

Carbon deposition by Russian forests on the example of taiga and forest-steppe zones

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Abstract. Due to the global warming of the climate, the assessment of the carbon cycle in forest ecosystems has become particularly important. One method for determining deposited carbon is based on the use of biomass expansion factors (BEF) and State Forest Inventory (SFI) data. By combining BEF models with SFI data in two ecoregions of Russia – taiga and forest-steppe - it was found that over a 20-25-year period, accumulating the carbon deposition in the taiga zone is significantly less (5%) compared to the forest-steppe zone (39%). Comparable results were obtained by the same method in different ecoregions of the planet (from 8% in 5 years in China to 68% in 50 years in Japan). A comparison of the results obtained by the proposed method and the IIASA method showed a minimal discrepancy (3%), which gives reason to consider the above estimates of carbon deposition close to reality. However, uncertainties remain related to the quality of the SFI data and the carbon deposition in the soil.

Keywords: carbon deposition, Russian forests, taiga, forest-steppe, expansion factors, forest inventory data.

1. Introduction

In recent years, the world is moving towards a low-carbon economy in order to prevent global climate change. The world's forests are the main stabilizing element of the earth's climate system, providing a carbon sink to the vegetation cover (Pan et al., 2011; Shvidenko & Schepaschenko, 2014). Russia, as a full member of the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement, has committed itself to limit greenhouse gas emissions at 70-75% of the 1990 level by 2030, subject to the maximum absorption capacity of forests (Analytical report, 2016). Countries that are parties to the UNFCCC are required to prepare and submit national reports to assess the level of carbon stock in their countries.

The current global warming caused by the anthropogenic increase in the concentrations of greenhouse gases in the atmosphere has led to a rapid increase in the number of scientific papers devoted to the assessment of the carbon cycle and other climate-

forming functions of forest cover. There are two generally accepted approaches to the calculation of wood biomass included in the carbon cycle using State Forest Inventory (SFI) data. The first is based on the use of allometric equations, the second is based on the use of biomass expansion factors (BEFs) (IPCC, 2003). BEF is defined as the ratio of total stand biomass (including above-, belowground and understorey) divided by stem volume. A comparison of these two methods in relation to the forests of Russia, Slovakia and Spain showed the results similar between methods (Utkin et al., 1997; Konôpka et al., 2011; González-García et al., 2013).

There are offered the BEFs in the form of mean values for woody species (Makarevskiy, 1991; Isaev et al., 1993; Van Camp et al., 2004; Durkaya et al., 2020), or dependent on stand age (Zamolodchikov et al., 1998; Lehtonen et al., 2007; Van Den Berge et al., 2021) or dependent on stem volume (Guo et al., 2010; Tang et al., 2016), or dependent on several of biometric indices obtained in the course of forest inventory (Shvidenko et al., 2007; Usoltsev et al., 2008; Teobaldelli et al., 2009; Usoltsev et al., 2011; González-García et al., 2013).

Estimates of carbon sink to Russian forests published in recent years range from 100 to 600 Mt C per year (Moiseev & Alyabina, 2007; Zamolodchikov et al., 2007; Vaganov et al., 2008; Moiseev & Filipchuk, 2009; Shvidenko et al., 2010a, 2011), which means that there may be biases that exceed the absolute values of the estimates (Zamolodchikov et al., 2011). Forest fires in Russia significantly reduce the actual carbon sink to Russian forests (Goodale et al., 2002; Shvidenko & Schepaschenko, 2013). In addition, there are conflicting trends in the component composition of forest biomass due to climate change (Lapenis et al., 2005). According to Houghton et al. (2009), our knowledges about changes in the biomass of the vegetation cover of the planet are still rudimentary in many respects.

The assessment of the forest carbon budget should be complete and verified (Nilsson et al., 2007; Shvidenko & Schepaschenko, 2014). It should include all classes of forest land and all the diversity of ecosystems. However, the full carbon budget represents a typical fuzzy system due to the incompleteness of our knowledge and the inability to verify the results (Nilsson et al., 2007). According to the Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC, 2003), the national reporting of carbon changes in woody biomass stocks can be calculated by a default method as the difference between growth and drain (harvest, natural mortality and natural disturbances) (Chapin et al., 2005; Stinson et al., 2011; Zamolodchikov et al., 2011; Shvidenko & Schepaschenko, 2014). Alternatively, these changes can be calculated by the stock change method as the change in stocks between two

consecutive inventories (Gitarsky et al., 2006; Zamolodchikov et al., 2007; Petersson et al., 2012). Although the validity of the second method was questioned (Moiseev & Filipchuk, 2009), the results of estimates of carbon deposition by Russian forests for the period since 1988 to 2005 were quite close (93 Mt per year versus 109 Mt per year) (Zamolodchikov et al., 2011). The authors note that after 2007 (when the SFI system was destroyed), the use of the second method in assessing carbon deposition in Russian forests became impossible (Zamolodchikov et al., 2011).

In our study, an attempt is made to estimate the change in the carbon pool in forested areas over a 20-25-year period using the example of two ecoregions of Russia, represented by the taiga and forest-steppe zones. The carbon of soils and agricultural land was not taken into account.

2. Objects and methods

In Russia, the main administrative unit of the State Forest Inventory (SFI) until 2006 was the state forestry enterprise (*leskhoz*). The forested area of each forestry enterprise was divided into relatively homogeneous inventory units (*vydel*, or polygon) ranging from 3 to 5 ha in European Russia to more than 50 ha in Siberia. Every 10-12 years, detailed ground taxation was carried out at these polygons and the species composition, the average diameter of trees at breast height, the height of the stand, the basal area in m² per ha, the stem volume in m³ per ha and the site index were determined (Lapenis et al., 2005; Shvidenko et al., 2007).

The data of polygon inventory were stored in forest management enterprises, and, these data were grouped by species, age groups, and stem volume for the aim of forest management (Table 1). Determining the biomass of stands was not part of the forest inventory task. After the introduction of the New Forest Code in 2006, the forest inventory system was destroyed.

In our study, the taiga and forest-steppe zones are represented by Perm and Orenburg territories, respectively (Fig. 1), in which we attempted to estimate the accumulation of forest biomass during the period preceding the destruction of the forest inventory system, i.e., since 1987 to 2007 in Perm (20 years) and since 1982 to 2007 in Orenburg (25 years) areas. The SFI system in Russian forests gave usually underestimated values of stem volume by 13 % (Kinnunen et al., 2007) and by other sources – up to 15% (Shvidenko et al., 2010b). Since our estimates are based on the difference in stem volume over a certain period of time, this underestimation should not cause any biases in our results.

In the Perm territory, the average annual air temperature is $+1.3^{\circ}\text{C}$. The average annual precipitation varies in the direction from the southwest to the northeast - from 450 to 1000 mm. In the Orenburg region, the average annual air temperature varies from $+2.5^{\circ}\text{C}$ in the north to $+4.5^{\circ}\text{C}$ in the south of the region. The average annual precipitation ranges from 450 mm in the north-west to 350 mm in the south and south-east of the region (Efimov, 1999). The Orenburg territory is located in the forest-steppe subzone that is a typical ecotone between the taiga and the steppe. It is characterized by an area of strong competition between forest and steppe vegetation, which are described by the phenomenon of hysteresis (trigger), i.e. a jump-like transition from one stable state to another (Armand, 1989; Armand & Vedyushkin, 1989; Vedyushkin, 1989, 1992). In this state, there are changing roles of heat and moisture as limiting factors of biological productivity. In the taiga zone, biological productivity increases due to the increase in heat supply, and in the steppe zone - with an increase in moisture supply. In the taiga zone, the growth of moisture leads to a decrease in biological productivity, and in the steppe zone, on the contrary, to its increase (Bazilevich et al., 1986).

Table 1. The data of the SFI in 2007 to Veslyansk forest enterprise on Perm territory: the first number is the forested area, ha; the second number is the average stem volume in the set of polygons of the given age group, m³ per ha; the third number is the total stem volume, thousand m³

Species	Stand age, years*					Total
	10(5)	30(15)	60(30)	80(40)	100(50) and above	
Scots pine	55,761/20.2	183,266/59.7	93,695/138.8	10,053/168.0	40,794/140.5	383,569/84.7/32,497.4
Spruce	16,802/14.0	22,156/48.4	11,856/130.5	4,346/156.4	104,273/167.1	159,433/131.4/20,957.4
Larch	-	37/100.0	-	-	244/143.4	281/137.7/38.7
Birch	14,535/11.6	10,277/38.1	39,216/118.1	15,031/200.9	9,732/183.5	88,791/112.6/9,997.1
Aspen	922/20.1	377/60.5	101/99.0	293/136.9	2,694/242.1	4,387/169.5/743.5
Total	88,020/17.6	216,113/57.6	144,868/132.5	29,723/182.6	157,737/162.5	636,461/100.9/64,234.1

*10...100 – age of coniferous species; (5)...(50) – age of small-leaved species.



Figure 1. The position of the Perm and Orenburg territories on the map of Russia

To assess the carbon-depositing capacity of the forests of the Urals and adjacent regions, a database on the structure of the biomass of forest-forming species was compiled on the basis of published works. It includes materials from 1357 sample plots, including for: *Pinus sylvestris* L. - 326, *Picea obovata* Ldb. - 71, *Abies sibirica* Ldb. - 52, *Larix Sukaczewii* N.Dyl. - 176, *Pinus sibirica* Du Tour. - 73, *Betula alba* L. - 172, *Populus tremula* L. - 81, *Alnus incana* (L.) Moench and *Alnus glutinosa* (L.) Gaern. – 64, *Tilia cordata* Mill. – 215 and *Quercus robur* L. – 127.

Based on the compiled database, regression models of the common form are calculated for each tree species:

$$\ln(BEF) = f [\ln A, (\ln A)^2, \ln V], \quad (1)$$

where BEF is the ratio of component stand biomass ($P_i, t \cdot ha^{-1}$) divided by stand stem volume ($V, m^3 \cdot ha^{-1}$); P_i includes P_S, P_F, P_B, P_R и P_U , i.e. the biomass of stems, foliage, branches, roots and the understorey, correspondingly, t per ha; A is the age of the stand, years; V is the stem volume, m^3 per ha. The calculated models (1) are published previously (Usoltsev, 2007; Table 4.22) and (Usoltsev, 2018; Table 2.1) and are not given here due to the large volume. The models are statistically significant at $p < 0.05$, and their determination coefficients range from 0.99 to 0.29.

The spreadsheets similar to Table 1 are compiled for each of the 32 forestry enterprises of the Perm territory and 27 forestry enterprises of the Orenburg territory. By tabulating models (1) upon stem volume V and stand age A , the P_i values for each forestry enterprise are calculated, weighted by age classes, stem volume, and the share of each tree species. The obtained values were multiplied by the forested area in each cell of a spreadsheet and summed up. The sequence of operations for combining models (1) with SFI data was shown earlier (Usoltsev et al., 2008;

Usoltsev, 2018). An automated version of the calculation algorithm is given in (Usoltsev et al., 2011). The absolutely dry mass of all components is converted to the carbon mass by a conversion factor of 0.5 (Matthews, 1993).

3. Results and discussion

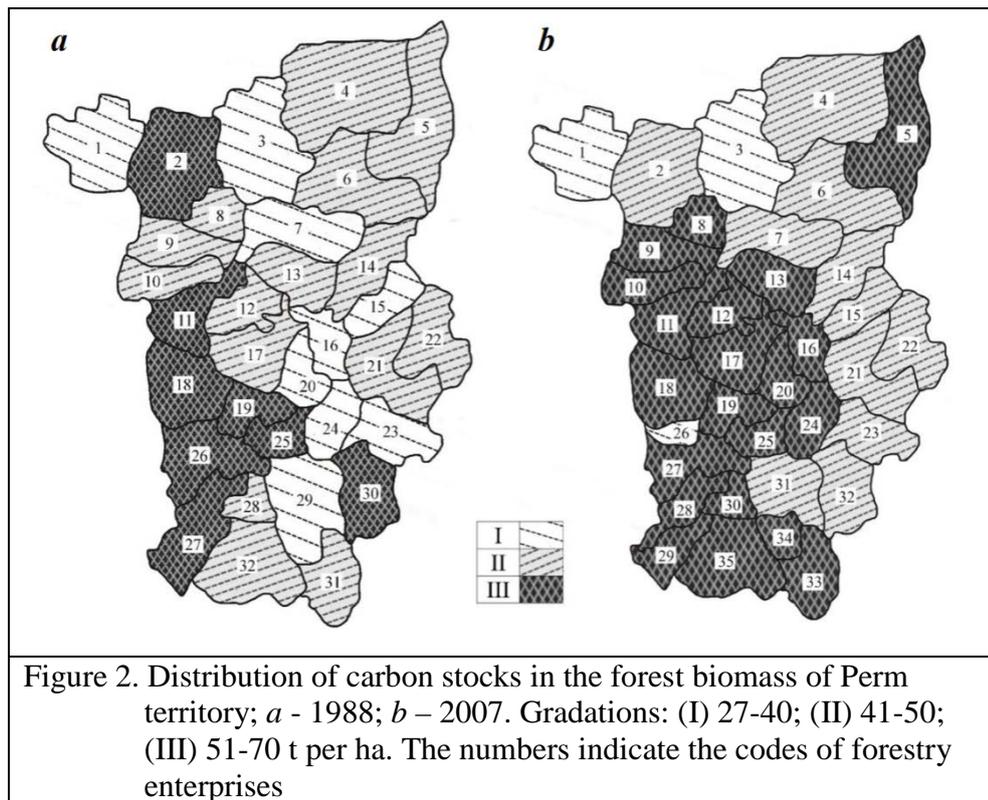
As a result of the combination of models (1) with SFI data, it was found that over 20 years (from 1987 to 2007) in the Perm territory, the total carbon stock in the biomass of forested areas increased from 458.5 to 479.2 million tons, or by 5%. In the Orenburg region, the carbon stock increased from 14.6 to 20.3 million tons, or 39%, over 25 years (from 1982 to 2007). In the Perm territory, the increase was mainly due to forest expansion and regrowth. In the Orenburg territory, the increase in carbon deposition occurred by 11% due to forest expansion and by 89% due to an increase in stem volume as a result of the growth of stands represented by young trees on 20-30% of the forested area.

We believe that the latest result obtained for the Orenburg territory is important. Its specificity is that, firstly, the region is located on the ecotone between the taiga and the steppe, and, secondly, a significant part of its territory is occupied by plantations. It is known that under severe growth conditions, afforestation opportunities are greatly reduced when the productivity of stands is due to a high risk of natural disturbances (Mansuy et al., 2013). Before afforestation can be considered as a contribution to climate change mitigation efforts, information is needed on the relationship between site productivity and risks from fires and droughts. Otherwise, afforestation may not be successful (Utkin, 2001; Mansuy et al., 2013). Our calculations have shown that, despite the existing risks of natural disasters in the forest-steppe ecotone, there is a significant increase in carbon deposition over a quarter of a century.

The values of the carbon pool in all forestry enterprises are grouped according to three gradations of the pool and are presented in the form of schematic maps (Fig. 2 and 3). It is obvious the shift of the carbon pool levels in the Perm territory in the eastern direction, i.e. in the direction of the western foothills of the Urals (Fig. 2). The shift of the carbon pool levels in the Orenburg territory occurred in the direction from north to south, i.e. from the southern taiga subzone to the steppe one (Fig. 3).

As a result of ignoring the changes in the soil carbon pool over the last quarter of a century, we can consider the results obtained as preliminary in our study. Nevertheless, the increase in the carbon pool in the two ecoregions of Russia in the range from 5 to 39% is comparable to the estimate of a similar indicator for the forests of Finland at 29%, calculated using the similar method of changes in stem volume for the period from 1922 to 2004 (Liski et al., 2006). Our results are also comparable to the estimate of the change in the carbon pool in

China's forests from 1984 to 2003, which was determined using the same method of the difference in stem volume for the mentioned period (Guo et al., 2010). This increase was 17% for boreal forests and 30% for deciduous species of temperate forests. For all forests in China, the same estimation method showed a 45% increase in the carbon pool over the same period (Xu et al., 2007) and a 37% increase (Fang et al., 2007), and an 8% increase between 1988 and 1993 (Pan et al., 2004). For the sub-equatorial zone of China, this increase from 1989 to 2003 was 17% (Yang & Guan, 2008). For all forests in Japan, a similar increase over the half-century (from 1947 to 1995) was 68% (Fang et al., 2005).



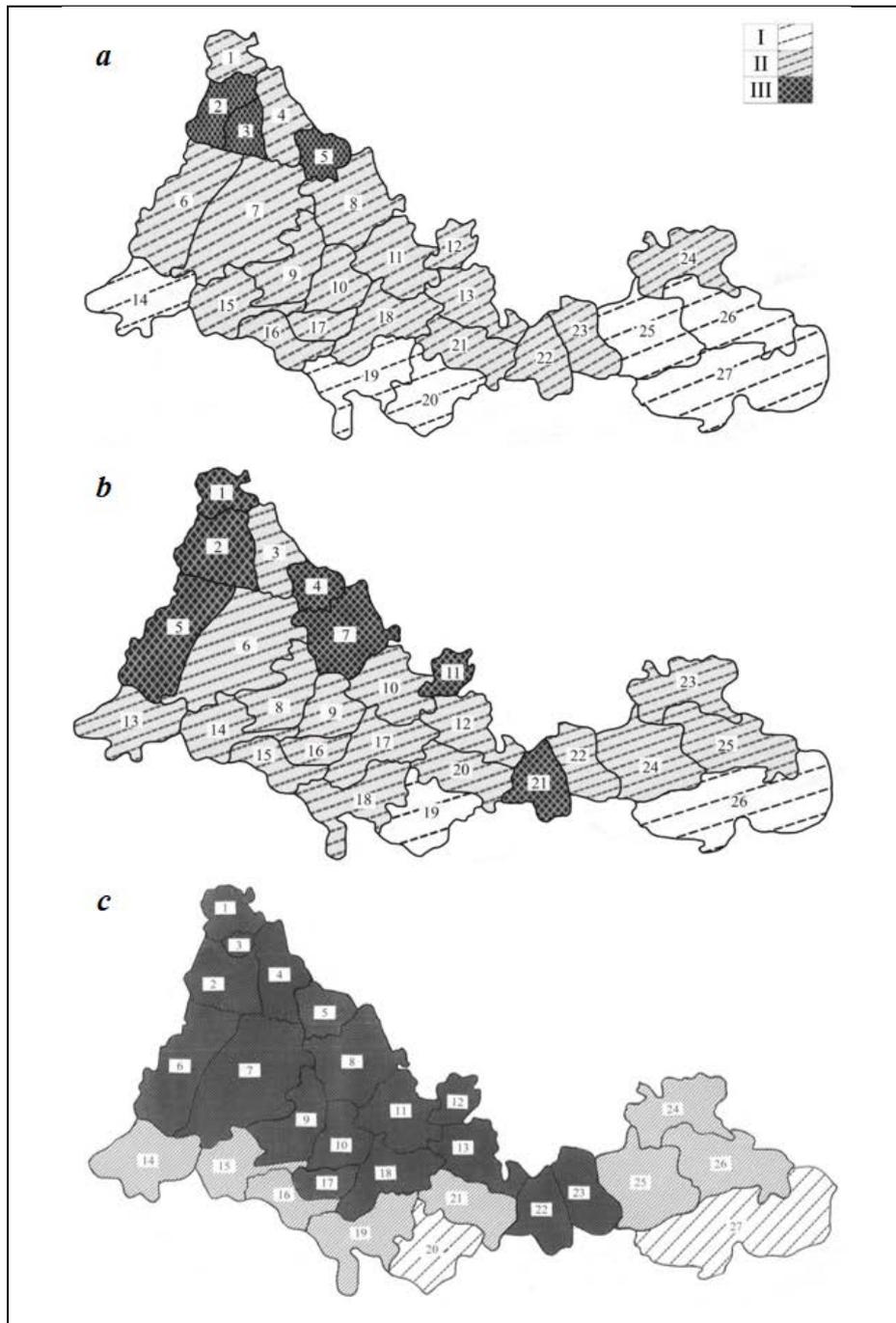


Figure 3. Distribution of carbon stocks in the forest biomass of Orenburg territory; *a* – 1982; *b* – 1993; *c* – 2007. Gradations: (I) 0.5-10; (II) 11-37; (III) 38-42 t per ha. The numbers indicate the codes of forestry enterprises

But our results are not comparable to the results obtained for the Russian forests for the period from 1988 to 2005 using the default method as the difference between growth and drain (Zamolodchikov et al., 2011). According to their calculations, the carbon sink to the forests of Russia has tripled over this period.

As mentioned above, the total carbon budget of forests is a fuzzy system due to the incompleteness of our knowledge and the inability to verify the results (Nilsson et al., 2007;

Shvidenko et al., 2010b). While verification of empirical biomass or BEF models is in principle possible using independent samples (Lau et al., 2019), verification of SFI data is in principle impossible, although attempts are being made to correct them (Alekseev & Markov, 2003).

Therefore, the question of verifying the results of carbon accumulation in two ecoregions of Russia can only concern the correctness of the calculation algorithm proposed by the authors. If the same result is obtained using two completely different methods, then the conclusion that both methods are correct is closer to reality than the conclusion that both methods are incorrect. However, there was a case when three methods were used to assess the net biome production (NBP) of Russian forests, each of which had its inherent uncertainties. However, the results obtained were close (-615, -662, -554 Tg C per year) (Dolman et al., 2012).

When using the same data of SFI of Russia at 2007, the calculations of the carbon pool in the Ural region in the area of 62 million hectares were fulfilled, as in the above method, and the method developed at IIASA (Austria). It turned out that the results obtained by two different methods differ by only 3% (Shvidenko et al., 2010b). This gives reason to believe that the obtained values of carbon deposition in the two ecoregions of Russia are close to reality, although there are still uncertainties related to the quality of the SFI data and soil carbon.

4. Conclusions

The following conclusions can be drawn from the results of the review and discussion presented in this paper:

- Of the two most common methods for estimating carbon deposition - using allometric equations and BEF – only the second of them is applicable for Russian forests due to the specific nature of the SFI.

- The method of estimating carbon deposition for a certain calendar period based on the difference in stem volume has disadvantages associated with inaccurate estimates of stem volume during forest inventory. However, the default method can significantly overestimate the estimates of deposited carbon.

- Our estimates of carbon deposition in the forests of two ecoregions of Russia over a period of 20-25 years showed that in the taiga zone its value is significantly less (5%) compared to the forest-steppe zone (39%). Comparable results were obtained by the same method in different ecoregions of the planet (from 8% in 5 years in China to 68% in 50 years in Japan).

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