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Aggregated Estimation of the Basic Parameters of Biological Production and the Carbon Budget of Russian Terrestrial Ecosystems: 1. Stocks of Plant Organic Mass

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Abstract—The data presented were obtained at the first stage (1993–1999) of studies on evaluating the basic parameters of biological production in Russian terrestrial ecosystems in order to provide information for assessing and modeling the carbon budget of the entire terrestrial biota of the country. Stocks of phytomass (by fractions), coarse woody debris, and dead roots (underground necromass) were calculated by two independent methods, which yielded close results. The total amount of phytomass in Russian terrestrial ecosystems was estimated at 81800 Tg (=10^{12} g = million t) dry matter, or 39989 Tg carbon. Forest ecosystems comprise a greater part (82.1%) of live plant organic matter (here and below, comparisons are made with respect to the carbon content); natural grasslands and brushwoods account for 8.8%; the phytomass of wetlands (bogs and swamps), for 6.6%; and the phytomass of farmlands, for only 2.5%. Aboveground wood contains approximately two-thirds of the plant carbon (63.8%), and green parts contain 9.9%. For all classes of ecosystems, the proportion of underground phytomass averages 26.7% of the total amount, varying from 22.0% in forests to 57.1% in grasslands and brushwoods. The average phytomass density on lands covered with vegetation (1629.9 million hectares in Russia) is 5.02 kg/m^2 dry matter, or 2.45 kg C/m^2. The total amount of carbon in coarse woody debris is 4955 Tg C, and 9180 Tg C are in the underground necromass. In total, the vegetation of Russian terrestrial ecosystems (without litter) contains 54124 Tg carbon.

Key words: biological production, phytomass stock and density, forest ecosystems, bogs, grasslands and brushwoods, farmlands, carbon stock

Studies on the basic parameters of biological production are very important for assessing the state and functioning of terrestrial ecosystems under conditions of global climate change and for quantifying their carbon budget. After the United Nations Framework Climate Change Convention (1992) and the Kyoto Protocol (1997) were ratified by most countries of the world, the problem of the terrestrial biota carbon budget, having high priority in science, became an important issue in international policy and economics. This paper presents the results of the systems evaluation of organic matter stocks in the Russian vegetation at the national level, which was performed by the International Institute for Applied Systems Analysis (IIASA) together with a number of Russian research institutes between 1993 and 1999. Traditional terminology is used throughout the paper, with small modifications relevant to the modeling of the full carbon budget. *Phytomass* (or live biomass) is defined as live plant organic matter accumulated by ecosystems (see Bazilevich, 1993, p. 8) and is expressed in units of dry mass, or carbon, per unit area. Aggregated estimates are given in Tg (= 10^{12} g = 1 million metric tons); densities, in kgm^{-2}. In order to recalculate dry matter into carbon, we used standard coefficients (Matthews, 1993): 0.45 for green parts and 0.50 for wood. Although recent studies suggest that the latter coefficient is underestimated for the main boreal tree species (*Uglerod v ekosistemakh*…, 1994; Vedrova, 1995), there are insufficient data for the reliable application of regional coefficients. *Coarse woody debris (CWD)*, or aboveground woody detritus, is determined as dead aboveground (standing dry trees, dry branches of live trees, stumps) and on-ground (downed wood, windbreak, etc., more than 1 cm in diameter at the thin end) wood retaining major elements of its morphological structure. *Dead roots* include fine (< 2 mm) and coarse (larger) roots. Litter, classified as a soil body, is not considered in this paper.

MATERIALS AND METHODS

The problem of estimating the phytomass stock, as well as other parameters of biological production in ecosystems, belongs to the category of fuzzy (weakly structured) problems due to the significant geographic and seasonal variation in the relevant parameters, the lack of any regular and complete system of their inventory and monitoring, and the theoretical and practical difficulties in extrapolating scarce and fragmentary data to vast territories. The systems (holistic) approach appears to be the only one suitable for solving such a problem (Utkin, 1975), and we used it in a modification appropriate to fuzzy systems. The principle of *systems minimization of uncertainties* has been realized by (1) using all available information sources and alternative methods, taking into account that such an approach offers one of very few possibilities of estimating uncertainty in fuzzy systems; (2) applying "transparent" algorithms of calculations within individual models and methods; and (3) relying on the available unified spatial basis for the transition from local (point) measurements to territorial aggregations. *Ecological regions* (ecoregions) served as the basic territorial units of aggregated estimation. We define them as spatial units satisfying a number of requirements, the most important of which are as follows: (1) all ecoregions must make comparable (similar) contributions to the global carbon budget and, consequently, have similar parameters of ecosystem productivity (phytomass, production, etc.); (2) on the relevant scale, ecoregions must be uniform with respect to the climate, soil cover, and indigenous plant formations; (3) the extent of the transformation of natural vegetation and the pattern, type, and intensity of anthropogenic pressure within an ecoregion must be similar; (4) the boundaries of ecoregions should not cross the boundaries of basic administrative units of the Russian Federation, i.e., each administrative unit contains one or several ecoregions. Although the latter requirement is inconsistent with a purely naturalist approach, it is impossible to avoid for two reasons: a number of relevant information sources and flows are formed on an administrative basis, and it is necessary to have the data on carbon budget for individual administrative units of the Russian Federation. Thus, Russia was divided into 141 ecoregions, 78 in the European part and 63 in the Asian part.

Climatic and soil uniformity was interpreted at the bioclimatic subzonal level. Taking into account the crucial role of forest phytomass in the carbon budget, forest site zoning (Kurnaev, 1973) was used as a basis, and ecoregion boundaries were drawn along the boundaries of forest enterprises or zones of their activity; mountain territories were separated from plains, areas with different regimes of ground freezing were separated from each other, etc. The classes of land use/land cover (LULC) were used as basic "thematic" units of estimation; the term "LULC" was understood as defined by the FAO (1976). The expediency of such an approach is confirmed by the fact that the current state and functioning of ecosystems are largely determined by direct and indirect anthropogenic influences.

The information basis used in the study consisted of the specially developed Geographic Information System (GIS), which included the following attributive databases (DBs): (1) published results of field measurements and aggregated estimations (e.g., those obtained by many authors who worked on the program "Man and Biosphere"); (2) data of various inventories and surveys; (3) formalized, modified, and supplemented legends to maps of different types (Stolbovoi *et al.*, 1997); (4) series of auxiliary models (e.g., for estimating forest phytomass and its increment); (5) statistical data collected by various Russian agencies (Federal Forest Service, State Land Committee, etc.); and (6) various archives (in particular, data collected by N. Bazilevich). The "ecological" DB was one of the most important. It comprised data on approximately 3200 sample plots established to study biological productivity (including several "semiempirical" aggregated estimations) and sources providing information on the parameters of the phytomass and production fractions (dry matter or carbon units) and the necessary minimum of data for subsequent modeling. The "forest inventory" DB, which contained data on approximately 5000 sample plots, was used for developing auxiliary models and cross-checking.

The GIS components included a number of digitized maps, which were usually modified considerably (compared to the original paper maps) on the basis of the aforementioned attributive DBs (Nilsson *et al.*, 2000). In particular, the following maps were used: (1) a vegetation map of the former Soviet Union, 1 : 4000000 (ed. Isachenko, 1990); (2) a land-use/land-cover map of the former Soviet Union, 1 : 4000000 (ed. Yanvareva, 1991); (3) a soil map of Russia, 1 : 5000000 (obtained by generalizing the Soil Map of the Soviet Union, 1 : 2500000; ed. Fridland, 1988); (4) a landscape map of the former Soviet Union, 1 : 2500000 (ed. Gudilin, 1987); (5) a litter map, 1 : 2500000 (made at the Dokuchaev Soil Institute and IIASA, 1999); (6) maps of the phytomass, necromass, and production for the restored plant cover, 1 : 8000000 (made at the Dokuchaev Soil Institute in 1995 on the basis of Bazilevich's map, 1993); (7) a forest map of Russia and other auxiliary maps (boundaries of forest enterprises, ecoregions, administrative boundaries, etc., 1 : 1000000; IIASA, 1993–1999). These maps and DBs represent a prototype, at the federal level, of the Integrated Land Information System (ILIS) developed within the framework of the Forest Project and other projects of the IIASA, with the term "land" understood as defined by the FAO (1976). In other words, it is assumed that the system contains a comprehensive description of the relief, parent rocks, soil, vegetation, land use, transformation and degradation of land cover, atmosphere, hydrosphere, etc.

Several independent methods were used in calculations. The phytomass and production of all land classes were estimated on the basis of GIS technologies. Primary polygons of basic LULC classes were generated by consecutively superimposing the initial geometric elements of the maps included in the GIS. At the top level of classification, these classes were as follows: (a) lands lacking vegetation, i.e., water areas, sands, glaciers, etc. (total area 79.6×10^6 ha); (b) farmlands, with the subclasses of arable lands (130.3×10^6 ha), cultivated grasslands and pastures (79.0×10^6 ha), and perennial vegetation—gardens, vineyards, etc. (2.6×10^6 ha); (c) wetlands, with the subclasses of bogs (116.2×10^6 ha) and swamps (105.8×10^6 ha); (d) forests (763.5×10^6 ha); and (d) natural grasslands and brushwoods (432.4×10^6 ha). The area of lands covered with vegetation comprises 1629.9×10^6 ha, and the total area of Russia is 1709.5×10^6 ha. Areas of the LULC classes were compared with the corresponding data of the State Land Inventory and the State Forest Inventory (1990) for administrative regions and ecoregions. The number of primary polygons in individual LULC classes varied from a few thousands to about 30000. The bioclimatic zones were delineated on the basis of the vegetation map.

At the lower classification levels, the average values of the phytomass and other parameters of bioproductivity were calculated with the aid of the DBs. To calculate the total stock, these averages were multiplied by the corresponding areas. The average values were calculated taking into account specific features of different LULC classes. For arable land and cultivated grasslands and pastures, the averages were calculated using regressions of by-products (straw, crop residues, root mass) to yield (Krylatov *et al.*, 1998), which were obtained from regional agricultural statistics. For forests, the average values of phytomass fractions were calculated on the basis of the ecological DB with regression corrections for the actual values of growing stock in individual ecoregions, which were obtained from the State Forest Inventory. For wetlands (an intrazonal category), the averages were calculated from data on the corresponding land classes within the limits of individual bioclimatic zones derived from the vegetation map. Finally, the averages for grasslands and brushwoods were calculated on the basis of the vegetation map classes (a total of 133 in the map legend), with regional corrections for the intensity and frequency of major disturbances of the vegetation, such as fires.

As the forest phytomass accounts for a major part of the total phytomass stock in Russia, the accuracy of its estimation is crucial for systemically evaluating the uncertainties of the results. Hence, the forest phytomass was additionally estimated by an independent method on the basis of data provided by the State Forest Inventory (SFI), which is the only source of information on all forests of Russia on a certain date. We used the SFI data of 1993 on each of approximately 1900 forest enterprises combined by ecoregions. For estimating the forest phytomass, we used multivariate regression equations for basic phytomass fractions: stem wood with bark, bark proper, crown wood with bark, leaves and needles, roots, undergrowth, and live ground vegetation. The development of aggregated models for the phytomass fractions of Russian forest ecosystems was considered in detail by Shvidenko *et al.* (2000); here, we provide only the necessary minimum of information.

To develop the models, a special DB was compiled, which included data on approximately 2700 sample plots used in more than 200 regional studies. The results of modeling showed that (1) indices reported by the SFI (growing stock, age, relative stocking density, and stand quality index by dominant species) were statistically significant ($P = 0.05$–0.1) in nonlinear regression equations of different analytical forms; therefore, only the multidimensional approach allowed us to extract the maximum amount of relevant information from the experimental data; (2) for evaluating phytomass by fractions, the following ratio proved to be most informative: $R_{fr} = M_{fr}/GS = f(A, SI, RS)$, where M_{fr} is the mass of a certain fraction, Mg ($= 10^6$ g $= 1$t) is dry matter; GS is growing stock, m^3; and A, SI, and RS are stand age, stand quality index, and relative stocking density, respectively. Eight types of nonlinear (in variables and coefficients) equations were tested, and the most accurate and adequate ones were used in the calculations. The multiple nonlinear correlation coefficients of regression equations varied from 0.4 for stem wood to 0.8 for foliage. The equations for major forest-forming species, which cover more than 95% of the forested areas, were usually derived for the European and Asian parts of Russia separately and, in some cases (for species covering vast areas), for aggregated bioclimatic zones. The systems analysis of uncertainties in modeling provided evidence that the regression equations produce no significant systematic errors and have acceptable random errors. The stocks of the phytomass fractions were calculated as $M_{fr} = R_{fr}\ GS^*$, where GS^* is the growing stock volume according to the SFI data.

The stock of coarse woody debris (CWD) was determined by two independent methods: one based on data included in the ecological DB, and the other, on the regional sets of forest inventory data. In both cases the model transformation of the initial data was necessary, as the ecological DB mostly provided data on the aboveground dead wood as a whole, and the forest inventory in Russia takes into account only a part of the CWD according to our definition (aboveground and onground dead wood is inventoried if its amount in a forest ecosystem exceeds a certain value, which varies from 10 to 30 m^3/ha depending on the method of inventory and the group of forests). The stock of dead roots was estimated using the data of the ecological DB and auxiliary models which took into account the effects of disturbances in forests (felling, fires, etc.) and the ratios between fine and coarse roots in the total stock of underground plant organic mass.

RESULTS AND DISCUSSION

The aggregated data on phytomass by major LULC classes are shown in Tables 1 (dry matter) and 2 (carbon). For forest ecosystems, we present the data calcu-

Table 1. Distribution of the phytomass of Russian terrestrial ecosystems by major land use/land cover classes and bioclimatic zones, Tg dry matter

Zone	Farmlands				Forests	Wetlands			GSL	Total
	arable	CMP	PER	total		swamps	bogs	total		
Arctic deserts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7
Tundras	0.0	10.0	0.0	10.0	109.2	834.8	151.9	986.7	2660.0	3765.9
Forest–tundra and northern taiga	2.4	7.2	0.4	10.0	6860.4	818.8	753.7	1772.5	487.1	9130.0
Middle taiga	59.9	62.2	3.6	125.7	41590.4	1037.1	1022.9	2060.0	3460.0	47236.1
Southern taiga	315.1	75.5	26.9	417.5	13802.3	84.7	775.1	859.8	480.1	15559.7
Temperate forests	239.2	54.9	32.7	326.8	3318.1	28.9	30.1	59.0	50.2	3754.1
Steppes	781.3	346.4	12.9	1140.6	720.8	9.1	3.8	12.9	390.6	2264.9
Semideserts and deserts	43.1	111.3	1.8	156.2	48.5	4.3	1.1	5.4	78.3	288.4
Total phytomass	1441.0	667.5	78.3	2186.8	66499.7	2817.7	2738.6	5556.3	7607.0	81799.8
Aboveground phytomass, %	61.3	46.9	78.4	57.5	77.9	65.5	53.6	59.6	41.8	72.7

Note: Here and in Tables 2–4, the number of decimal figures exceeds that required by the rules of approximate calculations. They are shown for the reason of arithmetic control and for taking into account considerable differences in the values of the parameters. The abbreviations are as follows: CMP, cultivated meadows and pastures; PER, perennial vegetation on farmlands; GSL, natural grasslands and brushwoods.

Table 2. Distribution of the phytomass of Russian terrestrial ecosystems by major land use/land cover classes and bioclimatic zones, Tg carbon

Zone	Farmlands				Forests	Wetlands			GSL	Total
	arable	CMP	PER	total		swamps	bogs	total		
Arctic deserts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3
Tundras	0.0	4.5	0.0	4.5	53.5	388.2	69.9	458.1	1215.3	1731.4
Forest–tundra and northern taiga	1.1	3.3	0.2	4.6	3375.3	395.1	350.5	745.6	224.6	4350.1
Middle taiga	26.9	28.2	1.7	56.8	20586.7	507.7	476.9	984.6	1611.7	23239.8
Southern taiga	141.8	34.2	13.2	189.2	6832.1	40.9	362.7	403.6	222.3	7647.2
Temperate forests	107.6	24.9	15.8	148.3	1635.8	13.9	14.0	27.9	23.2	1835.2
Steppes	351.7	156.6	6.2	514.5	354.6	4.3	1.7	6.0	176.9	1052.0
Semideserts and deserts	19.4	50.4	0.8	70.6	23.9	2.0	0.5	2.5	35.6	132.6
Total phytomass	648.5	302.1	37.9	988.5	32861.9	1352.1	1276.2	2628.3	3509.9	39988.6
Aboveground phytomass, %	61.3	46.9	80.2	57.6	78.0	66.3	54.6	60.6	42.9	73.3

lated by the SFI method, which are more detailed and precise. It is noteworthy that differences between estimates made by the SFI and GIS methods were –2.3% for the total forest phytomass and from –2.7 to +2.7% for aggregated phytomass fractions, i.e., both methods produced very close results.

The phytomass of Russian terrestrial ecosystems comprises 81800 Tg dry matter, or 39989 Tg carbon. A major part of the phytomass (82.1%) is concentrated in the forests (here and below, comparisons are made with respect to the carbon content); the class of grasslands and brushwoods accounts for 8.8%; wetlands, for 6.6% (of which bogs make up 3.2%); and farmlands, for only 2.5% of the total phytomass. A large proportion of the phytomass (55.6%) concentrates in the middle taiga subzone, which is explained by the large area of the latter (42.1% of the entire Russian land covered with vegetation). Forests have the highest phytomass density (4.30 kg C/m^2); the values of this parameter are relatively high for swamps, as this subclass includes a major part of unforested areas included in the forest fund (sparse forests, burned-out and dead stands, etc.).

Table 3. Density of the phytomass of Russian terrestrial ecosystems by major land use/land cover classes and bioclimatic zones, kg C/m^2

Zone	Farmlands				Forests	Wetlands			GSL	Total
	arable	CMP	PER	total		swamps	bogs	total		
Arctic deserts	0	0	0	0	0	0	0	0	0.05	0.05
Tundras	0	0.25	0	0.25	1.40	0.73	0.79	0.73	0.62	0.65
Forest–tundra and northern taiga	0.39	0.26	1.07	0.31	2.39	1.40	0.96	1.15	0.88	1.87
Middle taiga	0.51	0.31	1.48	0.39	4.52	2.39	1.17	1.59	1.05	3.44
Southern taiga	0.58	0.33	1.86	0.53	5.40	2.52	1.27	1.34	1.14	3.62
Temperate forests	0.51	0.34	1.44	0.50	6.18	2.31	1.20	1.57	0.87	3.04
Steppes	0.47	0.43	1.04	0.46	5.02	0.84	0.79	0.82	0.68	0.71
Semideserts and deserts	0.45	0.39	0.87	0.41	1.86	0.78	0.69	0.76	0.56	0.52
Total	0.50	0.38	1.48	0.47	4.30	1.28	1.10	1.19	0.81	2.454

The phytomass accumulation by the terrestrial vegetation as a whole and by individual LULC classes demonstrates a distinct bioclimatic zonal gradient (Table 3). For the entire land covered with vegetation, the biomass density averages 2.45 kg C/m^2 (or 5.02 kg/m^2 dry matter). The zonal density is minimal (0.05 kg C/m^2) in northern deserts and semideserts, increases to 0.65 kg C/m^2 in tundras, reaches its peak (3.62 kg C/m^2) in the southern taiga subzone, and decreases southward to 0.71 C/m^2 in the steppes and 0.52 kg C/m^2 in semideserts and deserts. The carbon of green parts comprises 3950 Tg (or 9.9% of the total amount); that of the aboveground wood is 63.8%, and 93% of this amount is in the forests. The proportion of underground phytomass averages 26.7% but varies greatly: from 22.0% in forests to 57.1% for grasslands and brushwoods.

The total stock of the phytomass in Russian forest ecosystems equals 32862 TgC, one-fourth (25.6%) is in European Russia and the rest is in Asian Russia. Stem wood with bark accounts for 60.2% of the forest ecosystem phytomass; contributions of other components are as follows: tree roots, 17.5%; crown wood, 8.8%; undergrowth and ground vegetation, 7.0%; and foliage, 3.9%. Forests with the prevalence of coniferous species contain 75.3% of the entire forest phytomass of Russia; 33.6% (of the total amount) are in larch forests, 16.7% in pine forests, 14.3% in spruce forests, 8.1% in cedar pine forests (*Pinus sibirica* and *P. korajensis*), and 2.5% in fir forests. Small-leaved deciduous (mostly birch and aspen) forests account for 18.7% of plant carbon, and hard-wooded deciduous forests (oak, hard-wooded birches, beech, etc.) account for only 3.4%. Brushwoods that are identified by current forest inventory as forested areas (for regions where “high” forests cannot grow because of severe climatic conditions) account for 2.6% of the total forest phytomass.

Table 4 presents aggregated estimates of the carbon in CWD and dead roots. CWD contains 4955 Tg carbon, of which 89% are in forests (the estimate for forests is an average of two independent estimates that differed by 3.6%). A considerable amount of carbon (9180 Tg) is concentrated in dead roots. The density of live and dead roots and the proportion of the latter in the total underground mass of vegetation demonstrate an obvious zonal gradient. The stock and proportion of fine roots (<2 mm) are especially important for gaining a deeper insight into the bioproduction process in terrestrial ecosystems, but the corresponding factual data (in particular, on Russian forests) are insufficient. Hence, the proportions of fine roots in the total underground phytomass were estimated on the basis of reported empirical ratios (Jackson *et al.*, 1996, 1997). According to the results obtained, the density of the total underground plant organic matter in forest ecosystems increases from 2.1–2.4 kg/m^2 (dry weight) in northern zones to a maximum of 3.56 kg/m^2 in the zone of temperate forests and subsequently decreases to 1.21 kg/m^2 in the forests of the semidesert and desert zones. The proportion of live fine roots (of the total underground root mass) is 8–12%, slightly increasing to the south. The proportion of dead fine roots is approximately one-fifth greater in northern zones and one-fifth smaller in the zone of temperate forests. Over all, the vegetation of the Russian terrestrial ecosystems contains 54124 Tg C; live phytomass and dead plant organic matter account for 73.9 and 26.1% of this amount, respectively.

Specific features of uncertainty estimation for tasks such as the full carbon budget were considered in our special study (Nilsson *et al.*, 2000). *Uncertainty* is the level of belief in the value by which the result obtained deviates from a true (and, apparently, unknown) value. For fuzzy problems, uncertainty cannot be determined by any formal methods; within the frameworks of individual models and series of measurements, it is only

Table 4. Stocks of dead plant organic matter, Tg dry matter and carbon

Land use/land cover classes and parameters	Dead plant organic matter by bioclimatic zones								Total, Tg	
	arctic deserts	tundras	forest–tundra and northern taiga	middle taiga	southern taiga	temperate forests	steppes	semideserts and deserts	dry matter	carbon
Dead roots										
Farmlands	0.0	0.0	0.1	0.2	1.8	2.0	1.2	0.6	5.9	2.8
Forests	0.0	55.6	1249.8	4996.1	1271.7	193.2	108.8	15.5	7890.7	3787.6
Wetlands	0.0	1630.5	1585.3	655.6	274.6	10.5	43.8	10.3	4210.6	1957.9
Grasslands and brushwoods	0.1	2928.1	443.1	3494.3	272.9	34.8	309.0	59.3	7541.6	3431.4
Total dry matter	0.1	4614.2	3278.3	9146.2	1821.0	240.5	462.8	85.7	19648.8	
Total carbon	0.1	2117.2	1538.7	4293.0	863.1	114.4	213.7	39.5		9179.7
Coarse woody debris										
Forests	0.0	13.0	1452.4	5436.7	1651.3	219.5	28.5	5.2	8806.6	4403.3
Wetlands	0.0	27.3	197.9	321.9	117.6	9.4	0.2	0.0	674.4	337.2
Grasslands and brushwoods	0.0	167.4	23.4	156.5	25.4	3.6	38.5	14.0	428.8	214.4
Total dry matter	0.0	207.7	1673.7	5915.1	1794.3	232.5	67.2	19.2	9909.7	
Total carbon	0.0	103.8	836.8	2957.6	897.2	116.2	33.6	9.6		4954.8
Sum total, dry matter	0.1	4821.9	4952.0	15061.3	3615.3	473.0	530.0	104.9	29558.5	
Sum total, carbon	0.1	2221.0	2375.5	7250.6	1760.3	230.6	247.3	49.1		14134.5

possible to calculate *precision* and *accuracy*. Without going into details, we should note that, according to our calculations, the precision in estimating the total phytomass stock is ±3.4% (a priori confidential probability 0.9) on the conditions that (1) the aggregated data of SFI and regression equations for both forest and agricultural phytomass have no significant biases and (2) maps used in the work adequately reflect the actual distribution of LULC classes and the boundaries of the initial polygons are drawn to an accuracy complying with the existing technological requirements of Russian cartography (errors generated by boundary shifting does not exceed 2 mm).

We compared the results obtained by different methods and analyzed their sensitivity to variation in the initial data, working hypotheses, and the accuracy and precision of models. On this basis, we came to the conclusion that, when their assumed variation remains within a reasonable range, errors in estimating the total phytomass stock and phytomass stocks by individual LULC classes do not exceed 6 and 4–8%, respectively (probability 0.9). Obviously, the reported figures are only true to the extent to which our DBs reflect reality. For instance, the average for the total underground phytomass stock of Russian forests is 22.0%, compared to 21.8% calculated from data on 1100 sampling plots distributed approximately in proportion to forest areas. This is no more than evidence that the calculations were fairly correct. “A chronic problem is the underestimation of fine roots biomass” (Jackson *et al.*, 1996), and there are indications that this is the problem with the available Russian data. In this respect, the greatest uncertainty is in the estimation of dead root stock, which is explained by (1) insufficient measurements, as only about 10% of the publications on forest bioproductivity include data on this parameter; (2) inconsistencies in approaches to the separation of the dead root fraction in areas with organogenic soils; and (3) a limited amount of data on disturbed areas (e.g., felling or burned-out areas), which greatly contribute to dead root stock. For these reasons, we consider our estimate of this stock for the entire country as some initial reference mark (we have not found any aggregated estimates for Russia in the available publications), and, in strict terms, its accuracy is unknown.

Tables 1–4 contain various data for comprehensive analysis, which the reader can perform independently, and we shall limit ourselves to only a few comparisons. The average of ten estimates of the global phytomass stock made during the past 20 years is about 578 Pg C (1 Pg = 10^{15} g = 10^9 t) (for review, see Goldewijk *et al.*, 1994), with an average density of 4.64 ± 0.64 (3.7–5.6) kg C/m^2. Thus, the total phytomass in Russia accounts for 6.4%, and its density is only 51% of this global estimate. Regional estimates calculated by major Dynamic Global Vegetation Models for northern Eurasia (e.g., IMAGE 2, Goldewijk *et al.*, 1994; TEM version 3, McGuire *et al.*, 1996) are approximately 2.5 times higher. Such a difference is explained by the fact that these models do not take into account the effect of disturbances, especially in forests. The last estimate of 466 Pg C for the entire plant carbon of the planet, made by the WBGU (1998), is very interesting and, in our opinion, most probable. The estimate for Russia comprises 11.6% of the latter.

N.I. Bazilevich's studies on terrestrial ecosystem bioproductivity in northern Eurasia are well-known. Based on her maps (Bazilevich, 1993), we estimated the stocks of the phytomass and necromass, which comprised 180.4 and 125.7 Pg dry matter, respectively. The corresponding phytomass density is 5.28 kg C/m^2; i.e., our estimate is only 45% of that calculated from the data of Bazilevich's maps. These maps were made for the *restored plant cover*, and, although this term has not been exactly defined in the available publications, its connection with the *potential* rather than *actual* vegetation is evident. Moreover, the initial data for making the production map reflected the results of biased sampling (e.g., with respect to the age and productivity of forests or the level of disturbances in tundra ecosystems). Hence, it is apparent that the aggregated data calculated on the basis of Bazilevich's maps are not intended for characterizing the *actual* productivity of terrestrial ecosystems and cannot be used for this purpose; they should be regarded only as an estimate of *achievable (optimal)* productivity (this fact by no means reduces the significance of Bazilevich's outstanding contribution to research on terrestrial ecosystem bioproductivity in northern Eurasia). Our estimates concerning dead organic matter (for comparable parameters) are also significantly lower.

We calculated the stock of phytomass in its "preindustrial" state using the data on land classes from the (potential) vegetation map and on the average phytomass densities from the ecological DB. The total stock was estimated at 104.8 Pg dry matter, which is approximately 30% greater than the estimate of the actual phytomass. Assuming that the level of natural disturbances and the productivity of nontransformed vegetation 300 years ago were similar to those observed today, it may be concluded that the anthropogenic transformation of vegetation during this period has resulted in the loss of at least 24 Pg of phytomass (dry matter).

Published data on the phytomass for some LULC classes, including forests, are fairly abundant. Our results for the tundra and forest–tundra zones are very close to those reported by Karelin *et al.* (1995). Their measurements were not included in our DB and, hence, can be regarded as an independent control. Two comprehensive inventories of the forest phytomass, both based on the SFI data of 1988, were made during the last five years (*Uglerod v ekosistemakh*…, 1994; Isaev *et al.*, 1995). Our estimate (by comparable parameters, such as average carbon density) is very close to their arithmetic mean: 7% lower than the estimate by Isaev *et al.* (1995) and 13% higher than that in *Uglerod v ekosistemakh*…(1994); therefore, current estimates of the Russian forest phytomass are consistent with one another. Other previous estimates of the Russian forest phytomass are 1.5–2 times higher (Dixon *et al.*, 1994; Kolchugina and Vinson, 1993), but they have not been based on any sufficiently designed inventory. As to the aboveground phytomass of forest stands, the average for Russia is very close to that for Canada (Bonnor, 1987). However, data on the aboveground phytomass of North American boreal forests (Botkin and Simpson, 1990) amount to only 60% of the average value for Russia.

REFERENCES

Bazilevich, N.I., *Biologicheskaya produktivnost' ekosistem Severnoi Evrazii* (Biological Productivity of Ecosystems in Northern Eurasia), Moscow: Nauka, 1993.

Bonnor, G.M., Forest Biomass Inventory, in *Biomass: Regerenable Energy*, Hall, D.O. and Overend, R.P., Eds., Wiley, 1987, pp. 47–73

Botkin, D.V. and Simpson, L.G., Biomass of the North American Boreal Forest, *Biogeochemistry*, 1990, vol. 9, pp. 161–174.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., and Wisniewski, J., Carbon Pools and Fluxes of Global Forest Ecosystems, *Science*, 1994, vol. 263, pp. 185–190.

FAO, A Framework for Land Evaluation, *Soil Bull.*, 1976, no. 32, p. 79.

Goldewijk, K.K., van Minnen, J.G., Kreileman, G.J.J., Bloedbeld, M., and Leemans, R., Simulating the Carbon Flux between the Terrestrial Environment and the Atmosphere, *Water, Air, Soil Pollut.*, 1994, vol. 76, pp. 99–230.

Isaev, A.S., Korovin, G.N., Utkin, A.I., Pryashnikov, A.A., and Zamolodchikov, D.G., Carbon Stock and Deposition in Phytomass of the Russian Forests, *Water, Air, Soil Pollut.*, 1995, vol. 70, pp. 247–256.

Jackson, R.B., Canadell, J., Ehleringer, J.B., *et al.*, A Global Analysis of Root Distribution for Terrestrial Biomes, *Oekologia*, 1996, vol. 108, pp. 389–411.

Jackson, R.B., Mooney, H.A., and Schulze, E.-D., A Global Budget for Fine Root Biomass, Surface Area, and Nutrient Contents, *Proc. Natl. Acad. Sci. USA*, 1997, vol. 94, pp. 7362–7366.

Karelin, D.V., Zamolodchikov, D.G., and Gil'manov, T.G., Carbon Stocks and Production in the Phytomass of Russian Tundra and Forest–Tundra Ecosystems, *Lesovedenie*, 1995, no. 8, pp. 29–36.

Kolchugina, T.P. and Vinson, T.S., Carbon Sources and Sinks in Forest Biomes of the Former Soviet Union, *Global Biogeochem. Cycles*, 1993, no. 7(2), pp. 291–304.

Krylatov, A.K., Nosov, S.I., Yuditskii, B.A., *et al.*, *Dinamika balansa gumusa na pakhotnykh zemlyakh Rossiiskoi Federatsii* (Dynamics of Humus Balance in Arable Lands of the Russian Federation), Moscow: Goskomzem Rossii, 1998.

Kurnaev, S.F., *Lesorastitel'noe raionirovanie SSSR* (Forest Site Zoning of the Soviet Union), Moscow: Nauka, 1973.

Matthews, G., *The Carbon Content of Trees, Forestry Committee Technical Paper 4*, Edinburgh, 1993, p. 21.

McGuire, A.D., Kicklighter, D.W., and Melillo, J.M., Global Climate Change and Carbon Cycling in Grasslands and Coniferous Forests, *Global Change: Effects on Coniferous Forests and Grasslands, SCOPE 56*, Breymeyer, A.I., Hall, D.O., Melillo, J.M., and Agren, G.I., Eds., Wiley, 1996, pp. 389–411.

Nilsson, S., Shvidenko, A., Stolbovoi, V., *et al.*, Full Terrestrial Carbon Budget: Case Study for Russia, *IR, International Institute for Applied Systems Analysis*, Laxenburg, Austria, 2000, p. 140.

Shvidenko, A., Nilsson, S., Shepashenko, D., and Lakida, P., Models for Aggregated Estimations of Forest Ecosystems Phytomass of Northern Eurasia, *IR, International Institute for Applied Systems Analysis*, Laxenburg, Austria, 2000, p. 32.

Stolbovoi, V., Fischer, G., Sizov, V., and Rozhkova (Kravets), B., *Georeferenced Database of the Former USSR*, vol. 5: *Land Categories. IR-97-087*, Laxenburg, Austria): IIASA, 1997, p. 15.

Uglerod v ekosistemakh lesov i bolot Rossii (Carbon Storage in Forests and Peatlands of Russia), Alexeyev, V.A. and Birdsey, R.A., Eds., Krasnoyarsk: Inst. Lesa im. Sukacheva, Ross. Akad. Nauk, 1994.

Utkin, A.I., Biological Productivity of Forests (Research Methods and Results), *Itogi Nauki Tekh. Ser.: Lesoved., Lesovod.*, Moscow: VINITI, 1975, vol. 1, pp. 9–189.

Vedrova, E.F., Carbon Pools and Fluxes of 25-Year Old Coniferous and Deciduous Stands in Middle Siberia, *Water, Air, Soil Pollut.*, 1995, vol. 82, nos. 1, 2, pp. 239–246.

WGBU, *Die Anrechnung biologisher Quellen und Senken im Kyoto-Protokoll: Fortschritt oder Rückschlag für dem globalen Umweltschutz*, Bremerhaven (Germany), 1998, p. 76.