Ecological Questions 32 (2021) 3: 49–57 http://dx.doi.org/10.12775/EQ.2021.23

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

Vladimir Andreevich Usoltsev[1,2], **Walery Zukow**[3,*], **Ivan Stepanovich Tsepordey**[2]

[1]Ural State Forest Engineering University, 620100 Yekaterinburg, Sibirskiy Trakt, 37, Russia
[2]Botanical Garden of Ural Branch of RAS, 620144 Yekaterinburg, str. 8 Marta, 202a, Russia
[3]Faculty of Earth Sciences and Spatial Management, Nicolaus Copernicus University, Lwowska 1 str., 87-100 Toruń, Poland
*corresponding author e-mail: zukow@wp.pl

Received: 24 February 2021 / Accepted: 9 April 2021

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 destroyd), 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 m^2 per ha, the stem volume in m^3 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°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°C in the north to +4.5°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).

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 plotss, 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:

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

where *BEF* is the ratio of component stand biomass (P_i, t·ha^{-1}) divided by stand stem volume (V, m^3·ha^{-1}); P_i includes P_S, P_F, P_B, P_R and 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.

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, m^3 per ha; the third number is the total stem volume, thousand m^3

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

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

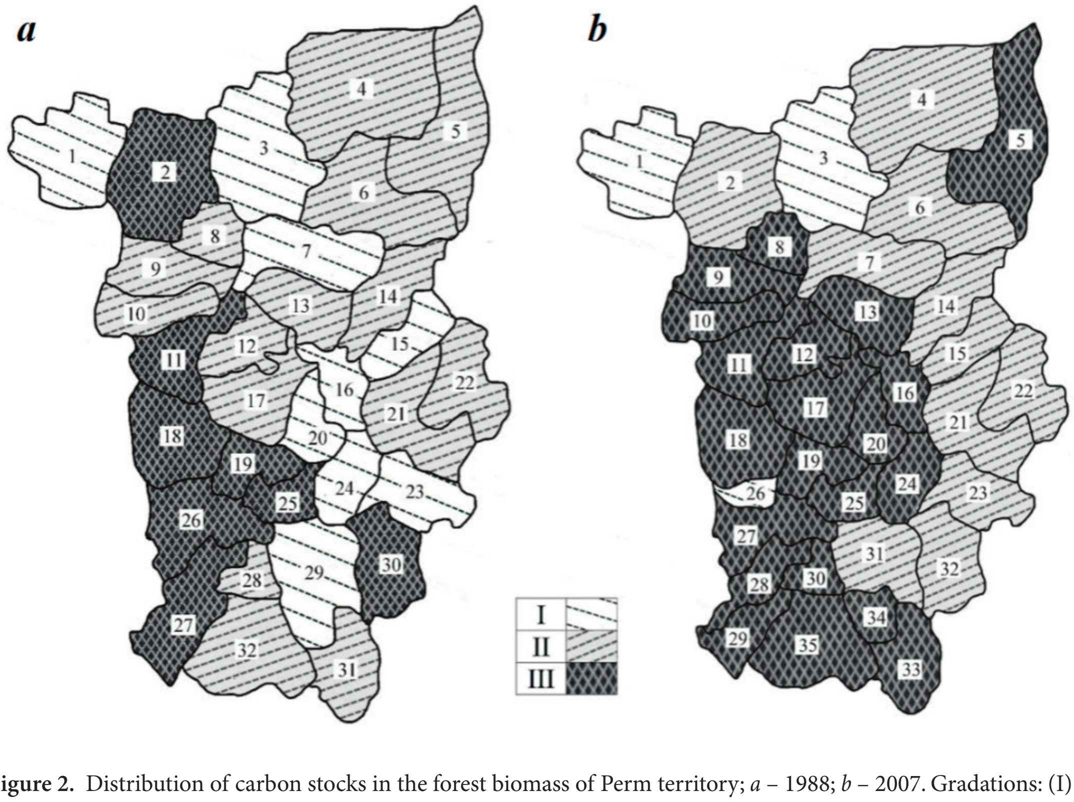

Figure 2. Distribution of carbon stocks in the forest biomass of Perm territory; *a* – 1988; *b* – 2007. Gradations: (I) 27–40; (II) 41–50; (III) 51–70 t per ha. The numbers indicate the codes of forestry enterprises

(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).

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

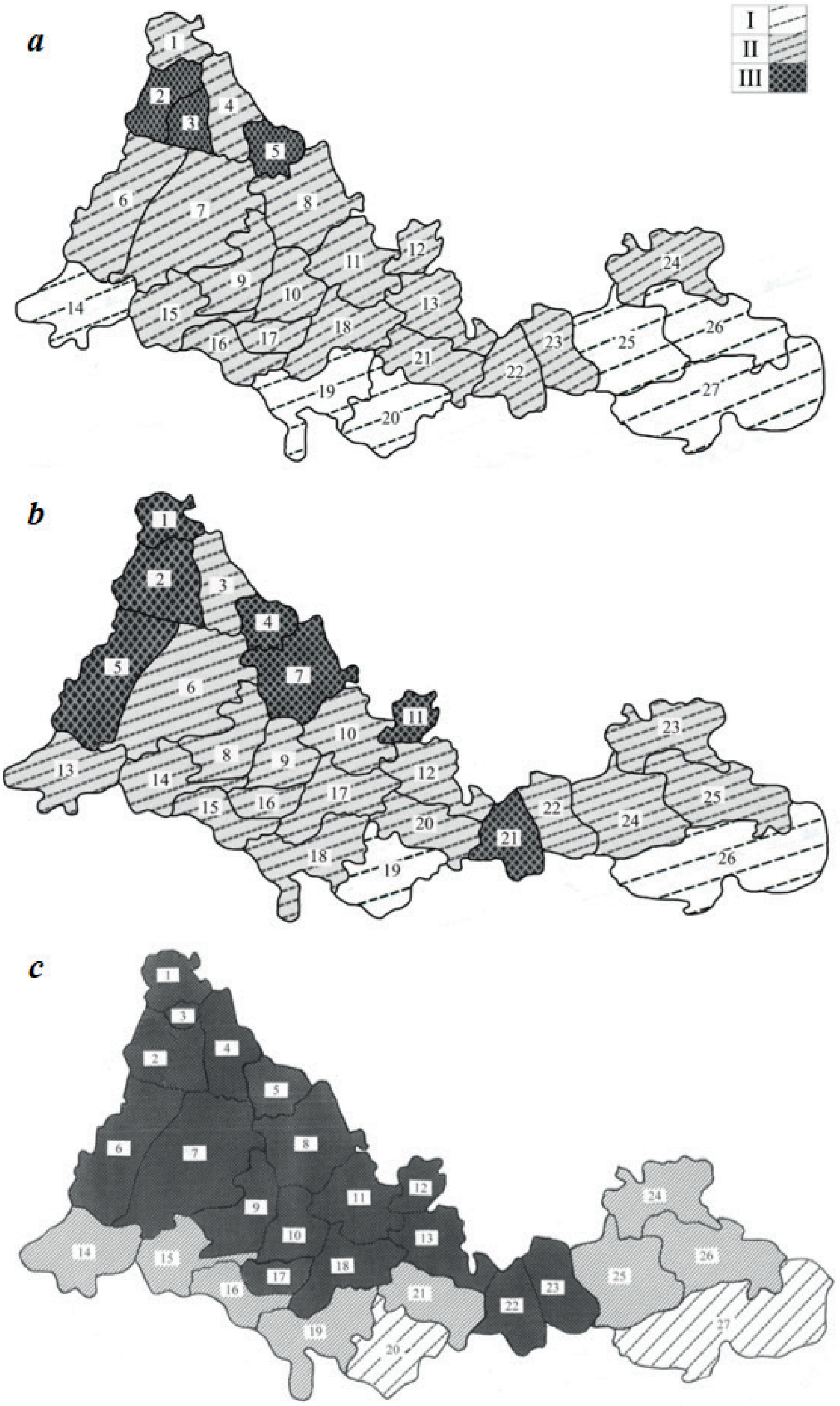

Figure 3. Distribution of carbon stocks in the forest biomass of Orenburg territory; *a* – 1982; *b* – 1993; c – 2007. Gradations: (I) 0.5–10; (II) 11-37; (III) 38–42 t per ha. The numbers indicate the codes of forestry enterprises

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).

References

Alekseev V.A. & Markov M.V., 2003, Statistical data on the forest fund and changes in forest productivity in Russia in the second half of the twentieth century. Saint-Petersburg Forest Ecological Center, Saint-Petersburg.

Analytical report, 2016. Risks of the implementation of the Paris Climate Agreement for the economy and national security of Russia. Institute of the Problems of Natural Monopolies, Moscow.

Armand A.D., 1989, Homeostasis of ecosystems [in:] Ecosystems are in a critical states. Nauka Publ., Mocow: 10–23.

Armand A.D. & Vedyushkin M.A., 1989, Trigger geosystems. Institute of Geography of the USSR Academy of Sciences, Moscow, 51 pp.

Bazilevich N.I., Grebenshchikov O.S. & Tishkov A.A., 1986, Geographical regularities of the structure and functioning of ecosystems. Nauka Publ., Moscow.

Chapin F.S., Woodwell G.M., Randerson J.T., Rastetter E.B., Lovett G.M., Baldocchi D.D., Clark D.A., Harmon M.E., Schimel D.S., Valentini R., Wirth C., Aber J.D., Cole J.J., Goulden M.L., Harden J.W., Heimann M., Howarth R.W., Matson P.A., McGuire A.D., Melillo J.M., Mooney H.A., Neff J.C., Houghton R.A., Pace M.L., Ryan M.G., Running S.W., Sala O.E., Schlesinger W.H. & Schulze E.-D., 2005, Reconciling carbon-cycle concepts, terminology and methodology. Ecosystems 9: 1041–1050. DOI: 10.1007/s10021–005–0105–7

Dolman A.J., Shvidenko A., Schepaschenko D., Ciais P., Tchebakova N., Chen T., van der Molen M.K., Belelli Marchesini L., Maximov T.C., Maksyutov S. & Schulze E.-D., 2012, An estimate of the terrestrial carbon budget of Russia using inventory-based, eddy covariance and inversion methods. Biogeosciences 9: 5323–5340. DOI:10.5194/bg-9-5323-2012

Durkaya B., Durkaya A. & Kaptan S., 2020, BEF-BCEF calculations for Turkey's impotant coniferous species. Bartın Orman Fakültesi Dergisi 22(3): 1053–1060. DOI: 10.24011/barofd.806310

Efimov A.I., 1999, Climate [in:] Geographical atlas of the Orenburg Region. DIK Publ, Moscow: 32–35.

Fang J.Y., Guo Z.D., Piao S.L. & Chen A.P., 2007, Terrestrial vegetation carbon sinks in China, 1981–2000. Science in China Series D: Earth Sciences 50(9): 1341–1350.

Fang J.Y., Oikawa T., Kato T., Mo W. & Wang Z.H., 2005, Biomass carbon accumulation by Japan's forests from 1947–1995. Global Biogeochemical Cycles 19, GB2004. DOI:10.1029/2004GB002253.

Gitarsky M.L., Zamolodchikov D.G., Korovin G.N. & Karaban R.T., 2006, Emission and absorption of greenhouse gases in the forests of Russia in connection with the fulfillment of obligations under the UN Climate Convention. Lesovedenie [Russian Journal of Forest Science] 6: 34–44.

González-García M., Hevia A., Majada J. & Barrio-Anta M., 2013, Above-ground biomass estimation at tree and stand level for short rotation plantations of *Eucalyptus nitens* (Deane & Maiden) Maiden in Northwest Spain. Biomass and Bioenergy 54: 147–157. DOI: 10.1016/j.biombioe.2013.03.019

Goodale C.L., Apps M.J., Birdsey R.A., Field C.B., Heath L.S., Houghton R.A., Jenkins J.C., Kohlmaier G.H., Kurz W., Liu S.R., Nabuurs G.-J., Nilsson S. & Shvidenko A., 2002, Forest carbon sinks in the northern Hemisphere. Ecological Applications 12: 891–899. DOI: 10.1890/1051-0761(2002)012[0891:FCSITN]2.0.CO;2

Guo Z.D., Fang J.Y., Pan Y.D. & Birdsey R., 2010, Inventory-based estimates of forest biomass carbon stocks in China: A comparison of three methods. Forest Ecology Management 259: 1225–1231. DOI: 10.1016/j.foreco.2009.09.047

Houghton R.A., Hall F. & Goetz S.J., 2009, The importance of biomass in the global carbon cycle. Geophysical Research Letters 114: G00E03. DOI: 10.1029/2009JG000935

IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. IPCC/OECD/IEA/IGES, Hayama, Japan.

Isaev A.S., Korovin G.N., Utkin A.I., Pryazhnikov A.A. & Zamolodchikov D.G., 1993, Estimation of carbon pool and its annual deposition in phytomass of forest ecosystems in Russia. Lesovedenie [Russian Journal of Forest Science] 5: 3–10.

Kinnunen J., Maltamo M. & Päivinen R., 2007, Standing volume estimates of forests in Russia: how accurate is the published data? Forestry 80 (1): 53–64. DOI: 10.1093/forestry/cpl042

Konôpka B., Pajtík J., Šebeň V. & Lukac M., 2011, Below-ground biomass functions and expansion factors in high elevation Norway spruce. Forestry 84(1): 41–48. DOI:10.1093/forestry/cpq042

Lapenis A., Shvidenko A., Schepaschenko A.D., Nilsson S. & Aiyyer A., 2005, Acclimation of Russian forests to recent changes in climate. Global Change Biology 11: 1–13. DOI: 10.1111/j.1365–2486.2005.001069.x.

Lau A., Calders K., Bartholomeus H., Martius C., Raumonen P., Herold M., Vicari M., Sukhdeo H., Singh J. & Goodman R.C., 2019, Tree biomass equations from terrestrial LiDAR: A case study in Guyana. Forests 10: 527. DOI: 10.3390/f10060527.

Lehtonen A., Cienciala E., Tatarinov F. & Mäkipää R., 2007, Uncertainty estimation of biomass expansion factors for Norway spruce in the Czech Republic. Annals of Forest Science 64(2): 133–140. DOI: 10.1051/forest:2006097.

Liski J., Lehtonen A., Palosuo T., Peltoniemi M., Eggers T., Muukkonen P. & Mäkipää R., 2006, Carbon accumulation in Finland's forests 1922–2004 – an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil. Annals of Forest Science 63: 687–697. DOI: 10.1051/forest:2006049.

Makarevskiy M.F., 1991, Carbon storage and balance in forest and peatland ecosystems of Karelia. The Soviet Journal of Ecology 22(3): 3–10.

Mansuy N., Gauthier S. & Bergeron Y., 2013, Afforestation opportunities when stand productivity is driven by a high risk of natural disturbance: a review of the open lichen woodland in the eastern boreal forest of Canada. Mitigation and Adaptation Strategies for Global Change 18: 245–264. DOI 10.1007/s11027-012-9362-x

Matthews G., 1993, The carbon content of trees. Forestry Commission. Techn. Paper 4. Edinburgh, 21 pp.

Moiseev B.N. & Alyabina I.O., 2007, Assessment and mapping of components of carbon and nitrogen balances in major biomes of Russia. Proceedings of the Russian Academy of Sciences. The geographical series 5: 1–12.

Moiseev B.N. & Filipchuk A.N., 2009, The IPCC methodology for calculating annual carbon deposition and assessing its applicability for Russian forests. Lesnoe Khozyaistvo 4: 11–13.

Nilsson S., Shvidenko A., Jonas M., McCallum I., Thomson A. & Balzter H., 2007, Uncertainties of a regional terrestrial biota full carbon account: A systems analysis. Water, Air, & Soil Pollution: Focus 7: 425–441. DOI 10.1007/s11267–006–9119–1

Pan Y., Birdsey R.A., Fang J., Houghton R., Kauppi P.E., Kurz W.A., Phillips O.L., Shvidenko A., Lewis S.L., Canadell J.G., Ciais P., Jackson R.B., Pacala S.W., McGuire A.D., Piao S., Rautiainen A., Sitch S. & Hayes D., 2011, A large and persistent carbon sink in the world's forests. Science 333: 988–993. DOI: 10.1126/science.1201609

Pan Y.D., Luo T.X., Birdsey R., Hom J. & Melillo J., 2004, New estimates of carbon storage and sequestration in China's forests: effects of age-class and method on inventory-based carbon estimation. Climatic Change 67: 211–236.

Petersson H., Holm S., Ståhl G., Alger D., Fridman J., Lehtonen A., Lundström A. & Mäkipää R., 2012, Individual tree biomass equations or biomass expansion factors for assessment of carbon stock changes in living biomass – A comparative study. Forest Ecology and Management 270: 78–84. DOI:10.1016/j.foreco.2012.01.004.

Shvidenko A., Schepaschenko D., Nilsson S. & Bouloui Y., 2007, Semi-empirical models for assessing biological productivity of Northern Eurasian forests. Ecological Modelling 204: 163–179. DOI: 10.1016/j.ecolmodel.2006.12.040

Shvidenko A.Z. & Schepaschenko D.G., 2014, Carbon budget of Russian forests. Siberian Journal of Forest Science 1: 69–92.

Shvidenko A., Schepaschenko D. & Maksyutov S., 2010a, Impact of terrestrial ecosystems of Russia on the global carbon cycle from 2003–2008: An attempt of synthesis. Proceedings of the International Conference on Environmental Observations, Modeling and Information Systems ENVIROMIS-2010, Tomsk: 48–52.

Shvidenko A., Schepaschenko D., Mc Callum I., Santoro M. &, Schmullius C., 2011, Use of remote sensing products in a terrestrial ecosystems verified full carbon account: Experiences from Russia. Proceedings of I Conference “Earth Observation for Land-Atmosphere interaction Science”, Frascat, Italy, 3–5 November 2010. ESA SP-688. CD ROM. 8 pp.

Shvidenko A., Schepaschenko D., McCallum I. & Nilsson S., 2010b, Can the uncertainty of full carbon accounting of forest ecosystems be made acceptable to policymakers? Climatic Change 103: 137–157. DOI:10.1007/s10584-010-9918-2

Shvidenko A.Z. & Schepaschenko D.G., 2013, Climate changes and wildfires in Russia. Lesovedenie [Russian Journal of Forest Scienc] 5: 50–61.

Stinson G., Kurz W., Smyth C., Neilson E., Dymond C., Metsaranta J., Boisvenue C., Rampley G.J., Li Q., White T.M. & Blain D., 2011, An inventory-based analysis of Canada’s managed forest carbon dynamics, 1990 to 2008. Global Change Biology 17: 2227–2244. DOI: 10.1111/j.1365-2486.2010.02369.x

Tang X., Fehrmann L., Guan F., Forrester D.I., Guisasola R. & Kleinn C., 2016, Inventory-based estimation of forest biomass in Shitai County, China: A comparison of five methods. Annals of Forest Research 59(1): 1–12. DOI: 10.15287/afr.2016.574

Teobaldelli M., Somogyi Z., Migliavacca M. & Usoltsev V.A., 2009, Generalized functions of bio-mass expansion factors for conifers and broadleaved by stand age, growing stock and site index. Forest Ecology and Management 257: 1004–1013. DOI: 10.1016/j.foreco.2008.11.002

Usoltsev V.A., Terekhov G.G. & Kanunnikova O.V., 2008, Carbon deposition in forests of the Ural Federal District. Contemporary Problems of Ecology 1(3): 295–303. DOI: 10.1134/S1995425508030028

Usoltsev V.A., 2007, Biological productivity of Northern Eurasia’s forests: methods, the database, and its applications. Ural Branch of the Russian Academy of Sciences, Yekaterinburg. http://elar.usfeu.ru/handle/123456789/3281

Usoltsev V.A., 2018, Carbon sequestration by forests of the Ural region of Russia (on the base of Forest State Inventory data 2007). Ural State Forest Engineering University, Yekaterinburg. DOI: 10.1111/gcb.14904. https://core.ac.uk/download/pdf/162319276.pdf

Usoltsev V.A., Voronov M.P. & Chasovskikh V.P., 2011, Net primary production of Ural forests: Methods and results of automated estimating. Russian Journal of Ecology 42(5): 362–370. DOI: 10.1134/S1067413611050122

Utkin A.I., 2001, On the possible dynamics of forest vegetation in the ecotones of Northern Eurasia under global warming, [in:] Classification and dynamics of forests of the Far East: Proceedings of the International conference. Institute of Biology & Soil Sciences Far Eastern Branch, Russian Academy of Sciences, Vladivostok.

Utkin A.I., Zamolodchikov D.G., Korovin G.N., Nefedev V.V., Gulbe T.A., Gulbe Ya.I. & Gamburg S.P., 1997, Determination of stand carbon stock in sample plots: comparison of allometric and conversion-volumetric methods. Lesovedenie [Russian Journal of Forest Science] 5: 51–66.

Vaganov E.A., Vedrova E.F., Verkhovets S.V., Efremov S.P., Efremova T.T., Kruglov V.B., Onuchin A.A., Sukhinin A.I. & Shibistova O.B., 2008, Forests and swamps of Siberia in the global carbon cycle. Contemporary Problems of Ecology 1(2): 168–182. DOI: 10.1134/S1995425508020021

Van Camp N., Vande Walle I., Mertens J., de Neve S., Samson R., Lust N., Lemeur R., Boeckx P., Lootens P., Beheydt D., Mestdagh I., Sleutel S., Verbeeck H., Van Cleemput O., Hofman G. & Carliere L., 2004, Inventory-based carbon stock of Flemish forests: A comparison of European biomass expansion factors. Annals of Forest Science 61(7): 677–682. DOI: 10.1051/forest:2004066

Van Den Berge S., Vangansbeke P., Calders K., Vanneste T., Baeten L., Verbeeck H., Parvathi S., Moorthy K. & Verheyen K., 2021, Biomass expansion factors for hedgerow-grown trees derived from terrestrial LiDAR. BioEnergy Research (Preprint). DOI: 10.1007/s12155-021-10250-y

Vedyushkin M.A., 1989, Hysteresis in competitive systems, [in:] Factors and mechanisms of stability of geosystems. Institute of Geography of the USSR Academy of Sciences, Moscow: 215–225.

Vedyushkin M.A., 1992, Modeling of spatial transitions between phytocenoses [in:] Mathematical modeling of plant populations and phytocenoses. Nauka Publ., Moscow: 24–30.

Xu X.L., Cao M.K. & Li K.R., 2007, Temporal-spatial dynamics of carbon storage of forest vegetation in China. Progress in Geography 26(6): 1–10 (in Chinese).

Yang K. & Guan D., 2008, Changes in forest biomass carbon stock in the Pearl River Delta between 1989 and 2003. Journal of Environmental Sciences (China) 20(12): 1439–1444. DOI: 10.1016/s1001-0742(08)62546-2

Zamolodchikov D.G., Grabovskii V.I. & Kraev G.N., 2011, Dynamics of carbon budget in forests of Russia for last twenty years. Lesovedenie [Russian Journal of Forest Science] 6: 16–28.

Zamolodchikov D.G., Korovin G.N. & Gytarsky M.L., 2007, Carbon budget of managed forests of the Russian Federation. Lesovedenie [Russian Journal of Forest Science] 6: 23–34.

Zamolodchikov D.G., Utkin A.I. & Korovin G.N., 1998, Determination of carbon reserves by conversion-volumetric coefficients related to age of stands. Lesovedenie [Russian Journal of Forest Science] 3: 84–93.