Article:

Romanov, AA, Tamarovskaya, AN, Gloor, E orcid.org/0000-0002-9384-6341 et al. (5 more authors) (2022) Reassessment of carbon emissions from fires and a new estimate of net carbon uptake in Russian forests in 2001–2021. Science of The Total Environment, 846. 157322. ISSN: 0048-9697

https://doi.org/10.1016/j.scitotenv.2022.157322

Article

Reassessment of carbon emissions from fires and a new estimate of net carbon uptake in Russian forests in 2001-2021

Aleksey A. Romanov[1,2*], Anastasia N. Tamarovskaya[1,2], Emanuel Gloor[3], Roel Brienen[3], Boris A. Gusev[1,2], Egor V. Leonenko[2], Alexander S. Vasiliev[2], Elijah E. Krikunov[1,2]

[1] Affiliation 1 a[2] Research & Development lab, a2rd.com, Soissons, France

[2] Affiliation 2 Siberian Federal University, Krasnoyarsk, Russia

[3] Affiliation 3 University of Leeds, Leeds, United Kingdom

*Correspondence: ARomanov@a2rd.com

Abstract

Russia has the largest forest area on earth. Its boreal forests officially store about 97 Pg C, which significantly affect the global carbon cycle. In recent years, forest fires have been intensifying on the planet, leading to increased carbon emissions. Here we review how differences in fire control management of Russian forests affect fire related emissions. Carbon emissions due to fire were estimated using satellite data and compared to official reports for 2001-2021. We found that the relative areas affected by fire did differ between different fire protection zones, and 89% of the area burnt was in forests controlled by fire-fighting aircraft or areas without protection. As a result, 417.7 Mha of poor or unprotected Russian forests (42% of total) account about a half of total carbon emissions. According to our estimates, the average area of burnt forests in Russia was about 8.3 Mha per year between 2016 and 2021, resulting in annual carbon emission of 193 million metric tons (Mt) C emissions, and 53% of them were from unprotected forest. These estimated carbon emissions are significantly higher than official national reports (79 Mt C yr-1). We estimated that net carbon uptake for Russia for 2015-2021 was about 333±37 Mt C, which is roughly double the official estimates.

Our results highlight large spatial differences in fire protection and prevention strategies in fire related emissions. The so-called control zone which stretches across large parts of Eastern Russia has no fire control and is the region of major recent fires. Our study shows that to estimate the Russian forest carbon balance it is critical to include this area. Implementation of some forest management in the remote areas (i.e., control zone) would help to decrease forest loss and resulting carbon emissions.

Keywords: forest fires; wildfires; forest management; carbon uptake; carbon emissions; CAMS.

Abbreviations

CAMS - Copernicus Atmosphere Monitoring Service;

FFA - Federal Forestry Agency;

IPCC - Intergovernmental Panel on Climate Change;

UNFCCC - United Nations Framework Convention on Climate Change;

RFCB - Regional Forest Carbon Budget;

NIR - National Inventory Report

1. Introduction

In 2020 Russian forests covered 815 Mha (*FAO. Global Forest Resources Assessment 2020: Main report. Rome,* 2020), representing 20% of the world's total forest area. The forest dynamics and management of this vast area plays an important role in the global carbon cycle (Filipchuk, 2020), and thus future atmospheric CO_2 levels (Keenan, 2015). In recent years, fires in Russian forests have become known worldwide as catastrophic: they spread over vast territories producing deep smoke that reaches other regions ("BBC News. Smoke from fires in Siberia reached the Volga region. Why are they not extinguished and what will happen next?," 2019; "EastRussia. The village of Byas-Kyuel burned down in Yakutia," 2021; "Euronews. 'Low chance' Siberia wildfires will be brought under control: Greenpeace fire expert," 2019; "The Moscow Times. Wildfire smoke blankets Russia's third-largest city," 2021; "TVK6. A forest fire rages near the village of Kolmogorovo, Krasnoyarsk Territory," 2021) and continents ("NASA. Siberian smoke reaches U.S., Canada," 2019; "NASA. Smoke from Siberian fires reaches Canada," 2018; "Novaya Gazeta. Smog is coming. There are no resources on the planet to extinguish the fires of Siberia without rain: experts and doctors say," 2019; "Tengrinews. Smoke from Siberian fires reached the Almaty region," 2019). Therefore, it is vital to adopt adequate forest management and forest fire protection strategies (Romanovskaya et al., 2020). Improved forest management and protection may help reducing fires occurrence and thus reduce risks to health as well as CO_2 emissions. However, the effects of different forest protection strategies on fire occurrences in Russia have not been studied before. This study provides the necessary background on current Russian forest legislation, forest classification, forest fire threats, fire monitoring and forest carbon uptake to help determine potential improvements.

Forest management in Russia faces a range of challenges given various threats to these forests. One of the forests' main threats are wildfires and human-caused fires (Kukavskaya et al., 2013; Masyagina, 2021), even with the current monitoring level. It has been shown that there is a correspondence of wildfires to moisture; predicted future temperature increases will lead to drier forests and a higher frequency of days with extreme weather conditions favorable for fire outbreaks (Flannigan et al., 2016). Many studies document unambiguously increases in wildfires over recent years which are attributed to global climate change, specifically increases in temperature (heatwaves) (Wang and Luo, 2020) and in the duration of dry periods (Liu et al., 2018; Talucci et al., 2022). In recent years, forest fires in Siberia have intensified (Andela et al., 2019; Masyagina, 2021).

According to the Copernicus Atmosphere Monitoring Service (CAMS) report ("Copernicus Atmosphere Monitoring Service (CAMS). Copernicus reveals summer 2020's Arctic wildfires set new emission records. ," 2020), the fires in the Far Eastern Federal District of Russia emitted a total of approximately 540 million metric tons (Mt) of CO2 between June and August 2020, which surpasses the previous highest total emissions for the year 2003. Far Eastern forests are mainly coniferous and mixed forests ("Space Research Institute of the Russian Academy of Sciences. Vegetation map," 2014), covering over 304 Mha (or the exact area of forests in the United States ("State of Forests and Forestry in the United States," 2016)). According to our calculations, based on the processing of the forest vegetation map ("Space Research Institute of the Russian Academy of Sciences. Vegetation map," 2014) and the forest fire zoning map (Forest Pyrology Center, 2019),160 Mha (54%) of them are not protected from fire. The forests of Siberia and the Far East that have been most affected by fires in recent years have a predominantly larch and coniferous species composition ("Roslesinforg. Interactive map Forests of Russia," n.d.; "Space Research Institute of the Russian Academy of Sciences. Vegetation map," 2014). Due to intensifying wildfires increasing amounts of carbon are released (Masyagina, 2021). This leads to the consequences of climate change (Kukavskaya et al., 2013; Zhu et al., 2017). Thus, there is a clear need and great potential for forest management to reduce carbon losses.

2. Materials and Methods

2.1 Forest accounting

The source of forest area is Land Cover CCI v. 2.0 and v.2.1 by Copernicus Climate Change Service (Copernicus Climate Change Service, 2021; Defourny et al., 2017). We used recommended classes for detect forest vegetation: tree cover, broadleaved, evergreen, closed to open (>15%); tree cover, broadleaved, deciduous, closed to open (>15%); tree cover, needleleaved, evergreen, closed to open (>15%); tree cover, needleleaved, deciduous, closed to open (>15%); tree cover, mixed leaf type (broadleaved and needleleaved); mosaic tree and shrub (>50%) / herbaceous cover (<50%); tree cover, flooded, fresh or brackish water. The zonal histogram in QGIS v. 3.16 (“QGIS,” 2021) was used to classify forest types.

2.2 Burnt forest area

Datasets from burned areas products based on MODIS (MCD64A1) (NASA, 2000) data were used to analyze fire-damaged areas (Giglio et al., 2018) for 2010-2020. MCD64A1 product includes Burn Date, Burn Data Uncertainty, Quality Assurance, First Day, and Last Day of reliable change detection. MODIS satellite observations provide global data on spatio-temporal patterns of biomass combustion (Andela et al., 2019). A rather coarse resolution can lead to errors in accounting for small fires with burnt area underestimation (Chuvieco et al., 2018; Humber et al., 2019; Zhu et al., 2017). However, in general, the MCD64A1 proved its reliability, demonstrating large areas of fires compared to other products, since it takes into account information about active fires and determines fires even in cloudy weather (Humber et al., 2019). Since the purpose of this work was to consider a large time series over a large area, this source of satellite data was chosen. Product uncertainties are related to the coarse resolution and can be up to ±18% of the burnt area reported in the paper.

We used MCD64A1 with 500 m pixel. The original burnt forest area data were in a raster. We converted them into a ESRI:102025 projection. Then we built vector polygons based on raster and crossed with a forest vegetation vector mask (Copernicus Climate Change Service, 2021) Then we calculated the burnt forest area in QGIS v 3.16 (“QGIS,” 2021).

2.3 Forest fire zoning

To compare the burnt areas in the ground fire protection, aviation fire protection and control (no fire protection) zones, we overlaid shapefiles of the burnt areas on the forest fire zoning map. Detailed information about zones is in the 3.3 section. The fire zoning map (Forest Pyrology Center, 2019) presented in JPG format was processed in several iterations using QGIS v. 3.16 tools (“QGIS,” 2021): raster snapping, cubic interpolation and intersection of vector polygons. As a result, vector layers were prepared to characterize the burnt areas in three fire protection zones. The uncertainity in converting a raster to a vector does not exceed 12%-18%, depending on the complexity of the zone boundaries. Classifying forests by zones was to study how fire protection methods affect fire areas and fire emissions.

2.4 Carbon uptake and emissions assessment

The National Inventory Report for United Nations Framework Convention on Climate Change (UNFCCC) (“UNFCCC. Russia. National Inventory Report.,” 2021) provided official values for carbon uptake and emissions from forest fires. Related sources analysis was used to compare existing estimates of carbon uptake in Russian forests. A significant drawback of the National Inventory Report (NIR) (“UNFCCC. Russia. National Inventory Report.,” 2021) is that it does not reflect emissions from unmanaged forests (reserve forests) in accordance with the current UNFCCC reporting policy. For a detailed description of managed and unmanaged forests, see Section 3. That is why we turned to satellite data for a comprehensive analysis of emissions from all over Russian forests.

The Copernicus data provide a comprehensive set of data for atmospheric composition (Rémy et al., 2017; Wagner et al., 2021). The CAMS algorithm uses the following reliable physical principle: the rate of release of thermal radiation by a fire-related to the rate at which fuel is being consumed, and smoke produced. Therefore, these daily averaged fire radiative power areal intensity data are used to estimate open vegetation fire trace gas and particulate emissions globally. The CAMS has good temporal consistency with real data (Flemming et al., 2017). CAMS has the smal bias with respect to most of the observation stations, with a small negative bias in the Northern Hemisphere (biases <-2 parts per billion) for CO. Comparisons with In-service Aircraft for a Global Observing System aircraft data show an underestimation of CO in the free troposphere in the Northern Hemisphere (<10 %) with larger underestimation in the lower troposphere (Inness et al., 2019).

Despite the abundance of datasets in the Copernicus system, we used the product specifically for forest fires (Inness et al., 2019), taking into account vegetation and synchronized with MODIS forest fires data. This made it possible to exclude other sources of emissions, such as industrial emissions from cities. We concentrated on emissions from biomass burning. CAMS (“Copernicus Atmosphere Monitoring Service,” 2021; Inness et al., 2019) assests carbon loss from biomass burning on the basis of the Global Fire Assimilation System v 1.2 (Kaiser et al., 2012) that considers the soil organic carbon by using Harmonized World Soil Database (Hiederer et al., 2011). Also, CAMS allows take into account the peatland fires (Giuseppe et al., 2017; Huijnen et al., 2012).

The dataset generated using Copernicus Atmosphere Monitoring Service Information [2004-2021] (“Copernicus Atmosphere Monitoring Service,” 2021) was used to estimate CO_2 from forest fires in Russia. Neither the European Commission nor European Centre for Medium-Range Weather Forecasts is responsible for any use that may be made of the information it contains. The collection consisted of raster maps with a daily timestamp from January 1, 2004, to December 31, 2021.

The original CAMS data were presented in a NetCDF format with a resolution of 0.1 degrees. Only the part belonging to the territory of Russia was cut from the maps. Raster maps have been converted to vector polygons, and every polygon was assigned a pixel value. Then vectorized it; reprojected to EPSG:7030. Then we processed the data in QGIS v 3.16 (“QGIS,” 2021). After converting all pixels to polygons, we calculated the area and multiplied it by the emission value previously assigned from the pixel. Since the original dataset values reflected emissions in kg m^{-2} s^{-1}, the total polygons values for each day were multiplied by the number of seconds per day. The daily data of each map was summed up to obtain the final indicators for the year.

The uncertainty associated with carbon emissions by zones is between 3% and 18%, and does not exceed 4% for the whole country.

3. Theory

3.1 Forest Management and Legislation in Russia

The Federal Forestry Agency (FFA) (“Federal Forestry Agency,” 2021) is responsible for forest management in Russia. Its tasks include planning of all activities on forests (nature protection, timber production), federal forest supervision of the regional executive authorities that carry out local forest management, forest protection, forest regeneration and providing state forest inventories. The FFA has several sub-departmental institutions, which aggregate forest management data from federal sub-divisions. In each federal district (eight federal districts are a grouping of Russia's 83 federal sub-divisions), FFA is represented by a territorial Forestry Department. The Forest Protection Center (“Forest Protection Center,” n.d.) and the Aviation Forestry Guard (“Aviation Forestry Guard,” n.d.)**Error! Reference source not found.** carry out forest phytomonitoring and reforestation and provide forest protection.

Article 1 of the Forestry Code of the Russian Federation (“Forestry Code,” 2006), the primary forest law, states that the normative legal acts regulating forest relations are based on sustainable forest management and conservation of forest biological diversity principles. This definition allows the Forestry Code to align formally with the global sustainable forest management plan, using international guidelines for sustainable nature management.

However, it should be noted that there is no 'managed forest' definition in Russian legislation yet. The Forestry Code's primary law governing forest management rules does not use managed and unmanaged forest terms. Lack of terminology and clear distinction between managed and unmanaged categories, which should be transparent in line with the Intergovernmental Panel on Climate Change (IPCC) guidelines (“IPCC. Intergovernmental Panel on Climate Change,” n.d.) causes misunderstanding in the forest management methodology at the regional level and contribution to the global carbon cycle of Russian forests.

3.2 Forest Classification

According to the Russian state definition, used by UNFCCC reporting ("Clarification to the National Report of the Russian Federation on the established amount of emissions," 2008), a forest is a community of trees and shrubs, with a minimum crown cover of 18% (or defined as a stand density of 0.3 ("Clarification to the National Report of the Russian Federation on the established amount of emissions," 2008)), a minimum tree height of 5.0 m, a minimum cover of 1.0 ha and the minimum width of 20.0 m.

Following the Forestry Code (Article 10) ("Forestry Code," 2006) **Error! Reference source not found.**and official government statistics ("Roslesinforg. Interactive map Forests of Russia," n.d.), that contain outdated data and correspond to forest condition as of 2012 rather than 2020, all Russian forests are classified into:

i) *Protected forests* that provide environmental, protective, sanitary and health-improving functions with forests' simultaneous use by local inhabitants if the user does not interfere with the conservation of forest (Article 12) **Error! Reference source not found.**("Forestry Code," 2006). This group occupies 164 Mha or 21.5% of the Russian forest area ("Roslesinforg. Interactive map Forests of Russia," n.d.).

ii) *Exploitable (timber-producing) forests*, whose function is the sustainable and efficient production of high-quality timber (Article 108) ("Forestry Code," 2006). These cover 435 Mha or 56.9% of the forest area ("Roslesinforg. Interactive map Forests of Russia," n.d.).

iii) *Remote unused forests*, further referred to as "Reserve forests", where timber harvesting is not planned for the next twenty years (Article 118) **Error! Reference source not found.**("Forestry Code," 2006). Reserve forest inventory lands cover 165 Mha or 21.6% of the forest area ("Roslesinforg. Interactive map Forests of Russia," n.d.). The vast inaccessible boreal forest areas in the Siberian Federal District and Far Eastern Federal District (from the Urals mountains to the East coast of Russia, Siberia) are classified under this category.

At the beginning of UNFCCC reporting in 2011, Russia decided to consider protected and timber-producing forests as managed and consider reserve forests as unmanaged ("UNFCCC. Baseline information for forest management in the Russian Federation," 2011), leaving any change in carbon uptake or losses from reserve forests covering 21.6% of Russia's forests unaccounted. Although reserve forests absorb about 120 kt C/year (Filipchuk, 2018), and there is an undetermined amount of carbon losses associated with fires, insect attacks, and illegal logging, reserve forests are still not included in the National

Inventory Report (National Greenhouse Gases Inventory) ("UNFCCC. Russia. National Inventory Report.," 2021).

3.3 Forest Fire Monitoring

Forests in Russia are divided into three zones according to the method of fire protection: a ground monitoring zone, an aviation monitoring zone and a control zone (i.e., zone without any fire protection) ("Electronic fund legal and regulatory technical documents. Ministry of Natural Resources and Ecology of the Russian Federation. Order № 426 dated 8 October, 2015.," 2018; Forest Pyrology Center, 2019).

The ground monitoring area has a well-developed road network that allows firefighters and vehicles to extinguish fires quickly and efficiently from the ground. Usually, this small area is located near settlements.

The aviation monitoring zone covers forests located at a distance from settlements. The largest area for monitoring and extinguishing fires from the air is limited by the distance that allows aircraft to fly to extinguish the fire and return to its base since it is impossible to land for refueling in Russian forests. The use of unmanned aerial vehicles allows increasing aviation monitoring areas at a lower cost. Unmanned aerial vehicles tests have already been carried out, but there is no mass use in Russian forestry yet ("Aviation Forestry Guard. The use of unmanned aerial vehicles in forestry.," n.d.; "Russian Drone. Monitoring and protection of forests using unmanned aerial vehicles.," 2018).

The control zone has an ambiguous name as in reality means precisely the opposite: only satellite monitoring of the occurrence and development of fires takes place in this zone. Fires in this zone do not need to be extinguished if there is no threat to people's lives and essential infrastructure facilities according to a new law adopted in November 2015 ("Electronic fund legal and regulatory technical documents. Ministry of Natural Resources and Ecology of the Russian Federation. Order № 426 dated 8 October, 2015.," 2018).

Table 1 reveals the correspondence between the forest classification and fire protection zones, and also provides information on the population density in the three zones.

Table 1. Forest fire protection zones and forest classification

Characteristics	Ground zone	Aviation zone	Control zone
Forest classification ("Forestry Code," 2006)	Protected forests, Exploitable (timber-producing) forests	Protected forests, Exploitable (timber-producing) forests	Exploitable (timber-producing) forests, Remote unused

			forests (reserve forests)
Mean population density, persons per 30 arc-second (~1 km²) (“CIESIN. Documentation for the Gridded Population of the World (GPWv4). NASA Socioeconomic Data and Applications Center (SEDAC).,” 2016)	18.3	3.0	0.1
Total population, mln. people (“CIESIN. Documentation for the Gridded Population of the World (GPWv4). NASA Socioeconomic Data and Applications Center (SEDAC).,” 2016)	68.8	36.4	1.2
Managed / unmanaged according to UNFCCC reporting (baseline information) (“UNFCCC. Baseline information for forest management in the Russian Federation,” 2011)	Managed	Managed	Exploitable (timber-producing) forests - managed; Remote unused forests (reserve forests) - unmanaged

The ground, aviation and so-called control fire protection zones are established at the sub-district level. However, these sub-districts do not have enough funds for quick and effective fire protection. The FFA provides funding for forest fire protection only for the ground and aviation zones, which is often not enough. This problem is especially acute in large regions with vast so-called control zones (hereinafter it means – no fire protection), such as Yakutia and Krasnoyarsk Territory.

3.4 Official Carbon Uptake Estimation

The current method for calculating and reporting the amount of carbon stored by forests is the Regional Forest Carbon Budget (RFCB) methodology (Zamolodchikov D G et al., 2011; Zamolodchikov et al., 2018, 2003). It is based on the division of forests into pools (phytomass, dead wood, litter, soil 0-30 cm), climatic zones, species and age composition based on maps and data from the state forest inventory. Each forest is assigned a carbon uptake coefficient by combining all characteristics (Zamolodchikov et al., 2018). Experimental approbation of the method is carried out exclusively in easily accessible forests. Fire areas with the type of fire and degree of destructiveness are used to calculate carbon losses from fires.

RFCB has several methodological limitations according to other studies (Filipchuk et al., 2016; Filipchuk, 2020, 2018; Malysheva et al., 2018)**Error! Reference source not found.**, which include:

- an assumption that mature forests reach an equilibrium and then maintain the same stocks over time, and thus have a net C uptake of zero (Filipchuk, 2018);
- failure to take into account reserve forests **Error! Reference source not found.** (Filipchuk, 2018) (i.e., 165 Mha, or 22% of the total ("Roslesinforg. Interactive map Forests of Russia," n.d.)) and the exclusion of some forest area on unclassified land or forests that are classified as shrubs and other sub-categories of the government classification system;
- use of unreliable and outdated (20 years old) forest inventory data (Malysheva et al., 2018); the last high-quality and full-fledged forest inventory was carried out when Russia was still a member of the Soviet Union (before 1991). Since then, many forests were entirely cut down or burned down; some of them regenerated and changed in species and age composition. In addition, young forests have been allowed to regenerate on large areas of abandoned agricultural lands. The methodology does not consider these changes, and use old forestry data;
- use of very shallow soil depth for estimating soil CO_2 stocks (only up to 30 cm deep), while alternative methods consider soil depth up to 1 meter (Filipchuk, 2020).

Russia needs to determine forest carbon uptake and loss more accurately. The effectiveness of the Forestry Code of the Russian Federation of 2006 was already questioned by the professional forestry community (Hitchcock, 2010; "WWF. New Forest Code is a threat to Russian forests," 2004) at the adoption stage. The control zone law adopted in November 2015 ("Electronic fund legal and regulatory technical documents. Ministry of Natural Resources and Ecology of the Russian Federation. Order № 426 dated 8 October, 2015.," 2018) is also very controversial, as will be shown below. The Results section will present an analysis and comparison of the official and independent satellite data of carbon and particle emissions due to forests fires of Russian forests in the ground, aviation and control zones, and emissions.

4. Results

4.1 Forest Accounting

Estimates of the Russian forest area differ between 808 Mha and 897 Mha. According to satellite data, the forest area was 808 Mha in 2014 (the latest open source update) ("Space Research Institute of the Russian Academy of Sciences. Vegetation map," 2014). According to the Russian Federation's official statistics, the total forest area is 821 Mha as of 2020 ("Roslesinforg. State forest inventory 2007-2020," 2021). In comparison, according to the Russian NIR, the total area of Russian forests is 897 Mha as of 2019 ("UNFCCC. Russia. National Inventory Report.," 2021) (including shrubs). Finally, according to the Food and Agriculture Organization of the United Nations, there are 815 Mha of Russian forest as of 2020 (*FAO. Global Forest Resources Assessment 2020: Main report. Rome,* 2020).

In this work, we use processed satellite data by Copernicus (Copernicus Climate Change Service, 2021) (see section 2.1) to calculate the forest areas in Russia for the fire protection zones and evaluate how the fire protection method affects burnt forest areas. Table 1 in Supplementary Materials shows the forest areas for the the three different protection zones (i.e. ground fire protection zone, the aviation fire protection zone and the control zone). The other contains all forest excluded from three fire protection zones (aglomerations, northern territoties, uncertainities of spatial distribution between zones).

According to these calculations, in 2020, 91.3 Mha, or 9% of Russia's forest was subject to ground fire protection (including 3.8 Mha of shrubs), and 397.7 Mha, or 40% belonged to the aviation zone (including 23.1 Mha of shrubs): forest fire monitoring and inspection patrols using aviation). The control zone contained 417.7 Mha (43%) of the total forest area (including 29.0 Mha of shrubs); the forests in this zone have no protection from fire if there is no threat to people's lives or a vital infrastructure facility ("Electronic fund legal and regulatory technical documents. Ministry of Natural Resources and Ecology of the Russian Federation. Order № 426 dated 8 October, 2015.," 2018). The other zone was about 72.7 Mha or 7% of the total forest area (including 15.3 Mha of shrubs). Thus, in 2020, Russian forests accounted for 982.0 Mha (56.6 of which are shrubs). In 2020, the total forest area was 977.0 Mha (71.2 of which are shrubs). The largest reduction in forest area from 2000 to 2020 was observed in the control zone -15 Mha. Forest in the aviation zone reduced on 5 Mha.

4.2 Burnt forest area

The Russian government reports burned forest areas to calculate carbon losses from fires in the NIR for UNFCCC ("UNFCCC. Russia. National Inventory Report.," 2021). It includes only information about losses from protected forests, timber-producing forests, defense and urban forests (all of them are managed according to baseline information ("UNFCCC. Baseline information for forest management in the Russian Federation," 2011)). Reserve forests have the status of unmanaged forests ("UNFCCC. Baseline information for forest management in the Russian Federation," 2011) and no records of carbon losses are kept in them. We compared the burnt areas in the NIR with the MODIS satellite data using MCD64A1 (NASA, 2000) (section 2.2). The results are presented in Figure 1.

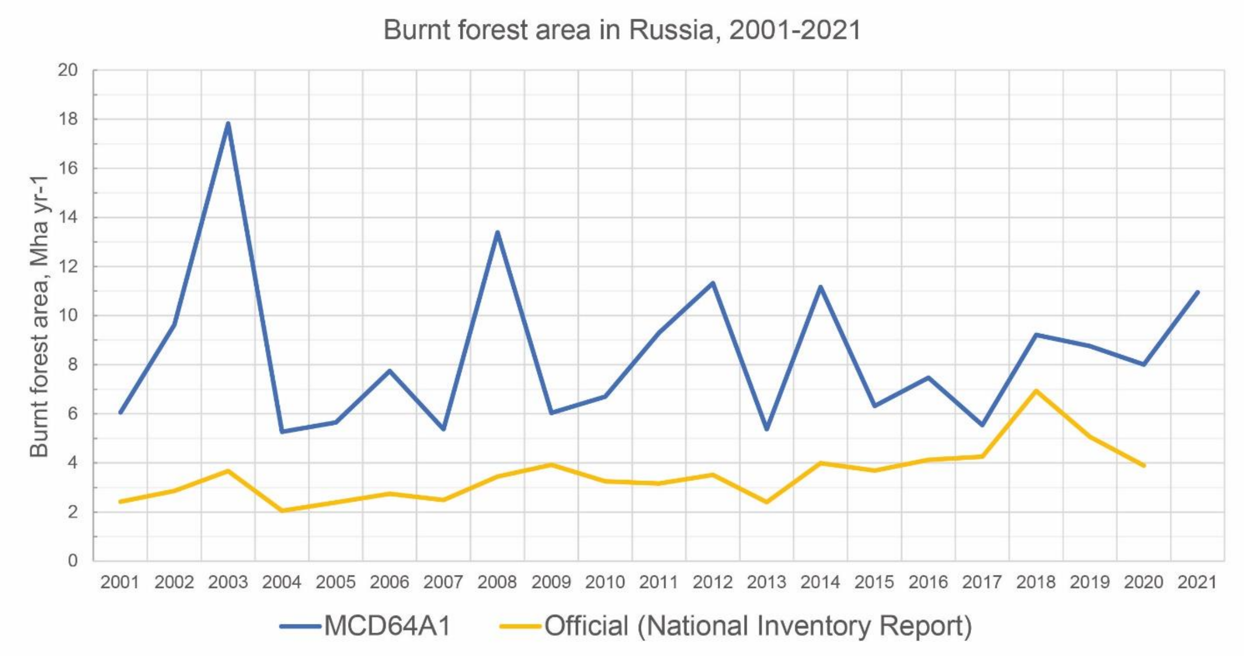

Figure 1. Burnt forest area from National Inventory Report (NIR) (blue colour) and MODIS (MCD64A1) (yellow colour) in Russia, 2001-2021

The total burnt area in Russian forests for 2001 – 2020 represented by NIR ("UNFCCC. Russia. National Inventory Report.," 2021) was underestimated by 95.9 Mha (or 4.8 Mha yr^{-1} in average) (Table 2 in Supplementary Materials).

We have also estimated the burnt areas 2001 – 2021 in the ground, aviation and control zones (section 2.3) separately, using MODIS MCD64A1 (NASA, 2000) remote sensing data (section 2.2) presented in Figure 2.

Figure 2. Burnt forest area in the ground (green colour), aviation (blue colour) and control (red colour) zones in Russia (2001-2021) using satellite monitoring data MCD64A1.*

As shown in Figure 2, extensive fire areas are typical for the aviation and control zones in the Eastern Siberia. According to MCD64A1, the total burnt forest area does not differ so much in average values for 2001-2010 (8.4 Mha yr^{-1}) and 2011-2020 (8.2 Mha yr^{-1}), but there was redistribution of burnt areas between zones.

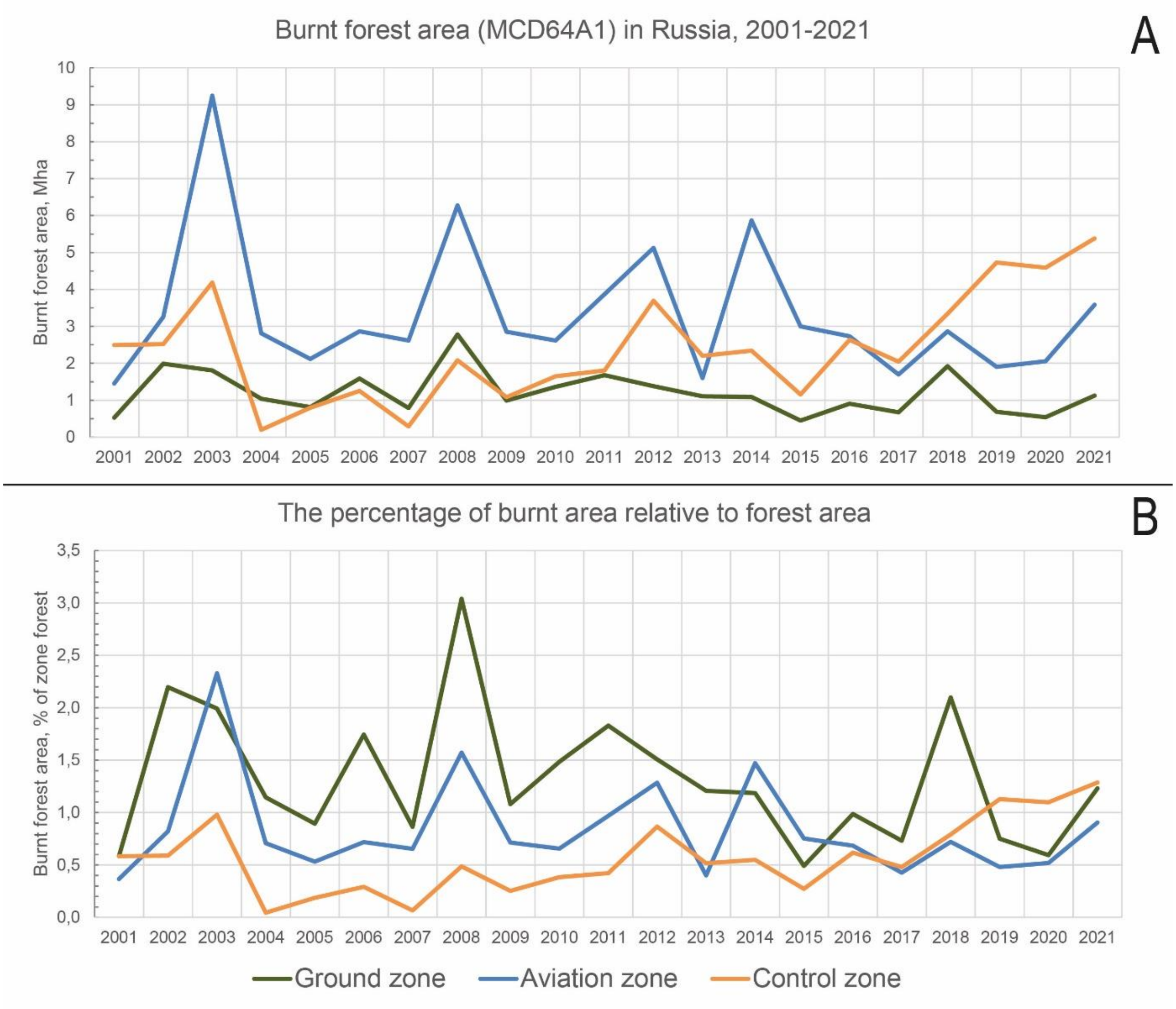

Figure 3. Burnt forest area in the ground (green colour), aviation (blue colour) and control (orange colour) zones by years from 2001 to 2021 in Russia estimated using satellite data from MODIS (MCD64A1). A) the absolute values, Mha; B) the percentage of burnt area relative to the forest area in every zone, %.

Figure 3A presents burnt forest area fluctuations in the ground, aviation and control zones from 2001 to 2021. The detailed information presented in Table 3 of Supplementary Materials. Burnt forest area in the control zone was highest in 2017-2021 relative to ground and aviation zones.

Figure 3B shows the percentage of burns relative to forest area for 2001-2020: it is about 1.3% in the ground zone and about 0.8% in the aviation zone; the average of burns in the control zone is 0.6%, but there is a fast growth in 2011-2020 (0.4% of zone forest) relative to 2001-2010 (0.7% of zone forest). We can see the record values for the control zone in 2019-2021 (1.1%-1.3%). It is not typical for zone with low population density, while in the ground and aviation zone where population density is higher (section 3.3), the percentage more then 1% is usual thing.

4.3 Forest carbon uptake and emissions

NIR estimates range between 77 and 87 Mt C yr^{-1} ("UNFCCC. Russia. National Inventory Report.," 2021) emissions from forest fires between 2001 and 2020 (81.2 Mt C yr^{-1} (or 298 Mt CO_2 yr^{-1}) and are assumed not to vary from year to year (i.e. to be constant). Considering the large interannual variation (and possible trends) in areas and destructiveness of fires, the assumption of an equal number of emissions every year raises serious concerns. Therefore, to obtain more accurate data, we analyzed carbon emissions generated by Copernicus Atmosphere Monitoring Service [2010-2020]("Copernicus Atmosphere Monitoring Service," 2021) (section 2.4). The results are presented in Figure 4.

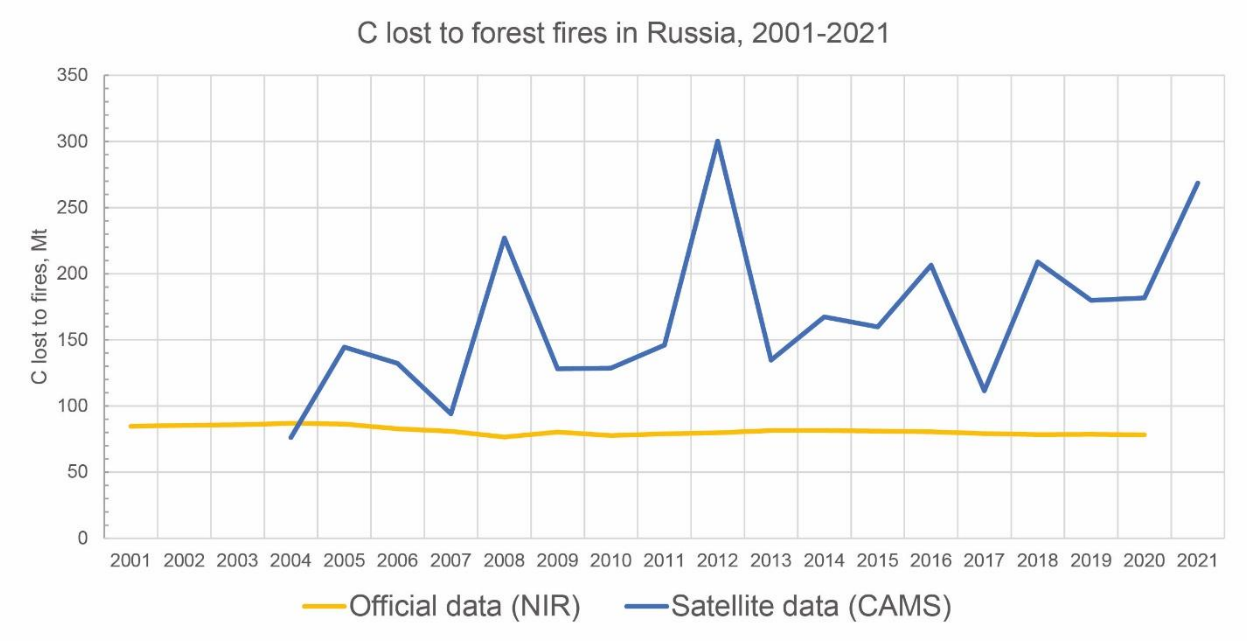

Figure 4. C lost as a result of forest fires as reported by the National Inventory Report (NIR) (blue colour) and estimated using Copernicus Atmosphere Monitoring Service (CAMS) data (yellow colour) over the period from 2001-2021.

The comparison raises doubts about the reliability of the NIR values or the NIR estimation methodology. We got the other values for fire emissions by processing the daily Fire Radiative Power rasters, representing the thermal radiation measured from space-borne sensors and detected as coming from actively burning vegetation from the Global Fire Assimilation System (GFAS) of the Copernicus Atmosphere Monitoring Service (CAMS) ("Copernicus Atmosphere Monitoring Service," 2021). It is a reliable source, verified against data from MODIS: pixel-based quality control for MODIS Aqua and Terra ("Moderate Resolution Imaging Spectroradiometer," 2000) and SEVERI observations ("Eumetsat. The Spinning Enhanced Visible and InfraRed Imager," 2021).

Our estimates using CAMS ("Copernicus Atmosphere Monitoring Service," 2021)**Error! Reference source not found.** showed that Russian forests annually emit 179.7 Mt C (equivalent to 659 Mt of CO_2) into the atmosphere from 2011 to 2020 (Table 4 in Supplementary Materials). Thus, about 99.9 Mt C (or 366 Mt CO_2) is not reflected in the NIR ("UNFCCC. Russia. National Inventory Report.," 2021) for the same period. In total, cumulative emissions from fires in Russian forests were higher on 1359 Mt C from 2004 to 2020 and these numbers are still not declared in NIR.

The total volume of emissions is unevenly distributed among the fire protection zones. Through spatial analysis, the following distribution of emissions from different zones was obtained (Table 2).

Table 2. Carbon lost to forest fires by fire protection zone in 2004-2020

Year	C lost to fires in ground zone from CAMS, Mt / % of total C lost to fires (in brackets)	C lost to fires in aviation zone from CAMS, Mt / % of total C lost to fires (in brackets)	C lost to fires in control zone (no fire protection) from CAMS, Mt / % of total C lost to fires (in brackets)	Sum C lost to fires in three fire protection zones[1], Mt C
2004	8.6 (14%)	45.6 (75%)	6.6 (11%)	60.8
2005	10.4 (10%)	76.0 (70%)	22.8 (21%)	109.2
2006	19.4 (17%)	66.2 (57%)	31.0 (27%)	116.6
2007	9.7 (13%)	59.0 (79%)	6.3 (8%)	75.0
2008	19.9 (10%)	138.6 (70%)	40.1 (20%)	198.6
2009	10.7 (10%)	67.6 (64%)	26.9 (26%)	105.2
2010	30.4 (27%)	41.2 (36%)	41.4 (37%)	113.0
2011	19.9 (16%)	69.1 (55%)	36.6 (29%)	125.6
2012	25.4 (9%)	157.2 (57%)	92.1 (34%)	274.7
2013	17.9 (15%)	57.1 (47%)	46.2 (38%)	121.1
2014	19.3 (13%)	81.9 (56%)	44.2 (30%)	145.4
2015	11.1 (8%)	95.4 (73%)	24.6 (19%)	131.1
2016	16.3 (9%)	94.0 (54%)	63.4 (36%)	173.7
2017	7.3 (7%)	45.0 (45%)	46.7 (47%)	99.0
2018	18.7 (10%)	75.9 (39%)	98.3 (51%)	192.8

2019	11.7 (7%)	51.4 (33%)	93.5 (60%)	156.7
2020	6.5 (4%)	45.8 (27%)	116.3 (69%)	168.6
2021	29.3 (11%)	96.0 (37%)	134.5 (52%)	259.7
Average 2004-2010	15.6 (14%)	70.6 (64%)	25.0 (22%)	111.2
Average 2011-2020	15.4 (10%)	77.3 (49%)	66.2 (41%)	158.9
Sum 2004-2021	292.5 (11%)	1363.0 (52%)	971.5 (37%)	2626.8

[1] value does not include emissions from any of these three fire protection zones (agglomerations, northern territories and other).

On average, 17 Mt C yr^{-1} - (10% of total carbon emissions from forest fires) was emitted from the ground zone in 2011-2020. For the aviation zone, the indicators are an order of magnitude higher: 77 Mt C yr^{-1} (49% of total). The control zone (no fire protection) emited 66 Mt C yr^{-1} (41% of total). The remaining 1.5 Mt C yr^{-1} are produced from territories not included in any of these three fire protection zones (agglomerations, northern territories and other); also it can be explained by uncertanities in the spatial definition of fire protection zones. Therefore, they are not considered in this proportion. Thus, 417.7 Mha of unprotected forests in the control zone (43% of the forest area) produced about half (53%) of all carbon emissions in 2016-2021, while the remaining 487 Mha emited the other half (47%).

Having studied carbon losses from forest fires, we propose a reassessment of the net carbon uptake of Russian forests. Thus, the estimated net carbon uptake of Russian forests was on 333±37 Mt C yr^{-1} during 2015-2020 if we apply Filipchuk's assessment (Filipchuk, 2018) for carbon accumulation: one of the latest and methodologically most rigorous (as it takes into account all types of vegetation) estimates of the carbon uptake, considering reserved forests. It estimated the carbon accumulation of Russian forests to be 630 ± 110 Mt of carbon in 2015 (Filipchuk, 2018) (about two times higher than the official 332 Mt C per year (“UNFCCC. Russia. National Inventory Report.,” 2021)). It was based on data from the State Forest Register 2015 and using the IPCC methodology. The main difference of this estimate compared to previous estimates is that it considers carbon accumulation in hard-to-reach reserve forests and includes areas of shrubs (about 80 Mha) (Filipchuk, 2018). It furthermore considers soil carbon up to 1 m depth, while RFCB considered only the upper 30 cm. To assess carbon emissions from clear cutting, we used the NIR estimation but took into account reserve forests where probable losses could be. The detailed data for every year is provided in Table 3.

Table 3. The net carbon uptake by Russian forests in 2015-2021

Year	**Carbon accumulation, Mt C yr^{-1}**	**C lost to fires from CAMS, Mt C yr^{-1}**	**C lost to clear cutting[2], Mt C yr^{-1}**	**Net carbon uptake, Mt C yr^{-1}**
2015	630±110[1] (Filipchuk, 2018)	159.9	98.2 ("UNFCCC. Russia. National Inventory Report.," 2021)	371.9±66.9
2016	630±110	206.5	101.5	322.0±51.5
2017	630±110	111.5	105.5	413.0±45.4
2018	630±110	208.9	109.3	311.8±24.9
2019	630±110	179.8	113.4	336.8±43.8
2020	630±110	181.8	118.0	330.2±23.1
2021	630±110	268.6	118.0[3]	243.4±7.3
Average 2015-2021	630±110	188.2	109.1	332.7±36.6

[1] carbon accumulation by Filipchuk et al. (Filipchuk, 2018) used as the last and taking into account the reserve forests estimate.

[2] carbon losses from clear cutting based on NIR estimation ("UNFCCC. Russia. National Inventory Report.," 2021) but including the share of clear cutting in reserve forests (21.6% of total).

[3] there are not data for 2021 in NIR, so used previous year value.

Russian forests emit more carbon than reported in the NIR (Table 4 in Supplementary materials), where claimed just 46% of total losses.

4. Discussion

The Russian government provides information on carbon uptake and carbon emissions from the forest in the NIR ("UNFCCC. Russia. National Inventory Report.," 2021). According to NIR, the average carbon sequestration by Russian forests was 332 Mt C per year for the period 2010-2019 ("UNFCCC. Russia.

National Inventory Report.," 2021). There were several independent attempts to estimate the carbon uptake of Russian forests. All of these estimates much higher net carbon uptake compared to the official numbers from NIR using the official RFCB methodology ("UNFCCC. Russia. National Inventory Report.," 2021; Zamolodchikov D G et al., 2011; Zamolodchikov et al., 2018, 2003) that ignores reserve forests and underestimates carbon accumulation in soils.

Different studies obtain different estimates of net carbon uptake of Russian forests ranging from 175 Mt C yr^{-1} to 1000 Mt C yr^{-1} (see Table 4).

Table 4. Estimates of net carbon uptake by Russian forests according to different studies and different periods

№	Research	Period	Carbon accumulation (Mt yr^{-1})	Carbon lost to fires (Mt yr^{-1})	Carbon lost to clear cutting (Mt yr^{-1})	Net carbon uptake (Mt yr^{-1})	Commentaries
1	Kudeyarov et al., 2000 (Kudeyarov, 2000)	1990	1 000	90			based on net production of photosynthesis; considering root and soil respiration
2	Gurney et al., 2003 (Gurney et al., 2003)	1992-1996				580	inversion intercomparison in TransCom3; Bayesian synthesis method for set of annual mean inversion experiments in which 17 different transport models were used to calculate regional carbon sources and sinks from the same data with a standardized method

3	Ciais et al, 2010 (Ciais et al., 2010)	2000-2004				600-1000	comparing four atmospheric inversions with land-based C accounting data
4	Pan et al, 2011 **Error! Reference source not found.**(Pan et al., 2011)	2000-2007				463±116	forest inventory data and long-term ecosystem carbon studies
5	Zamolodchikov et al., 2011 (Zamolodchikov et al., 2011)	1988-2009	382	122	85	175	regional forest carbon budget accounting (official method for Russian National Inventory Report)
6	Dolman et al, 2012 (Dolman et al., 2012)	2009	692	56		614	inventory-based Land Ecosystem Assessment
7	Shvidenko, Schepaschenko, 2014 (Shvidenko and Schepaschenko, 2014)**Error! Reference**	2007-2009				546±120	landscape-ecosystem approach for assessment full carbon budget of forest ecosystems using integrated land information system

	source not found.						
8	Filipchuk et al, 2018 (Filipchuk, 2018)	2015	630±110				based on the State Forest Register 2015 data following the IPCC methodology for Net Ecosystem Production (NEP)
9	Filipchuk et al., 2020 (Filipchuk, 2020)	2003-2016	529	23	37	468	assessment of carbon cycle in boreal forests based on State Forest Register
10	Schepaschenko et al., 2021 (Schepaschenko et al., 2021)	1988-2014				354	combination of recent National Forest Inventory and remote sensing data
11	Our assessment	2015-2020	630±110 (Filipchuk, 2018)	175	107	333±37	Carbon accumulation by Filipchuk et al. (Filipchuk, 2018) minus carbon lost from forest fires using CAMS and minus carbon lost to harvesting based on National Inventory Report ("UNFCCC. Russia. National Inventory Report.," 2021) but including losses in reserve forests

An accurate assessment of the net carbon uptake is given in a recent article by Schepashchenko (Schepaschenko et al., 2021) based on satellite data, but it only reports the net result after all the losses that have occurred, while we needed an estimate of the level of carbon accumulation in order to then calculate the losses by fires ("UNFCCC. Russia. National Inventory Report.," 2021). Therefore, we base our analysis on the Filipchuk's carbon accumulation estimation (Filipchuk, 2018). It should be noted that the estimate of the net carbon uptake obtained in our work for 2015-2020 is quite close to Schepashchenko's (Schepaschenko et al., 2021) assessment for ther period from 1988 to 2014 (Schepaschenko et al., 2021).

The net carbon uptake assessment in Russian forests by Filipchuk's team (Filipchuk, 2018) compares favorably with the current RFCB (Zamolodchikov et al., 2018) methodology still used in the NIR for UNFCCC ("UNFCCC. Russia. National Inventory Report.," 2021). It considers reserve forests and provides more complete estimates of carbon accumulation, which are double the official values. Filipchuk's methodology should be used for reporting. However, the opinion that these reserve forests, now excluded from official statistics, should be considered as managed (Filipchuk, 2018) reflects an overly optimistic view of forest management in Russia. It must be recognized that reserve forests and others in the control zone do not have fire protection and are unmanaged.

We reviewed Russian forest management organizations and legislation concerning fires dynamics and carbon emissions assessments for the last decade. This article presents a new estimate of carbon emissions from forest fires in Russia from 2010 to 2020, supplementing and refining the official National Inventory Report data. The emissions contextualization by forest fire protection zones is presented for the first time in this paper.

It helps to view the official records of NIR in a different way. The NIR indicates emissions from fires in managed forests only: an average of 79.8 Mt C yr^{-1} in 2011-2020 ("UNFCCC. Russia. National Inventory Report.," 2021), while carbon losses were 179.7 Mt C yr^{-1}. Reserve forests considered unmanaged are excluded from these official statistics ("UNFCCC. Baseline information for forest management in the Russian Federation," 2011). Accordingly, NIR presents incomplete values for fire areas accompanied by incomplete data on carbon emissions. We tried to estimate total burnt forest area and associated fire emissions more accurately using the MODIS ("Earth Science Data Systems (ESDS) Program. MCD64A1.," n.d.) and CAMS ("Copernicus Atmosphere Monitoring Service," 2021) satellite data.

Based on the satellite monitoring data, the spatial analysis demonstrated inefficiency in forest management The control zone where the official policy is not to extinguish forest fires has led to an increase in fire areas in remote forests. Fire services have concentrated their efforts on the ground and aviation zones, where fire areas decreased in 2016-2020 while we observed a modest increase in fire areas in the control zone (Fig. 3). The destructive fires in the control zone are visible in the increasing fire areas by satellite monitoring (from average 1.7 Mha yr^{-1} in 2001-2010 to 2.9 Mha yr^{-1} in 2011-2020). These intensifying fires increased average emissions in the control zone from 25 Mt C yr^{-1} (2004-2010) to 66.2 Mt C yr^{-1} (2011-2020) and reached 92.1 Mt C yr^{-1} (2016-2021).

In Russia, 1.2 million people live in the control zone (0.8% of population) ("CIESIN. Documentation for the Gridded Population of the World (GPWv4). NASA Socioeconomic Data and Applications Center (SEDAC).," 2016). They are more susceptible to the risk of forest fires directly approaching settlements ("EastRussia. The village of Byas-Kyuel burned down in Yakutia," 2021; "TVK6. A forest fire rages near the village of Kolmogorovo, Krasnoyarsk Territory," 2021). At the same time, the rest of the inhabitants of the Urals, Siberia and the Far East also often suffer from smoke ("BBC News. Smoke from fires in Siberia reached the Volga region. Why are they not extinguished and what will happen next?," 2019; "NASA. Siberian smoke reaches U.S., Canada," 2019; "NASA. Smoke from Siberian fires reaches Canada," 2018; "Novaya Gazeta. Smog is coming. There are no resources on the planet to extinguish the fires of Siberia without rain: experts and doctors say," 2019; "Tengrinews. Smoke from Siberian fires reached the Almaty region," 2019; "The Moscow Times. Wildfire smoke blankets Russia's third-largest city," 2021), especially in cities that have emissions from industry and transport, seriously aggravated by smoke from forest fires. In the summer of 2021, the level of air pollution in Krasnoyarsk from the smoke of forest fires in Yakutia reached 1054 mg m^{-3} PM2.5 (exceeding 70 times the average daily pollution level) ("IQAir. Krasnoyarsk. Archived page 7 August 2021," 2021). The reasons for the increased smoke in recent years lie in the intensification of forest fires, which can be triggered by changes in meteorological conditions due to climate change (Romanov et al., 2022). The assessment of the burnt forest area is about 18 Mha ("The Guardian. Russia forest fire damage worst since records began, says Greenpeace," 2021) with significant emissions ("Copernicus Atmosphere Monitoring Service. Northern Hemisphere wildfires follow pattern of warm and dry weather," 2021; "The Guardian. Global wildfire carbon dioxide emissions at record high, data shows," 2021). According to our estimates, in 2021, 269 Mt C (or 985 Mt CO_2) were lost from forest fires, 135 Mt C of them was in the control zone (or 495 Mt CO_2).

A country is responsible for fires, whether they occur in managed or unmanaged forests. Excessive carbon emissions into the atmosphere neutralize efforts to combat climate change. As a party to climate agreements, Russia, like other countries, needs to provide up-to-date information on emissions from all forest fires. It is necessary to revise the reporting methodology UNFCCC, currently excluding unmanaged lands from the NIR and the urgent use of satellite monitoring of forest fire areas and resulting emissions.

The most probable cause of fires in the ground zone is the proximity to the population (mainly in the western part of the country), some of which are careless with fire. Fires in the control zone were not extinguished and spread naturally; therefore, even rare, and small fires here lead to significant, long fires and large carbon emissions, as shown above. The law adopted in 2015 ("Electronic fund legal and regulatory technical documents. Ministry of Natural Resources and Ecology of the Russian Federation. Order № 426 dated 8 October, 2015.," 2018) only legalized the long-established practice of no fire protection in the remote Siberian and Far Eastern forests. Since these remote forests are not included in the official reporting, we studied what proportion they belong to and presented it in the results.

5. Conclusions

This article presents a reassessment of carbon from fires in Russian forests in 2010-2020 with contextualization by fire protection zones. The official estimates for carbon emission due to fire submitted to the UNFCCC are lower than those obtained from satellite data by an average of 48% for the period under review. At the same time, net carbon uptake in 2015-2020 has been underestimated by 165 Mt C yr^{-1} (i.e., it is almost double the official estimate). Since 2016, carbon emissions from forest fires have significantly increased in remote forests of Siberia and the Far East. These forests do not appear in official statistics because they are considered unmanaged, but they produce about a half (53%) of all emissions 2016-2020. It is necessary to provide a complete picture of emissions from forest fires, nevertheless managed or unmanaged and take measures to reduce the unprotected zone and improve forest management.

Acknowledgements

We would like to thank the following institutions and persons: Teams from the NASA-Goddard Space Flight Centre, Dr Ross F. Nelson and Dr Chris Justice from the University of Maryland (for developing and making open-access available the MODIS Fire Product); all fire services and volunteers fighting wildfires, especially Gregory Kuksin from the Greenpeace fire centre; Romanov Kotelnikov from the Branch of FBU VNIILM "Center of the forest pyrology"; Vladimir Soldatov and his team from the Center for Forest Protection in Krasnoyarsk Region (Regional branch of the Russian Center for Forest Protection at the Federal Forestry Agency).

Author's contibutions

AAR and ANT initiated the design of the study. EG and RB supported the original idea and guided the writing of the paper. EEK and ASV retrieved satellite data. BAG was responsible for the data processing.

EVL and ANT reviewed official statistics and benchmarking against processed satellite data. ANT completed the paper, after which AAR, EG and RB assisted in finalizing the manuscript. All authors read and approved the final manuscript.

Availability of data and materials

Supplementary Materials are available in Mendeley Data.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interests

The authors declare that they have no competing interests.

References

Andela, N., Morton, D.C., Giglio, L., Paugam, R., Chen, Y., Hantson, S., van der Werf, G.R., Anderson, J.T., 2019. The Global Fire Atlas of individual fire size, duration, speed and direction. Earth System Science Data 11. https://doi.org/10.5194/essd-11-529-2019

Aviation Forestry Guard. The use of unmanned aerial vehicles in forestry. [WWW Document], n.d. URL https://aviales.ru/default.aspx?textpage=123 (accessed 3.18.22).

Aviation Forestry Guard [WWW Document], n.d. URL https://aviales.ru/ (accessed 3.17.22).

BBC News. Smoke from fires in Siberia reached the Volga region. Why are they not extinguished and what will happen next? [WWW Document], 2019. URL https://www.bbc.com/russian/features-49128145 (accessed 3.17.22).

Chuvieco, E., Lizundia-Loiola, J., Lucrecia Pettinari, M., Ramo, R., Padilla, M., Tansey, K., Mouillot, F., Laurent, P., Storm, T., Heil, A., Plummer, S., 2018. Generation and analysis of a new global burned area product based on MODIS 250 m reflectance bands and thermal anomalies. Earth System Science Data 10. https://doi.org/10.5194/essd-10-2015-2018

Ciais, P., Canadell, J.G., Luyssaert, S., Chevallier, F., Shvidenko, A., et al., 2010. Can we reconcile atmospheric estimates of the Northern terrestrial carbon sink with land-based accounting? Current Opinion in Environmental Sustainability 2, 225–230. https://doi.org/10.1016/j.cosust.2010.06.008

CIESIN. Documentation for the Gridded Population of the World (GPWv4). NASA Socioeconomic Data and Applications Center (SEDAC)., 2016. https://doi.org/http://dx.doi.org/10.7927/H4D50JX4

Clarification to the National Report of the Russian Federation on the established amount of emissions [WWW Document], 2008. URL https://unfccc.int/files/national_reports/initial_reports_under_the_kyoto_protocol/application/msword/initial_report_corr_new_rev_mg_an.doc (accessed 3.18.22).

Copernicus Atmosphere Monitoring Service (CAMS). Copernicus reveals summer 2020's Arctic wildfires set new emission records. [WWW Document], 2020. URL https://atmosphere.copernicus.eu/copernicus-reveals-summer-2020s-arctic-wildfires-set-new-emission-records (accessed 3.18.22).

Copernicus Atmosphere Monitoring Service. Northern Hemisphere wildfires follow pattern of warm and dry weather [WWW Document], 2021. URL https://atmosphere.copernicus.eu/northern-hemisphere-wildfires-follow-pattern-warm-and-dry-weather (accessed 3.18.22).

Copernicus Atmosphere Monitoring Service [WWW Document], 2021. URL https://confluence.ecmwf.int/pages/viewpage.action?pageId=151530675 (accessed 11.26.21).

Copernicus Climate Change Service, 2021. ICDR Land Cover [WWW Document]. URL https://datastore.copernicus-climate.eu/documents/satellite-land-cover/D5.3.1_PUGS_ICDR_LC_v2.1.x_PRODUCTS_v1.1.pdf (accessed 4.22.22).

Defourny, P., Lamarche, C., Bontemps, S., de Maet, T., van Bogaert, E., Moreau, I., Brockmann, C., Boettcher, M., Kirches, G., Wevers, J., Santoro, M., Ramoino, F., Arino, O., 2017. Land Cover Climate Change Initiative - Product User Guide v2. Issue 2.0. [WWW Document]. URL http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf (accessed 4.22.22).

Dolman, A.J., Shvidenko, A., Schepaschenko, D., et al., 2012. An estimate of the terrestrial carbon budget of Russia using inventory-based, eddy covariance and inversion method. Biogeosciences 9, 5323–5340.

Earth Science Data Systems (ESDS) Program. MCD64A1. [WWW Document], n.d. URL https://lpdaac.usgs.gov/products/mcd64a1v006/ (accessed 3.18.22).

EastRussia. The village of Byas-Kyuel burned down in Yakutia, 2021.

Electronic fund legal and regulatory technical documents. Ministry of Natural Resources and Ecology of the Russian Federation. Order № 426 dated 8 October, 2015. [WWW Document], 2018. URL https://docs.cntd.ru/document/420310212?marker=6520IM (accessed 3.18.22).

Eumetsat. The Spinning Enhanced Visible and InfraRed Imager [WWW Document], 2021. URL https://www.eumetsat.int/seviri (accessed 3.18.22).

Euronews. “Low chance” Siberia wildfires will be brought under control: Greenpeace fire expert [WWW Document], 2019. URL https://www.euronews.com/2019/08/06/siberian-wildfires-engulf-area-almost-the-size-belgium-as-states-of-emergency-are-declared (accessed 3.17.22).

FAO. Global Forest Resources Assessment 2020: Main report. Rome, 2020. https://doi.org/https://doi.org/10.4060/ca9825en

Federal Forestry Agency [WWW Document], 2021. URL http://rosleshoz.gov.ru/agency (accessed 3.17.22).

Filipchuk, A.N., Malysheva, N. v, Moiseev, B.N., Strakhov, V. v, 2016. Analytical overview of methodologies calculating missions and absorption of greenhouse gases by forests from the atmosphere. Forestry information 3, 36–85.

Filipchuk, A.N.; M.N.V.; Z.T.A.; Y.A.N., 2020. Boreal forests of Russia: opportunities for mitigating climate change. Forestry information 92–113.

Filipchuk, A.M.B.M.N.S. v, 2018. Russian forests: a new approach to the assessment of carbon stocks and sequestration capacity. Environmental Development 68–75. https://doi.org/10.1016/j.envdev.2018.03.002

Flannigan, M.D., Wotton, B.M., Marshall, G.A., de Groot, W.J., Johnston, J., Jurko, N., Cantin, A.S., 2016. Fuel moisture sensitivity to temperature and precipitation: climate change implications. Climatic Change 134, 59–71. https://doi.org/10.1007/s10584-015-1521-0

Flemming, J., Benedetti, A., Inness, A., Engelen J, R., Jones, L., Huijnen, V., Remy, S., Parrington, M., Suttie, M., Bozzo, A., Peuch, V.H., Akritidis, D., Katragkou, E., 2017. The CAMS interim Reanalysis of Carbon Monoxide, Ozone and Aerosol for 2003-2015. Atmospheric Chemistry and Physics 17. https://doi.org/10.5194/acp-17-1945-2017

Forest Protection Center [WWW Document], n.d. URL http://rcfh.ru/affiliates.html (accessed 3.17.22).

Forest Pyrology Center, 2019. Forest fire zoning map [WWW Document]. URL https://firescience.ru/event/092019/zonirovanie.html (accessed 5.20.20).

Forestry Code [WWW Document], 2006. URL http://pravo.gov.ru/proxy/ips/?docbody=&nd=102110364 (accessed 3.18.22).

Giglio, L., Boschetti, L., Roy, D.P., Humber, M.L., Justice, C.O., 2018. The Collection 6 MODIS burned area mapping algorithm and product. Remote Sensing of Environment 217. https://doi.org/10.1016/j.rse.2018.08.005

Giuseppe, F. di, Emy, S.R.´, Pappenberger, F., Wetterhall, F., 2017. Improving CAMS biomass burning estimations by means of the Global ECMWF Fire Forecast system (GEFF).

Gurney, K.R., Law, R.M., Denning, A.S., Rayner, P.J., Baker D, et al., 2003. TransCom 3 CO2 inversion intercomparison: 1. Annual mean control results and sensitivity to transport and prior flux information. Tellus B 55, 555–579.

Hiederer, Roland., Köchy, Martin., European Commission. Joint Research Centre. Institute for Environment and Sustainability., 2011. Global soil organic carbon estimates and the harmonized world soil database. Publications Office. https://doi.org/10.2788/13267

Hitchcock, E., 2010. The 2006 Forest Code of the Russian Federation: an evaluation of environmental legislation in Russia. ASEES 24, 19–39.

Huijnen, V., Flemming, J., Kaiser, J.W., Inness, A., Leitão, J., Heil, A., Eskes, H.J., Schultz, M.G., Benedetti, A., Hadji-Lazaro, J., Dufour, G., Eremenko, M., 2012. Hindcast experiments of tropospheric composition during the summer 2010 fires over western Russia. Atmospheric Chemistry and Physics 12, 4341–4364. https://doi.org/10.5194/acp-12-4341-2012

Humber, M.L., Boschetti, L., Giglio, L., Justice, C.O., 2019. Spatial and temporal intercomparison of four global burned area products. International Journal of Digital Earth 12. https://doi.org/10.1080/17538947.2018.1433727

Inness, A., Ades, M., Agustí-Panareda, A., Barr, J., Benedictow, A., Blechschmidt, A.M., Jose Dominguez, J., Engelen, R., Eskes, H., Flemming, J., Huijnen, V., Jones, L., Kipling, Z., Massart, S., Parrington, M., Peuch, V.H., Razinger, M., Remy, S., Schulz, M., Suttie, M., 2019. The CAMS reanalysis of atmospheric composition. Atmospheric Chemistry and Physics 19, 3515–3556. https://doi.org/10.5194/acp-19-3515-2019

IPCC. Intergovernmental Panel on Climate Change [WWW Document], n.d. URL https://www.ipcc-nggip.iges.or.jp/public/index.html (accessed 3.18.22).

IQAir. Krasnoyarsk. Archived page 7 August 2021, 2021.

Kaiser, J.W., Heil, A., Andreae, M.O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J.J., Razinger, M., Schultz, M.G., Suttie, M., van der Werf, G.R., 2012. Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. Biogeosciences. https://doi.org/10.5194/bg-9-527-2012

Keenan, R.J., 2015. Climate change impacts and adaptation in forest management: a review. Annals of Forest Science 145–167. https://doi.org/10.1007/s13595-014-0446-5

Kudeyarov, V.N., 2000. Contribution of soil to atmospheric CO2 balance in Russia. Doklady Biological Sciences 375, 610–612.

Kukavskaya, E.A., Amber, J.S., Petkov, A.P., Ponomarev, E.I., Ivanova, G.A., Susan G. Conard, 2013. Fire emissions estimates in Siberia: evaluation of uncertainties in area burned, land cover, and fuel consumption. Canadian journal of forest research 43, 493–506. https://doi.org/10.1139/cjfr-2012-0367

Liu, Z., Ballantyne, A.P., Cooper, L.A., 2018. Increases in Land Surface Temperature in Response to Fire in Siberian Boreal Forests and Their Attribution to Biophysical Processes. Geophysical Research Letters 45, 6485–6494. https://doi.org/10.1029/2018GL078283

Malysheva, N., Zolina, T., Moiseev, B., 2018. GIS support the methods for assessment of carbon sequestration capacity in the Russian forests. ICIGIS 24, 426–436. https://doi.org/10.24057/2414-9179-2018-1-24-426-436

Masyagina, O. v., 2021. Carbon dioxide emissions and vegetation recovery in fire-affected forest ecosystems of Siberia: Recent local estimations. Current Opinion in Environmental Science & Health 23, 100283. https://doi.org/10.1016/J.COESH.2021.100283

Moderate Resolution Imaging Spectroradiometer [WWW Document], 2000. URL https://modis.gsfc.nasa.gov/about (accessed 3.18.22).

NASA, 2000. MCD64A1. https://doi.org/DOI: 10.5067/MODIS/MCD64A1.006

NASA. Siberian smoke reaches U.S., Canada [WWW Document], 2019. URL https://www.nasa.gov/image-feature/goddard/2019/siberian-smoke-reaches-us-canada (accessed 3.17.22).

NASA. Smoke from Siberian fires reaches Canada [WWW Document], 2018. URL https://www.nasa.gov/image-feature/goddard/2018/smoke-from-siberian-fires-reaches-canada (accessed 3.17.22).

Novaya Gazeta. Smog is coming. There are no resources on the planet to extinguish the fires of Siberia without rain: experts and doctors say [WWW Document], 2019. URL https://novayagazeta.ru/articles/2019/08/02/81468-na-planete-net-resursov-chtoby-potushit-pozhary-sibiri-bez-dozhdya (accessed 3.17.22).

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., et al., 2011. A large and persistent carbon sink in the world’s forests. Science (1979) 333, 988–993.

QGIS [WWW Document], 2021. URL https://qgis.org/en/site/ (accessed 1.26.22).

Rémy, S., Veira, A., Paugam, R., Sofiev, M., Kaiser, J.W., Marenco, F., Burton, S.P., Benedetti, A., Engelen, R.J., Ferrare, R., Hair, J.W., 2017. Two global data sets of daily fire emission injection heights since 2003. Atmospheric Chemistry and Physics 17. https://doi.org/10.5194/acp-17-2921-2017

Romanov, A.A., Tamarovskaya, A.N., Gusev, B.A., Leonenko, E. v., Vasiliev, A.S., Krikunov, E.E., 2022. Catastrophic PM2.5 Emissions from Siberian Forest Fires: Impacting Factors Analysis. SSRN. https://doi.org/http://dx.doi.org/10.2139/ssrn.4045859

Romanovskaya, A.A., Korotkov, V.N., Polumieva, P.D., Trunov, A.A., Vertyankina, V.Yu., Karaban, R.T., 2020. Greenhouse gas fluxes and mitigation potential for managed lands in the Russian Federation. Mitigation and Adaptation Strategies for Global Change 25, 661–687. https://doi.org/10.1007/s11027-019-09885-2

Roslesinforg. Interactive map Forests of Russia [WWW Document], n.d. URL http://geo.roslesinforg.ru:8282/#/ (accessed 3.18.22).

Roslesinforg. State forest inventory 2007-2020 [WWW Document], 2021. URL https://roslesinforg.ru/services/gil/ (accessed 3.18.22).

Russian Drone. Monitoring and protection of forests using unmanned aerial vehicles. [WWW Document], 2018. URL https://russiandrone.ru/publications/monitoring-i-okhrana-lesov-s-primeneniem-bespilotnykh-letatelnykh-apparatov/ (accessed 3.18.22).

Schepaschenko, D., Moltchanova, E., Fedorov, S., Karminov, V., Ontikov, P., Santoro, M., et al., 2021. Russian forest sequesters substantially more carbon than previously reported. Sci Rep 11, 12825. https://doi.org/10.1038/s41598-021-92152-9

Shvidenko, A.Z., Schepaschenko, D.G., 2014. Carbon budget of Russian forests. Sib. Lesn. Zh. 1, 69–92.

Space Research Institute of the Russian Academy of Sciences. Vegetation map [WWW Document], 2014. URL http://smiswww.iki.rssi.ru/files/maps/glc2005_poster_%D0%BA%D0%B0%D1%80%D1%82%D0%B0_%D1%80%D0%B0%D1%81%D1%82%D0%B8%D1%82%D0%B5%D0%BB%D1%8C%D0%BD%D0%BE%D1%81%D1%82%D0%B8_v2014_stat.jpg (accessed 3.18.22).

State of Forests and Forestry in the United States [WWW Document], 2016. URL https://www.fs.usda.gov/speeches/state-forests-and-forestry-united-states-1 (accessed 3.18.22).

Talucci, A.C., Loranty, M.M., Alexander, H.D., 2022. Siberian taiga and tundra fire regimes from 2001–2020. Environmental Research Letters 17, 025001. https://doi.org/10.1088/1748-9326/ac3f07

Tengrinews. Smoke from Siberian fires reached the Almaty region [WWW Document], 2019. URL https://tengrinews.kz/kazakhstan_news/dyim-ot-sibirskih-pojarov-doshel-do-almatinskoy-oblasti-375054/ (accessed 3.17.22).

The Guardian. Global wildfire carbon dioxide emissions at record high, data shows, 2021.

The Guardian. Russia forest fire damage worst since records began, says Greenpeace [WWW Document], 2021. URL https://www.theguardian.com/world/2021/sep/22/russia-forest-fire-damage-worst-since-records-began-says-greenpeace (accessed 3.18.22).

The Moscow Times. Wildfire smoke blankets Russia's third-largest city [WWW Document], 2021. URL https://www.themoscowtimes.com/2021/04/27/wildfire-smoke-blankets-russias-third-largest-city-a73750 (accessed 3.17.22).

TVK6. A forest fire rages near the village of Kolmogorovo, Krasnoyarsk Territory [WWW Document], 2021. URL https://tvk6.ru/publications/news/58995/ (accessed 3.17.22).

UNFCCC. Baseline information for forest management in the Russian Federation [WWW Document], 2011. URL https://unfccc.int/files/meetings/ad_hoc_working_groups/kp/application/pdf/awgkp_russia_2011_rus.pdf (accessed 3.18.22).

UNFCCC. Russia. National Inventory Report. [WWW Document], 2021. URL https://unfccc.int/documents/273477 (accessed 3.18.22).

Wagner, A., Bennouna, Y., Blechschmidt, A.M., Brasseur, G., Chabrillat, S., Christophe, Y., Errera, Q., Eskes, H., Flemming, J., Hansen, K.M., Inness, A., Kapsomenakis, J., Langerock, B., Richter, A., Sudarchikova, N., Thouret, V., Zerefos, C., 2021. Comprehensive evaluation of the Copernicus Atmosphere Monitoring Service (CAMS) reanalysis against independent observations: Reactive gases. Elementa 9. https://doi.org/10.1525/elementa.2020.00171

Wang, H., Luo, D., 2020. Summer Russian heat waves and their links to Greenland's ice melt and sea surface temperature anomalies over the North Atlantic and the Barents-Kara Seas. Environmental Research Letters 15. https://doi.org/10.1088/1748-9326/abbd03

WWF. New Forest Code is a threat to Russian forests [WWW Document], 2004. URL https://wwf.panda.org/?11588/New-Forest-Code-is-a-threat-to-Russian-forests (accessed 3.18.22).

Zamolodchikov D G, Grabovskii V I, Kraev G N, 2011. Dynamics of carbon budget in forests of Russia for last two decades. Russ J For Sci (Lesovedenie) 6, 16–28.

Zamolodchikov, D.G., Grabovskii, V.I., Kraev, G.N., 2011. A twenty year retrospective on the forest carbon dynamics in Russia. Contemp. Probl. Ecol. 4, 706–715. https://doi.org/10.1134/S1995425511070022

Zamolodchikov, D.G., Grabowsky V I, Chestnykh O V, 2018. Dynamics of the carbon budget of forests of federal districts of Russian Federation. FSI 1. https://doi.org/10.31509/2658-607x-2018-1-1-1-24

Zamolodchikov, D.G., Utkin, A.I., Chestnykh, O. v, 2003. Conversion coefficients of growing stocks of tree stands to phytomass for the main forest forming species of Russia. For Invent For Manag (Lesnaya taksatsiya i lesoustroystvo) 32, 119–127.

Zhu, C., Kobayashi, H., Kanaya, Y., Saito, M., 2017. Size-dependent validation of MODIS MCD64A1 burned area over six vegetation types in boreal Eurasia: Large underestimation in croplands. Scientific Reports 7. https://doi.org/10.1038/s41598-017-03739-0