean ± SE).

Region[a]	Species group	Young (m^3/ha)[b]		Middle age (%)		Mature and old (%)	
		Logs	Snags	Logs	Snags	Logs	Snags
Northwest	Hardwoods	9±2	2±1	2.5±0.9	1.2±0.3	5.7±2.0	4.0±1.4
	Conifers			6.7±0.9	4.4±1.1	12.1±1.6	3.0±0.4
Central	Hardwoods	8±2	2±1	4.4±0.4	2.1±0.3	7.9±2.0	3.0±0.4
	Conifers			3.9±0.5	1.5±0.3	7.8±2.7	2.9±0.5
West Siberia	Hardwoods	6±1	5±2	7.0±4.7	8.5±4.65	5.5±1.5	1.3±0.2
	Conifers			2.0±0.4	1.5±0.5	4.4±0.5	1.9±0.2
East Siberia	Hardwoods	37±11	22±10	7.4±1.4	3.7±0.9	10.9±2.1	4.1±1.0
	Conifers			8.4±2.3	3.4±0.9	7.6±0.9	1.9±0.3
	Larch			9.0±3.7	6.2±1.5	11.2±3.6	2.9±0.9
Far East	Hardwoods	92±19	30±6	4.1±3.6	1.4±0.3	24.8±5.8	7.3±1.7
	Conifers			21.6±3.6	9.1±3.4	11.8±2.9	9.1±2.0
	Larch			18.0±7.3	4.6±1.8	12.8±2.9	7.1±1.6

[a]Administrative units within each region as in Table 1.
[b]Mean volume of logs and snags in young forests was calculated for a combined set of plots that included all species groups.

rately for conifer-, larch-, and hardwood-dominated plots in three age groups (Table 4). Means were compared using a two-tailed t test with $p < 0.05$ (SAS Institute 1990). These densities were used to convert into mass CWD volumes computed from the forest inventory database (Fig. 2).

Forest inventory data

We used two types of inventory data: regional summaries for selected regions updated to January 1, 1993 (Filimonov et al. 1995), and stand-level databases for portions of each region (0.2×10^6 – 4.7×10^6 ha, or 6–27% of the total forest area). Stand-level forest inventory databases were processed for two to seven forests in each region. The forests were selected among the most recently inventoried ones to represent the variation in site conditions and successional patterns within each region (Table 2). The field inventory (survey) data for these forests were acquired in the process of routine forest inventory that was conducted by the respective regional forest inventory enterprises between 1992 and 1997. Field crews surveyed each forest stand polygon (a homogeneous patch of forest vegetation) delineated from air photos on the entire territory of selected forests (Russian Federal Forest Service 1995). The standard set of data gathered in the field included site productivity and drainage; tree species composition, mean height, diameter, and age; canopy structure; wood volume; and characteristics of different types of land without tree cover (e.g., clearcuts, bogs, meadows). Over 200 different variables measured or visually estimated in the field were used to describe stand polygons, depending on land category and management requirements at a given forest (Kukuev et al. 1997). This included visual estimates of dead wood volume made separately for logs and snags in every forest stand where these volumes exceeded a certain minimum (10–30 m^3/ha depending on the region). CWD volume was estimated as part of routine forest inventories for purposes of forest health maintenance and for assessing the resources for potential wood salvage. Consequently, wood at advanced stages of decay was excluded from volume estimates.

The primary forest inventory data described above were processed and corrected with a system of ratios derived from measurements in sample plots as described above and in

Table 4. Bulk density (Mg/m^3) of logs and snags in different forest categories calculated from measurements in sample plots.

Region[a]	Species group	Young[b]		Middle age		Mature and old	
		Logs	Snags	Logs	Snags	Logs	Snags
Northwest	Hardwoods	0.185±0.016	0.280±0.025	0.110±0.035	0.333±0.027	0.274±0.026	0.345±0.019
	Conifers			0.246±0.006	0.327±0.006	0.237±0.008	0.319±0.008
Central	Hardwoods	0.324±0.023	0.369±0.005	0.333±0.010	0.380±0.014	0.319±0.008	0.369±0.017
	Conifers			0.266±0.006	0.344±0.010	0.269±0.016	0.347±0.010
West Siberia	Hardwood	0.218±0.018	0.317±0.005	0.187±0.018	0.292±0.023	0.249±0.012	0.355±0.011
	Conifers			0.282±0.014	0.339±0.004	0.273±0.004	0.340±0.002
East Siberia	Hardwoods	0.260±0.018	0.356±0.028	0.199±0.016	0.329±0.024	0.234±0.014	0.304±0.019
	Conifers			0.242±0.013	0.332±0.013	0.237±0.006	0.341±0.005
	Larch			0.253±0.018	0.394±0.023	0.304±0.013	0.440±0.006
Far East	Hardwoods	0.272±0.020	0.372±0.012	0.240±0.036	0.395±0.021	0.208±0.018	0.332±0.021
	Conifers			0.170±0.007	0.302±0.026	0.210±0.008	0.350±0.005
	Larch			0.258±0.023	0.424±0.011	0.253±0.008	0.418±0.004

Note: Values are means ± SEs. For recently disturbed forests in all regions, the mean density of logs and snags is 0.291 ± 0.018 (n = 19) and 0.359 ± 0.020 (n = 16), respectively. Snag densities are significantly higher than log densities in the same species × age groupings; the difference between the means of logs and snags was not significant (at 0.05 alpha level in two-tailed t test) in only two cases: young stands in the Central region and mature and old hardwoods in the northwestern region.

[a]Administrative units within each region are as in Table 1.

[b]Mean densities in young forests were calculated for a combined set of plots that included all species groups.

Krankina et al. (2001). All stands in the database were divided into two categories depending on whether or not the visually estimated CWD volume data were available. For stands where CWD volume was reported, it was corrected for underreporting using correction factors (Fig. 2). For middle-aged and older forest stands where CWD was not reported in the forest inventory database, the growing stock of live trees was used as a basis (i.e., auxiliary variable) for estimating CWD volume. Stand age group and dominant tree species were used to determine the selection of the appropriate CWD/live wood ratios or mean volumes for young and recently disturbed forests (Table 3). All calculated volumes were then converted to biomass using the mean bulk density of CWD for a given forest category and woody debris type (logs or snags) (Table 4). Because the average density of snags was higher than the density of logs in many stand categories, the two types of CWD were processed separately.

The large forest inventory databases we analyzed provided sufficient number of observations (Table 2) to assess the effect of several factors on CWD stores. Within each selected forest, stand records were grouped by dominant tree species, stand age, and site productivity class. Area-weighted averages of CWD amount and CWD to live wood volume ratio were computed for each group. Poorly represented groups (with ≤3 stand records) were excluded from further analysis. Thus, the visual estimates of CWD were used to adjust the plot-derived ratios and 801 000 stand records in the inventory databases were reduced to 1608 forest-level averages. These averages were treated as individual observations in further statistical analysis. Because the data set was unbalanced, we applied the general linear models (GLM) procedure to assess the influence of region, dominant tree species, stand age, site productivity class, and interaction of these factors on three dependent variables: (*i*) CWD volume and (*ii*) mass per hectare and (*iii*) CWD to live wood volume ratio (SAS Institute Inc. 1990).

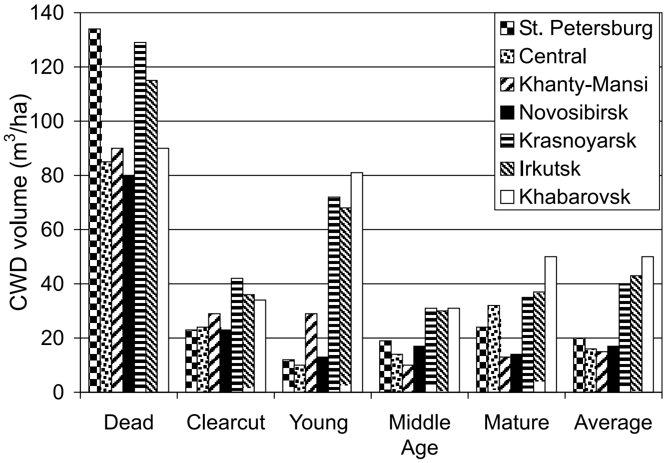
The results from stand-level databases were also used in calculations of regional stores of CWD from regional summaries of forest inventories (e.g., Filimonov et al. 1995). In each forest examined, ratios of CWD volume and CWD mass to growing stock of live trees were calculated for all the dominant tree species in three age groups. These ratios were averaged within each region and used to calculate CWD stores in middle-aged and mature stands based on their growing stock volume in the region. For young stands of all species, for clearcuts and for naturally disturbed (burned and dead) forests the mean volume and mass of CWD per hectare was used in each region. These ratios and means differed from analogous variables derived from sample plots because processing stand-level forest inventory databases allowed us to incorporate CWD volumes visually estimated in the field as part of the routine forest inventory (Fig. 2). The difference was substantial. For example, in mature forests of East Siberia the mean CWD to live wood volume ratio derived from plot measurements was 0.10 to 0.15 depending on species group (Table 3, logs + snags). These ratios were used in processing stand-level databases of five forests in Krasnoyarsk krai (Table 2) and the resulting regional ratios for mature forests increased to 0.13–0.20.

Results

Visual estimates of CWD were present in only a fraction of all records in stand-level databases and ranged from 6% in the Novosibirsk region to 32% in Khabarovsk krai (Table 2). However, these records account for 15–42% of the estimated total CWD volume in the examined forests, because they represent the sites with the highest concentration of CWD. The fraction of forest area where CWD was reported varied with region and age of forest stands. It was higher for burned and dead forests where visual estimates of CWD were recorded for 47–86% of the total area.

The average amount of dead wood in the western part of Russia (St. Petersburg, Central, Khanty-Mansi, and Novosibirsk regions) ranged from 14 to 20 m^3/ha or 4.0–5.8 Mg/ha and was lower than in the East Siberian and Far Eastern regions (40–51 m^3/ha or 11.0–14.3 Mg/ha) (Fig. 3). The highest stores of CWD were found in naturally dis-

Fig. 3. Mean volume of CWD in different categories of forest lands, age groups of forest stands, and overall averages in selected regions. The "dead" category includes forests where the greater part of the basal area is represented by dead trees (killed by fire, insects, droughts, flooding, and other types of disturbance) (Russian Federal Forest Service 1995).



turbed forests (in all regions) and in young forests (in Khanty-Mansi, Krasnoyarsk, Irkutsk, and Khabarovsk regions). The amount of CWD in young forests generally increased from west to east; in middle-aged and older forests this pattern was also present but less clear (Fig. 3, Table 5). The lowest levels of CWD occurred in young forests in the St. Petersburg, Central, and Novosibirsk regions, whereas in the remaining regions the amount of CWD was the lowest in middle-aged forests.

The eastern regions of Russia had higher CWD stores both in absolute terms and as CWD to live wood volume ratio (Fig. 4). In addition, the ratio varied dramatically by age group and young forests had higher ratios than other age groups. In the young forests in the St. Petersburg, Central, and Novosibirsk regions the CWD to live wood volume ratio was lower (0.18–0.30) than in the remaining four regions (1.45–2.85). In middle-aged and older forests the ratio was less variable: 0.07–0.14 in the four western regions and 0.18–0.33 in the three eastern ones.

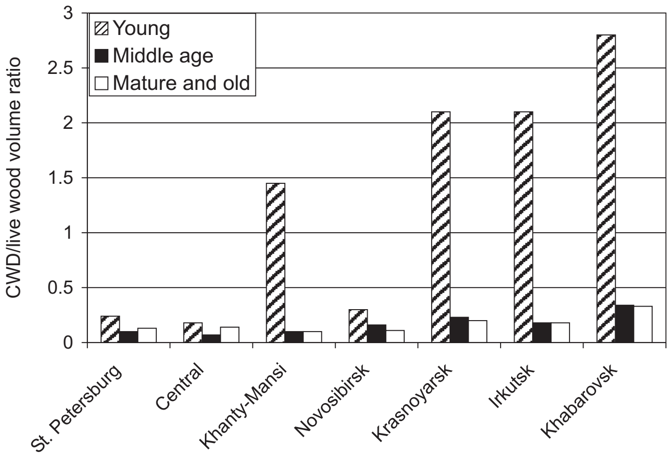
The variance of CWD volume and mass per hectare was analyzed within the following classes: region × dominant species (pine, spruce–fir, larch, birch, aspen) × age group (young, middle age, mature and old) × productivity level (high, medium, low). Area-weighted means were calculated for the above classes in each of the 37 forests examined, yielding 1608 observations. The analysis showed that the selected factors and their interactions explained 87 and 88% of the total variance of CWD volume and mass, respectively. The effect of age group on CWD mass was the strongest ($F_{[2,1335]}$ = 335.7), followed by region ($F_{[6,1335]}$ = 267.4); the effects on CWD volume were similar.

The effects of region and age on CWD volume (Fig. 3) were mitigated by species (data not shown; $F_{[47,1335]}$ = 4.6 for region × species × age group interaction) and productivity class (Fig. 5; $F_{[4,1335]}$ = 10.2 for age group × productivity interaction). There were no consistent differences among species in young forests, but in middle-aged and especially in mature and older forests, species was an important factor.

Table 5. Areas of different forest age groups, mean live wood volume, and stores of CWD in selected regions.

Region	Young				Middle age				Mature and old				Total		
	Area (ha, ×10^3)	Live wood volume (m^3/ha)	CWD (Mg/ha)	CWD (m^3/ha)	Area (ha, ×10^3)	Live wood volume (m^3/ha)	CWD (Mg/ha)	CWD (m^3/ha)	Area (ha, ×10^3)	Live wood volume (m^3/ha)	CWD (Mg/ha)	CWD (m^3/ha)	Area (ha, ×10^3)	CWD (Mg/ha)	CWD (m^3/ha)
St. Petersburg	716	50	2.4	12	1 745	186	5.1	19	1 237	180	8.5	24	3 698	5.7	19
Central	7 787	55	3.4	10	11 537	189	4.6	14	3 988	234	10.4	32	23 312	5.2	16
Khanty-Mansi	2 008	20	7.3	28	9 931	123	3.0	10	14 780	125	3.8	13	26 719	3.8	13
Novosibirsk	278	43	3.3	13	1 432	109	4.3	17	895	123	3.7	14	2 605	4.0	15
Krasnoyarsk	4 593	34	21.2	72	14 894	137	8.3	31	29 936	173	8.9	35	49 423	9.9	37
Irkutsk	10 885	33	20.4	68	19 153	171	8.0	30	24 652	207	10.9	37	54 690	11.8	41
Khabarovsk	8 938	28	24.4	82	15 272	105	8.1	31	21 380	150	13.6	50	45 590	13.9	50

Fig. 4. CWD/live wood volume ratio in three forest age groups (young, middle age, mature and old) within the selected regions.



Middle-aged and older forests dominated by larch had the highest stores of CWD in three (Khanty-Mansi, Krasnoyarsk, and Irkutsk) of the five regions where larch occurs naturally. Forests dominated by spruce and fir had the highest CWD stores in middle-aged and older forests of three other regions (St. Petersburg, Central, and Khabarovsk). Birch forests had the lowest or second-lowest stores of CWD in all seven regions. Among young forests the sites with the highest productivity had the lowest stores of CWD, while the opposite effect was found in other age groups (Fig. 5). Productive sites are more likely to be harvested and cleared of slash in preparation for planting, and these treatments reduce the stores of CWD in young stands. In middle-aged and older forests greater mortality inputs associated with higher stand productivity evidently increased the amount of CWD on more productive lands. Interestingly, unlike CWD mass (and volume), CWD to live wood volume ratio was inversely correlated with forest productivity class (data not shown), and the difference between high and low productivity was significant in all age groups. For example, in mature and older forests of high productivity the CWD/live wood volume ratio averaged across all regions was 0.161 ± 0.006, whereas in mature and older forests of low productivity the ratio was 0.201 ± 0.007. This difference may be attributed to the greater extent of thinning and nonclearcut harvest in productive forests and possibly to higher decomposition rates on productive sites.

The contribution of different categories of forest lands to the total regional CWD stores varied across the territory of Russia (Fig. 6). Middle-aged and older forests represented the largest fraction in the overall CWD store in all regions. Dead wood on clearcuts played a minor role in overall stores, especially in the east. The proportion of dead wood stored in naturally disturbed forests was very small in the St. Petersburg and Central regions relative to other regions examined. The fraction of regional CWD stores in recently disturbed and young forests increased from <10% in the west to >40% in the east (Fig. 6).

Fig. 5. Effect of site productivity (high, medium, and low) on CWD mass in three forest age groups (mean ± SE). Bars for a given age group with the same letter are not significantly different (ANOVA with the Tukey pairwise mean comparison test, $p < 0.05$ (SAS Institute Inc. 1990)).

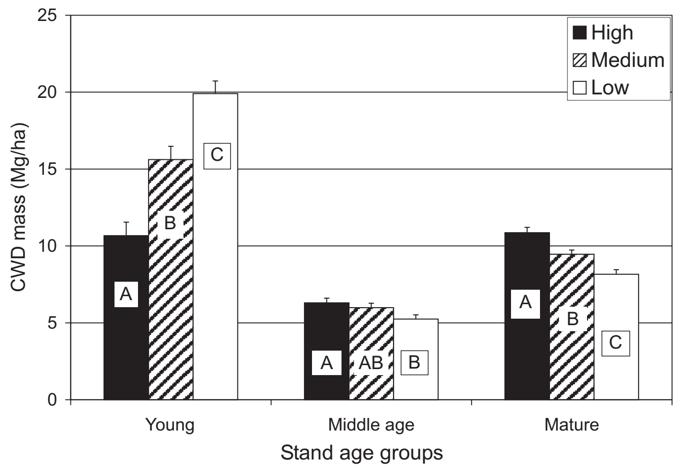
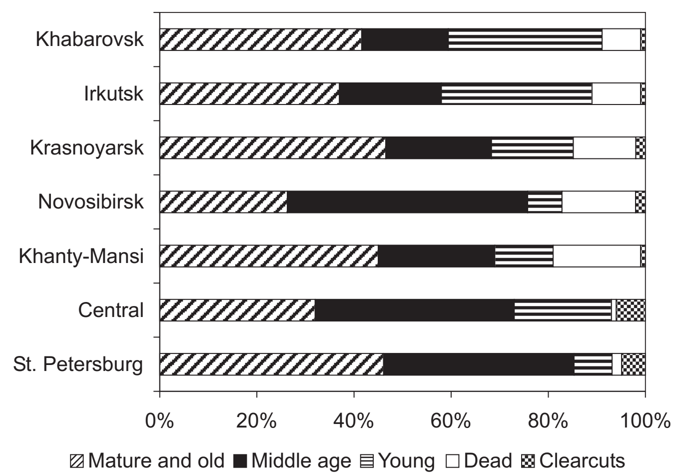


Fig. 6. Contribution of different categories of forest lands to regional stores of CWD (% of total CWD mass in region).



Discussion

Comparisons of results from different studies of CWD require caution, because methods of field measurements and calculation procedures vary among studies. Furthermore, in regional studies the approach used to sample forest lands may influence the result. For example, the volume of CWD on managed forest lands in Sweden estimated with statistical sampling was higher than the results from local studies (Fridman and Walheim 2000), whereas our results for the Central region are lower than estimates based on plot measurements in Kirov oblast and Republic Mari El (15.4 Mg/ha; Kurbanov and Krankina 2000). Similarly to the approach used by Fridman and Walheim (2000), this study was designed to complement the existing system of National Forest Inventory. However, unlike Fridman and Walheim (2000) we used plot measurements to derive correction factors and ratios (rather than averages) for all classes of forest stands, except those that were young or recently disturbed (Table 3). This allowed us to better utilize the extensive stand-level databases collected by the Russian forest inventory system in the regions examined (Table 2). Our results show that the method used in this study can be employed for estimating CWD stores in other parts of Russia and, more generally, on forest lands where survey-based inventory data are available. A clear advantage of integrating CWD estimation methods into existing forest inventory systems is that results are fully compatible with estimates of other ecosystem components derived from National Forest Inventories, making it easy to incorporate the CWD component into broader systems of carbon assessment and monitoring.

A recent review of methods used to calculate carbon stores in Russian forests concluded that estimates of CWD stores remain highly uncertain and that developing methods for estimating CWD is one of the priority steps towards reducing the uncertainty in the overall estimate of carbon stores in forest ecosystems (Moiseev et al. 2000). However, the use of growth tables for calculating ratios of CWD to live biomass as suggested by Moiseev et al. (2000) appears problematic, primarily because of the lack of data on decomposition rates for many major tree species and different regions of Russia. In addition, this and other studies (e.g., Clark et al. 1998; Spetich et al. 1999; Siitonen et al. 2000) clearly show that disturbance regime plays a major role in defining CWD stores in all age groups, but especially in young and middle-aged forests. Calculating CWD stores for these age groups based on background mortality inputs ignores the main source of CWD material in these forests, which is the preceding generation of trees (see also Krankina et al. 1999; Tarasov 1999). The use of growth tables for estimating CWD in mature and older forests also appears questionable, because few growth tables include data for stands older than 200 years, the age when large trees begin to die and the accumulation of CWD accelerates (Clark et al. 1998; Spies et al. 1988).

While the age of live trees had the most significant influence on CWD stores and CWD/live wood volume ratio, this influence was moderated by the effects of region, species, and productivity class. Because all of these factors appear significant, a more differentiated system of ratios than we used in this study (Table 3) could help reduce the uncertainty in CWD estimates. Generalized CWD/live wood volume ratios may be acceptable for large-scale estimates in mature and old and, to a lesser degree in middle-aged forests, but not in the young ones, where disturbance regime is the primary control. Differentiating between young forests established on harvested sites and those initiated by natural disturbance would also improve CWD estimates.

The results of this study are consistent with other studies of CWD stores in similar ecosystems and forest categories. For example, in conifer forests of southwestern Alberta the simulated CWD stores ranged from 1.1 to 8.4 Mg/ha (Laiho and Prescott 1999), which is consistent with regional means estimated in this study (Table 5). In the Lower Wye Valley, U.K., the total CWD volume in managed seminatural stands was 23.9 m^3/ha (Green and Peterken 1997), and in midwestern U.S. second-growth forests it was 30 m^3/ha (Spetich et al. 1999), which is comparable with the 14 m^3/ha in middle-aged and 32 m^3/ha in mature forests of the Central region in our study. In southern Finland the CWD volume in mature and overmature forests was 14.4 and 22.3 m^3/ha, respectively (Siitonen et al. 2000), compared with 24 m^3/ha in mature and older forests in the St. Petersburg region (this study). CWD volumes reported for the St. Petersburg and Central regions (Table 5) are higher than CWD volumes reported for Sweden in the same age groups: 3.5 m^3/ha for ages ≤40 years; 6.2 m^3/ha for ages 41–100 years; and 10.5 and 15.6 for ages 101–140 and >141 years, respectively (Fridman and Walheim 2000). More intensive forest management in Sweden than in the European part of Russia is the most obvious reason for this difference. However, some of the difference may also be due to the fact that the Swedish study apparently excluded extremely decomposed CWD material (our decay class 5, i.e., soft logs with elliptical cross section commonly covered with understory vegetation). The volume and mass of this material was quite low in the St. Petersburg region (Harmon et al. 2001), and therefore, this difference in method can only explain a small fraction of the difference in results. In northern Sweden, where the impact of forest management is relatively low, the CWD/live wood volume ratio (0.11) was similar to that in the St. Petersburg region (Fig. 4), while in other parts of Sweden it was substantially lower (Fridman and Walheim 2000).

Many of the studies mentioned above measured only the volume of CWD, and this limits their utility for calculating carbon stores. This is one reason why large-scale estimates of biomass and carbon stores in CWD have to rely primarily on a limited number of studies where the mass of CWD was measured (Harmon et al. 2001). Several published national-level assessments for Russia (Moiseev et al. 2000) used the results of numerous local studies of vegetation mass and productivity compiled by Basilevich (1993). Resulting estimates show the average stores of CWD at 17–20 Mg C/ha (or 34–40 Mg/ha), which is significantly higher than the stores that we found in this study. A study by Shvidenko and Nilsson (2000) used lower values of 7.4 Mg/ha for the European and 15 Mg/ha for the Asian part of Russia; however, even these estimates are high compared with our results (Table 5).

Regional differences in CWD stores and successional patterns represent a combined effect of variation in natural conditions and disturbance history in selected regions. The prevailing disturbance type in western Russia is clear-cut harvest, and CWD dynamics in two western regions (St. Petersburg and Central) followed the pattern of change observed in other regions where managed forests prevail: low levels of CWD in young forests and then a gradual increase with the advancing age of live trees (Spetich et al. 1999; Fridman and Walheim 2000). In contrast, natural disturbance, including fire and insect outbreaks, is a major cause of stand initiation in the eastern part of Russia where young stands inherit large amounts of material from the previous (pre-disturbance) forest stand (Fig. 3, Table 5). The decomposition losses in this large initial store of CWD may exceed the accumulation of CWD material produced by the current stand of trees for many decades following disturbance (Harmon et al. 2001). The retention of pre-disturbance material most likely accounts for the relatively high CWD stores in middle-aged forests of the Krasnoyarsk, Irkutsk, and Khabarovsk regions. In these three regions and in Khanty-Mansi (another region with active natural disturbance) the mass of CWD in middle-aged forests is between 33 and 41% of CWD mass in young stands. The lower absolute values in Khanty-Mansi may reflect lower forest productivity in this region (Table 5) and perhaps a greater role of repeated burns (Clark et al. 1998).

Lower decomposition rates of CWD may also contribute to greater accumulation of CWD in the east. Harsher climatic conditions are thought to slow down decomposition processes even though sparse published data suggests that the decay resistance of wood can also play an important role (Harmon et al. 2001). Larch decomposes slower than other major tree species in Russia, and its significant presence in eastern regions is a likely reason for higher overall CWD stores. Higher stores of CWD in larch-dominated forests relative to other species in the Khanty-Mansi, Krasnoyarsk, and Irkutsk regions corroborate the role of slower decomposition in greater stores of CWD in Siberia.

The differences in CWD stores among regions with different histories of forest use indicate potential consequences of expanding forest utilization in regions where it was limited in the past. In the near term, the greatest loss of CWD from expanding timber harvest can be expected in young forests because of the reduced transfer of material from predisturbance stands. Over time this would affect the middle-aged stands as well. The removal of the most productive forests from the mature and older category and the eventual shift from old-growth, uneven-aged forests to relatively young stands at about 80- to 120-year harvest age would reduce CWD stores in this age group as well. For a rough estimate of potential long-term losses in regional CWD stores, we compared two western regions (St. Petersburg and Central) with two regions in Siberia (Krasnoyarsk and Irkutsk), which appear to have similar overall forest productivity as measured by the mean live tree volume in mature and older forests (Table 5). The difference in CWD stores between these regions (4.2–6.6 Mg/ha) may represent potential loss of CWD from expanding forest use in the Krasnoyarsk and Irkutsk regions. In projecting future changes in regional carbon stores, these losses need to be counted against the potential gains in live biomass resulting from improved forest regeneration, disturbance control, etc. In contrast, CWD stores in regions with a long history of forest use can be increased by expanding protected forest areas, extending harvest rotations, and increasing CWD retention on clearcuts.

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