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Balance of Anthropogenic and Natural Greenhouse Gas Fluxes of All Inland Ecosystems of the Russian Federation and the Contribution of Sequestration in Forests

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Abstract: In order to achieve global climate goals, it is necessary to estimate greenhouse gas (GHG) fluxes from ecosystems. To obtain a comprehensive assessment of CO_2, CH_4, and N_2O natural fluxes for the Russian Federation, we used the "bottom-up" method and updated estimates for forest ecosystems based on State Forest Inventory data and satellite monitoring of forest disturbances. For grassland ecosystems, it was based on the correct distribution of areas between steppe and non-steppe zones. The estimated net uptake of natural ecosystems in Russia was 1.1 ± 1.8 billion tons of CO_2-eq./year. The study shows that if only CO_2 is taken into account, the net absorption of terrestrial ecosystems in Russia corresponds to more than −2.5 billion tons of CO_2 (35% of forests' contribution). However, given the emissions of non-CO_2 GHGs, total net absorption in Russia's natural ecosystems is reduced to about −1 billion tons of CO_2-eq (with the forests' contribution increasing to 80%). With regard to anthropogenic fluxes, the overall balance of GHGs in Russia corresponds to net emissions of 1 billion tons of CO_2-eq/year into the atmosphere. To improve reporting under the Paris Agreement, countries should aim to include only anthropogenic ("manageable") GHG fluxes on managed land.

Keywords: GHG fluxes; carbon balance; ecosystems; managed land; anthropogenic emissions and removals; total net emissions; Russia

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Citation: Romanovskaya, A.; Korotkov, V. Balance of Anthropogenic and Natural Greenhouse Gas Fluxes of All Inland Ecosystems of the Russian Federation and the Contribution of Sequestration in Forests. *Forests* **2024**, *15*, 707. https://doi.org/10.3390/f15040707

Academic Editor: Wenjie Liu

Received: 24 February 2024
Revised: 12 April 2024
Accepted: 13 April 2024
Published: 17 April 2024

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1. Introduction

In order to develop the correct trajectories of countries' efforts towards achieving global climate goals and to assess the degree of their fulfillment, including within the framework of the global stocktake under the Paris Agreement, it is necessary to conduct a comprehensive assessment of anthropogenic and natural fluxes of all major greenhouse gas (GHG) types of both anthropogenic and natural character [1].

For estimations of GHG emissions and sinks, the "top-down" method based on satellite monitoring and inverse modeling are currently widely applied [2–7]. A top-down approach can ensure continuity of observations over the territory; however, a way to determine single sources or sinks from the global spatiotemporal distribution of the GHG concentrations in the atmosphere is uncertain. To verify the results obtained from top-down estimates, data from a ground-based, calculated inventory of large anthropogenic sources of emissions as well as data using models of interaction of the atmosphere with the biosphere and the ocean ("bottom-up" approach) are used. The errors in top-down emission estimates increase when moving from global to regional scales and require verification with bottom-up data.

Bottom-up estimates are highly accurate at the local scale and provide a continuous series of measurements or modeling over time, but they require more detailed activity data and are usually more expensive, so they are often lacking. At both global and national levels, there is a lack of research on integrated assessment of anthropogenic and natural fluxes of all types of major GHGs (carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)) from ecosystems using the "bottom-up" method. In order to obtain robust

GHG data for the stocktake under the Paris Agreement, both top-down and bottom-up approaches are to be further developed.

One valuable source of bottom-up data on GHG fluxes for ecosystems comes from national reports under the United Nations Framework Convention on Climate Change (UNFCCC). These reports, provided by various countries, include data on anthropogenic GHG fluxes in the agriculture and land use, land use change, and forestry (LULUCF) sectors [8]. For this purpose, the so-called managed lands are singled out. However, the magnitudes of natural GHG fluxes from natural ecosystems are not sufficiently studied; there are practically no such publications with regard to the territory of the Russian Federation.

Data on GHG fluxes from ecosystems of the Russian Federation come from several sources: large regional studies based on bottom-up model calculations [2,3,9,10], inverse modeling data [3], and individual studies that focus on specific ecosystem types [11–15] or particular types of GHGs [16–18].

Russia also prepares annual national reporting (GHG Inventory) within the framework of the UNFCCC and the Paris Agreement commitments on anthropogenic emissions and removals of GHGs [19]. For reporting purposes, the Russian Federation distinguishes between managed lands where anthropogenic GHG fluxes are observed (operational and protective forests; protected areas; peat mining; drained peatlands; arable land; hayfields; pastures; settlement lands), and natural (unmanaged) ecosystems, where there are no human activities and no anthropogenic GHG fluxes (forests where there is no obligation to extinguish fires (reserve forests); tundras; marshes; natural grasslands; steppes; rivers and lakes). Thus, the National GHG inventory is not representative in the case of the Russian Federation for the total GHG fluxes over the territory of all inland ecosystems.

Korotkov et al. [20] undertook the only attempt to fully assess the role of all ecosystems in Russia, specifically in terms of the balance of anthropogenic and natural GHG fluxes using a bottom-up study. This article critically analyzes the results presented by Korotkov et al. [20], updates the data on forest and grassland ecosystems in Russia, and estimates the balance of anthropogenic and natural GHG fluxes in Russia as a whole. The feasibility of extending reporting under the UNFCCC and the Paris Agreement to unmanaged ecosystems is discussed.

2. Materials and Methods

2.1. Research Methods Are Described in the Study by Korotkov et al. [20]

The estimates presented by Korotkov et al. [20] are based on the analysis of direct measurement data published in the scientific literature. They employed methods of computational monitoring, mathematics, and geoinformation modeling. The estimates were performed as of 2016.

Data from the Land Cadastre of the Russian Federation [19,21], as well as remote sensing data and ground surveys for individual ecosystems, were used as input data for areas. Thus, wetlands areas by Russian territorial subjects were estimated based on the data of the "Wetlands of Russia" GIS of the Institute of Forest Science of the Russian Academy of Sciences [22,23]. The whole area of natural ecosystems in Russia considered in the study by Korotkov et al. [20] is 85% of the total area of the country. Forest lands (61% of the natural ecosystems considered in the study), tundra (18%), and wetlands (10%) make up the majority of the area, while grass ecosystems (6%) and freshwater ecosystems (5%) make up a smaller share. However, forests, wetlands, and grasslands are not subdivided into managed and unmanaged areas.

To assess the balance of GHGs in tundra ecosystems, we used the results of field measurements of GHG fluxes using infrared gas analyzers as well as the eddy covariance method in combination with measurements of the main environmental parameters. Korotkov et al. [20] utilized a geoinformation approach to obtain regional estimates of the GHG balance by analyzing digital maps of tundra landscapes, a database of meteorological characteristics, and models of aboveground phytomass dynamics and carbon fluxes [24–26].

The GHG balance of forest ecosystems was assessed using the ROBUL methodology [27–29], which assumes a balance approach based on accounting for carbon accumulation by different pools of forest ecosystems (phytomass, dead wood, litter, soil) and losses due to destructive disturbances (clearcuts, fires). Initial data for calculations were taken from the departmental statistics data of the Federal Forestry Agency (Rosleshoz) State Forest Register [19].

Assessment of CO_2 balance in steppe ecosystems was based on estimates of net primary productivity (NPP) and microbial respiration (MR). Regional estimates of CO_2 balance on the territory of the Russian Federation were made using the approximation method or book-keeping models (BK-Apr). To implement this approach, the areas of steppe ecosystems and average specific (expressed per unit area) values of CO_2 fluxes in the ecosystem (NEE, NPP, and MR) were used [30,31].

The annual change in soil C stocks in grassland ecosystems was calculated on the basis of a balance estimation of C compounds entering and leaving soils. The methodology for the calculation of CH_4 and N_2O emissions is based on the use of initial statistical data on the number of grazing animals and the application of conversion factors and emission factors [32].

Estimation of GHG fluxes from wetland ecosystems was based on the use of area emission factors of carbon dioxide, methane, and nitrous oxide, calculated and differentiated by types of wetland ecosystems for each territorial subject of the country. Net ecosystem exchange values were based on data reported in peer-reviewed scientific publications as well as IPCC synthesis reports [33].

For freshwater ecosystems, CO_2 and CH_4 emissions were estimated separately for stagnant water bodies and for rivers and streams. The calculations took into account water body areas, CO_2 and CH_4 emission factors (including those recommended by the IPCC [34]), and the duration of the ice-free period estimated from meteorological archive data [35].

2.2. Methods Used in This Study

Specification of GHG fluxes through forest ecosystems performed in this study is based on the following aspects:

- specification of initial data on forest carbon stocks according to the first cycle of State Forest Inventory [36];
- specification of initial data on forest disturbance and mortality based on satellite monitoring data [37–39].
- using initial data on logging volumes according to Rosleshoz's sectoral reporting data.

We obtained updated net absorption data for forest land based on the results of the first cycle of the State Forest Inventory (SFI), which ended in 2020. Quantitative forest characteristics of the regions and the country as a whole were obtained instrumentally from 69.1 thousand sample plots (SP) during 2007–2020. The first summarizing results of the SFI are published [36]. International experience shows that data from National Forest Inventories (NFIs) can serve as a source of information on the state of forest resources and the parameters of forest ecosystems, which allows for estimating the absorptive capacity of forests for reporting under the UNFCCC and the Paris Agreement. Several countries, including China, the USA, the Federal Republic of Germany, Finland, Sweden, and Japan, utilize NFI results to estimate carbon stock changes in managed forests. Notably, the Nordic countries and the USA generate the longest time series data. This vast amount of data, generated as a result of successive NFI cycles, makes it possible to directly estimate the carbon stock differences in forest ecosystems using the IPCC's recommended stock-difference method [34].

For Russia, SFI is a new type of survey work which results in an array of data on tree measurements and various ecosystem characteristics of forest communities to be obtained at sample plots. Processing the first SFI cycle in the Russian Federation yielded generalized forest condition characteristics for its territorial subjects. These data include information on forest area distribution, growing stock, volume of dead wood by species and 10-year age classes, litter and soil characteristics, and other indicators. Hence, the data obtained during the first SFI cycle allows for specifying timber stocks, but not increments (changes in growing stock per year), which can be calculated from actual data only after the second SFI cycle.

The main task in interpreting the results of the first SFI cycle is to obtain calculated values of phytomass growth and dead wood stock changes for one year. This can serve as the basis for estimating forest carbon storage. Data from the SFI on forest area distribution and growing stock by species, stand quality (bonitet), and age classes allows for calculating the current net growth using modal forest growth models [40] and the normative reference base of growth and productivity in Northern Eurasian forests. These models make it possible to take into account regional characteristics, species composition, age, and the bonitet of stands. The models used allow estimation of wood stocks of a particular species, certain bonitet, and age in 1-year increments. Similarly, models by Shvidenko et al. [41] are used to estimate stocks of different fractions of dead wood (dead standing trees, dry branches, dead-fallen wood, stumps) in one-year increments. Current growth is estimated as the difference in growing and dead wood stocks from growth models at a given age and one year prior. The obtained values of the current net growth increment (in m^3 ha^{-1} y^{-1}) for each species of a certain bonitet and age make it possible to convert them into phytomass growth through updated models of conversion factors—Biomass Expansion Factors [42]. Given that 50% of dry phytomass is carbon [43], it is possible to estimate annual changes in carbon stocks in phytomass per 1 ha. Since the area of forest stands is known, the total value of phytomass and dead wood increments for the region as a whole is obtained.

The balance approach also requires estimation of carbon losses, which are calculated on the basis of actual data on stocks of cut wood and areas of dead stands due to fires and other causes. Carbon losses due to logging are calculated by considering losses of unlogged wood [44] and using conversion factors [42]. Carbon losses due to stand mortality are based on average values of carbon stock in forests in the region, derived from SFI calculations. Unfortunately, the litter and soil data obtained from SFI do not allow estimation of carbon stocks or carbon stock changes in these pools. Estimates of net uptake by litter and soil pools in this study are based on specific net uptake values (from the National Inventory Report) per forested area. According to the National GHG Inventory [19], the contribution of the litter and soil pools to total CO_2 net uptake by forests does not exceed 15% (2017–2021 mean: litter is 2.7%, soil is 12.3%). The results of the net forest uptake estimates obtained in our study represent the mean value for the 2017–2021 period.

The areas of abandoned arable lands in the steppe zone of Russia were specified in this study based on the estimation of the difference between data from Rosreestr [21] on total area of arable land and data from the Federal State Statistics Service [45] on the total area of crops and fallow land by territorial subjects of the Russian Federation. In steppe subjects defined by Korotkov et al. [20], we identified the share of agricultural land attributable to the steppe zone based on data from the state agricultural statistics [46], Romanovskaya [47] and the Unified State Register of Soil Resources of Russia [48]. Accordingly, secondary steppe areas were recalculated.

The identified areas of fallow land outside the steppe zone were considered separately. The estimation of net uptake on these lands was based on modeling soil C stock dynamics using the calibrated RothC model for fallow lands in the context of Russian Federation territorial subjects, different soil types, and vegetation zones [47]. The obtained data were added to the total net absorption of grassland in Russia.

The areas of natural steppes attributable to forage lands (hayfields and pastures) and unmanaged grasslands were analyzed separately. For the distribution of natural steppe areas by these two categories, the general distribution of areas of managed and unmanaged grasslands, according to Rosreestr data [21], was applied (76.5% of grasslands in the country as a whole are fodder lands (70,789 ha) and 23.5% are unmanaged grasslands (21,720 ha). The net balance of GHGs for steppe lands was calculated according to Korotkov et al. [20].

The net balance for managed and unmanaged grasslands outside the steppe zone was calculated using the method proposed by Romanovskaya and Karaban' [32]. Estimates of methane and nitrous oxide fluxes from forage lands were not recalculated and assumed to be equal to the estimates given by Korotkov et al. [20].

The activity data, methods, and approaches applied to estimate GHG fluxes from inland ecosystems in this study are summarized in Table 1.

Table 1. Activity data and methods used in this study to assess CO_2, CH_4 and N_2O fluxes from inland ecosystems.

Types of Land	Activity Data	Methods and Approaches
Forest lands	Area: Rosleshoz State Forest Register [19]; Growing stocks: state forest inventory [36]; Forest disturbance and mortality: satellite monitoring data [37–39]; Forest harvesting: Rosleshoz sector reporting [19]; Drained organic soils: Rosleshoz State Forest Register [19].	A balance approach based on the difference between annual increment (phytomass, dead wood, litter, soil) and losses of carbon from destructive disturbances (clearcuts, fires) [23,24]; Models to estimate stocks of different fractions of biomass and dead wood by Shvidenko et al. [40,41]; Drained organic soils: IPCC Tier 1 [33].
Grasslands		
out of which: - managed grasslands		
including deposits	Total area: data of Rosreestr Land Cadastre [19,21] and Rosstat—Federal State Statistics Service data [45]; Area of drained organic soils: based on assumptions described in the National GHG Inventory [19];	RothC model for soil carbon [47]; Drained organic soils: GHG emission factors in accordance to IPCC Tier 1 [33].
including secondary steppes	Area of steppe used as fodder lands: research data [46,47] and Unified State Register of Soil Resources of Russia [48];	NEE estimations based on NPP and MR rates [20,30,31].
including hayfields and pastures (fodder lands)	Total area and area of drained organic soils used for hayfields and pastures: Rosreestr Land Cadastre [19,21]; Annual volume of hay harvesting and pasture feed consumption; number of grazing animals: Rosstat—Federal State Statistics Service data [45]; Area of grass fires: satellite monitoring data [39]; Area of steppe used as fodder lands: research data [46,47] and Unified State Register of Soil Resources of Russia [48].	Model to estimate the annual balance of carbon input and output into the soil [19,32]; Drained organic soils: GHG emission factors in accordance to IPCC Tier 1 [33]; Emissions from manure on pastures: IPCC Tier 2 [19,32]; Emissions from fires: IPCC Tier 1 [43]; For steppe NEE estimations based on NPP and MR rates [20,30,31]; CH_4 flux in steppe zone estimated from field measurement data [20].

Table 1. *Cont.*

Types of Land	Activity Data	Methods and Approaches
- unmanaged grasslands	Total area: data of Rosreestr Land Cadastre [19,21] and Rosstat—Federal State Statistics Service data [45]; Area of grass fires: satellite monitoring data [39].	Model to estimate the annual balance of carbon input and output into the soil [19,32]; Emissions from fires: IPCC Tier 1 [43].
including natural steppes	Area of steppe used as fodder lands: research data [46,47] and Unified State Register of Soil Resources of Russia [48].	NEE estimations based on NPP and MR rates [20,30,31]; CH_4 flux estimated from filed measurement data [20].
Wetlands		
out of which: - swamps	Total area and peat extraction area: data of Rosreestr Land Cadastre [19,21] and research database [22,23].	GHG emission factors in accordance to peer-reviewed scientific publications [14,15] and IPCC report [33].
- areas under water	Total area: data of Rosreestr Land Cadastre [19,21]; Duration of the ice-free period: meteorological archive data [35].	IPCC Tier 2 methodology [34].
Other lands		
out of which: - tundra	Total area: data of Rosreestr Land Cadastre [19,21].	GHG flux estimations based on field measurements and the models of aboveground phytomass dynamics and carbon fluxes [24–26].

In order to clearly distinguish the effect of our study's specifications, we followed a simplified approach for estimating "natural" GHG balance similar to Korotkov et al. [20]. This approach considers the total area of forests, grasslands, wetlands, water ecosystems, and tundras across the Russian Federation without differentiating between managed and unmanaged ecosystems or natural and anthropogenic fluxes, as recommended by the IPCC Guidelines [43,49].

However, GHG flux estimates from croplands and land use change are entirely anthropogenic and were not considered by Korotkov et al. [20]. For a complete balance, data on net-emissions from these sources, as well as estimates of GHG emissions from other anthropogenic sources in the energy, industry, livestock, and waste sectors, were taken from the National GHG Inventory Report [19]. The mapping between natural and anthropogenic fluxes considered in this study and the National GHG Inventory are presented in Figure 1.

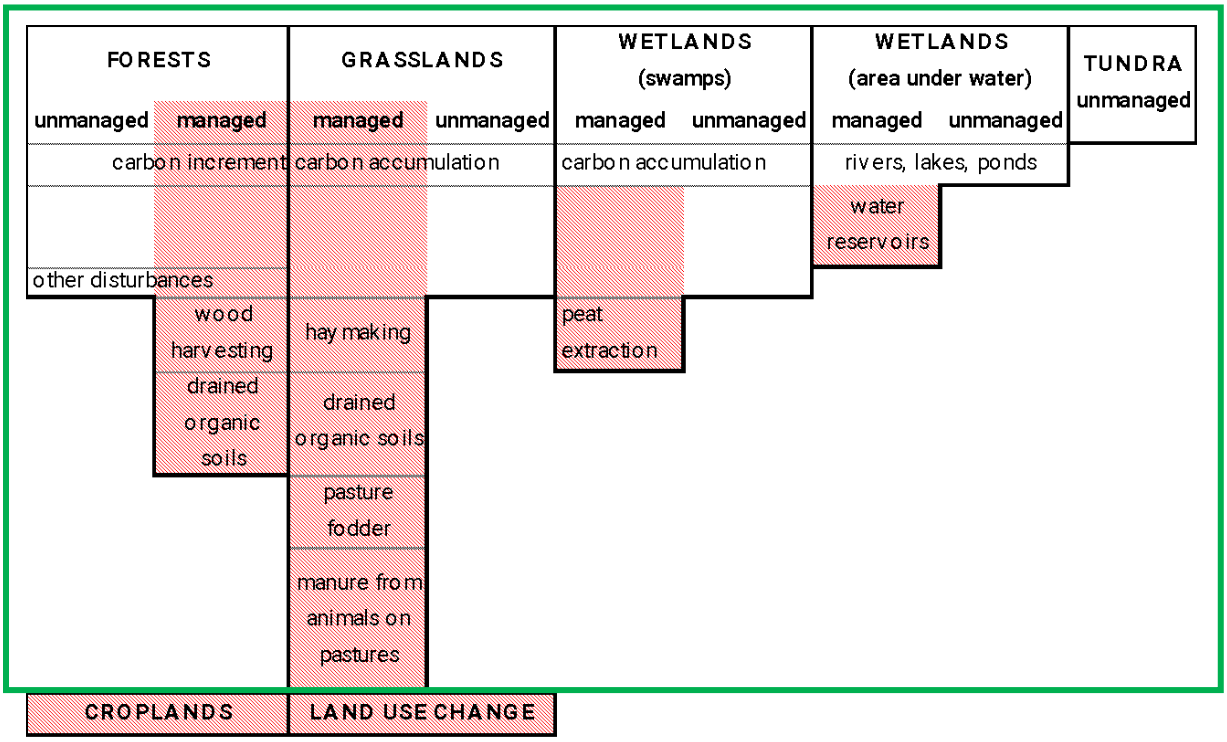

Figure 1. Scheme of natural and anthropogenic GHG fluxes from ecosystems considered in the study (green line) and National GHG Inventory [19] (red shading).

3. Results

3.1. GHG Fluxes from Ecosystems of the Russian Federation

Natural ecosystem areas included in the calculation by Korotkov et al. [20] do not always coincide with statistical data (Table 2). Thus, the recorded wetlands appear to partially overlap with forest land and tundra. At the same time, estimates of GHG fluxes from peatlands on forest lands according to the methodology used do not lead to double counting but complement each other, whereas in the case of tundra, there is a possible risk of double counting. This issue requires further study.

In the inventory, the category "managed grasslands" includes hayfields and pastures as well as overgrown cropland. However, in the study by Korotkov et al. [20], abandoned arable lands were fully accounted for in the secondary steppe category, which raises some doubts. Apparently, it is a consequence of the overestimation of these areas in the steppe zone. As a result, overestimation of carbon accumulation in secondary steppe soils occurs. The sum of hayfields, pastures, and steppes turned out to be higher than the total area of grasslands in the state statistics, which may also indicate an overestimation of the areas of natural steppes outside forage lands. A recent paper by the authors of this assessment reported roughly the same results [31]. In this study, the areas of grasslands and fodder lands were harmonized with the data of the Russian Land Cadastre [21]. Natural steppes are mostly used as pastures [50], which was taken into account during redistribution in order to eliminate double counting of areas. In addition, clarification of the share of steppe abandoned lands allowed for correct identification of abandoned arable lands in other regions and natural zones of the country (almost 20 thousand hectares). Natural steppe areas were also redistributed between managed and unmanaged grasslands.

The analytics of the obtained results on GHG fluxes in natural ecosystems by gas type and by administrative division of Russia, according to Korotkov et al. [20], are shown in Figure S1 in the Supplementary Material section. Maximum net absorption of CO_2 is a characteristic of the most forested regions, including those with extensive wetlands. They are in the northern regions of the European part of the Russian Federation, Western and Eastern Siberia, and the Far East. Methane emissions are also associated with wetlands and tundra ecosystems, while nitrous oxide emissions are associated with tundra ecosystems only. Maximum fluxes of each GHG are typical for the Krasnoyarsk Territory of Central and Eastern Siberia and are characterized by natural ecosystems of all climatic zones, largely compensating each other. The net GHG flux of the Krasnoyarsk Territory refers to a small net source (9 million tons of CO_2-eq.).

Table 2. Land area in 2016 according to national reporting data used by Korotkov et al. [20] and, in this study, million hectares.

Types of Land	Inventory [19]	In the Study by Korotkov et al. [20]	In This Study
Forest lands	897.0	897.0	897.0
out of which: - managed forests	688.2		
- unmanaged forests	208.8		
Croplands [1]	92.6	92.6	92.6
Grasslands	122.0	125.1	122.0
out of which: - managed grasslands	100.3		
including abandoned lands	29.5 (including secondary steppes)		14.0
including secondary steppes		32.4	16.3
including hayfields and pastures (fodder lands)	70.8	70.8	70.8 (including natural steppes, 16.8) 21.0 (including natural steppes, 5.2) Including total natural steppes, 22.0
- unmanaged grasslands	21.7		
including natural steppes		22.0	
Wetlands	226.8	322.8	322.8
out of which: - swamps	157.5	253.5	253.5
- areas under water	69.3	69.3	69.3
Settlements	14.2	14.2	14.2
Other lands	359.9	260.8	263.9
out of which: - tundra		258.5	258.5
- other lands		2.4	5.4
Total lands	1712.5	1712.5	1712.5

[1] including fallow lands and perennial plantations.

Net absorbers in terms of the sum of all GHGs are forest regions in the Northwestern Federal District of Russia and the Central, Siberian, and Far Eastern Federal Districts. At the same time, significant wetland areas in these counties determine relatively high methane emissions, which offset part of the carbon sequestration in forest biomass. Conversely, regions in the Asian part of Russia rich in forests but with fewer wetlands, especially in the southern areas, exhibit maximum net absorption. In contrast, southern regions of the European part—the Southern, North Caucasus, and Volga Federal Districts—have smaller forest areas and larger areas of pasture lands and freshwater bodies, making them net sources. In general, the territory of the natural ecosystems of the country has a negative balance for all types of GHGs and belongs to net absorbers.

The data for forest land obtained by Korotkov et al. [20] require updating for the value of net CO_2 uptake (-804 million tons of CO_2). These estimates were obtained based on initial data on timber reserves from the State Forest Register (SFR). SFR information, according to expert estimates, is 15–30 years old. In addition, due to the existing peculiarities of accounting, SFR includes information only about the first tier of the stand having a marketable value, while SFI sample plots collect information on all trees, which is more correct in terms of estimating carbon balance. Therefore, it is likely that the resulting estimates of the forest carbon budget may be underestimated by 30%–40% [51,52]. According to modeling estimates by Friedlingstein et al. [2] based on the comparison of 16 dynamic global vegetation models, net uptake in managed forests of the Russian Federation exceeds the national inventory data (−0.68 billion t CO_2) and amounts to about −1.1 billion t CO_2 per year [53]. However, it should be noted that the range of estimates of carbon sequestration by Russian forests available in the literature is quite wide and ranges from −220 to −2500 million tons of CO_2 [54].

The results of the refined assessment for forest lands based on updated information on timber reserves within the SFI and updated estimates for abandoned lands, fodder lands, and natural and secondary steppes within this study are shown in Table 3 in comparison with the data of Korotkov et al. [20].

Table 3. GHG net fluxes according to Korotkov et al. [20] and in the present work, mln t CO_2-eq. (negative values are absorption, positive values are emissions).

Types of Land	In the Work by Korotkov et al. [20]	In This Study
Forest lands	−775.2	−895.6 *
Grasslands	−370.8	−330.7
out of which: - natural steppes, total	−107.0	−107.0
- unmanaged grasslands outside the steppe zone		−62.1
- fodder lands (hayfields and pastures) outside the steppe zone	49.5	−21.7
- abandoned lands, including:		−139.9
- secondary steppes	−313.3	−111.5
Wetlands	32.5	32.5
out of which: - swamps	−119.2	−119.2
- areas under water	151.7	151.7
Tundra	64.7	64.7
Total	−1048.6	−1129.1

* mean value for 2017–2021 out of which CO_2 is −937.5 million tons CO_2-eq; CH_4 is 25.5 million tons CO_2-eq, and N_2O is 16.4 million tons CO_2-eq.

According to the data in Table 3, the recalculations made for forest lands (increase in net absorption by 120 million tons of CO_2-eq.) and clarification of the distribution of grassland areas between steppe and non-steppe zones (decrease in net absorption by 50 million tons of CO_2-eq.) did not lead to a significant difference in the aggregate estimate of the net balance of GHG from the country's natural ecosystems. The difference amounted to 80.3 million tons of CO_2-eq., which is within the area of uncertainty of the aggregate estimate.

Table 3 data for this study are summarized in Figure 2 by GHG and ecosystem types. Vertical lines show uncertainty ranges (95% confidence interval). Two almost equal but differently directed fluxes of CO_2 and CH_4 in wetland ecosystems determined a high uncertainty of the resulting value: ±1580%. Thus, CO_2 uptake was calculated with an uncertainty of ±200%, and CH_4 was calculated with an uncertainty of ±100%. Figure 2 shows that the key fluxes in Russia include carbon sequestration by forest, wetland, and tundra ecosystems and methane emissions by wetlands and tundra. Humid areas, where anaerobic conditions are often created in soils, although they store carbon, are characterized by relatively high methane emissions into the atmosphere. Given that the global warming potential of methane is 25–30 times higher than that of CO_2, these areas may be net emitters of GHGs. High methane emissions from wetlands in the boreal zone, as well as their increase during 2007–2021 in relation to the level of 2000–2006, are noted by Zhang et al. [55].

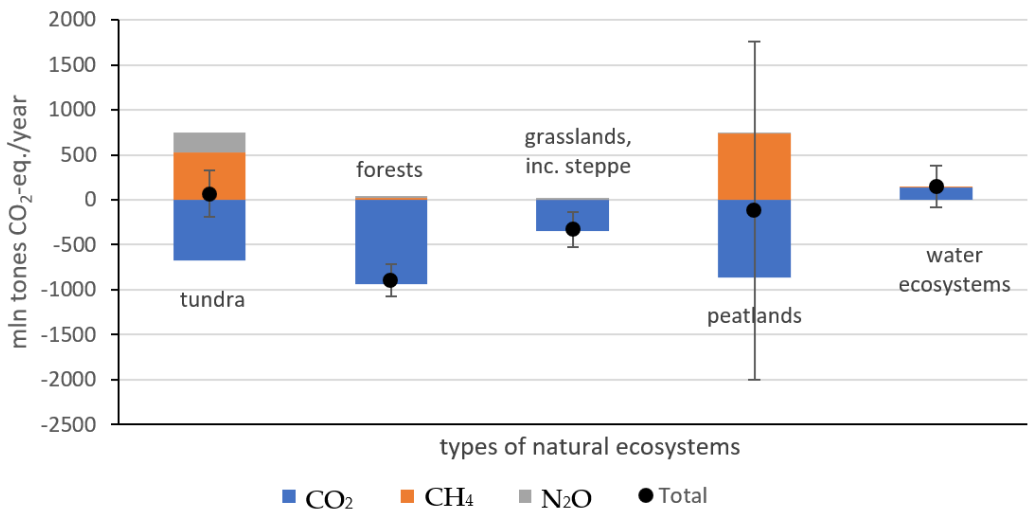

Figure 2. GHG fluxes by types of gases and types of natural ecosystems in Russia, millions of tons of CO_2-eq. per year (negative values are absorption, positive values are emissions) (tundra, wetlands, and freshwater ecosystems are presented according to Korotkov et al. [20]; forests and grasslands are presented according to this study). The figure shows the error bars of GHG balance values for each ecosystem type.

Obtained GHG flux estimates (Figure 2), according to the authors, require further study on clarification of the following directions:

- Specification of data on carbon stock changes in litter and soil pools in forest ecosystems. It is reasonable to consider stock changes in the 0–100 cm soil layer, given that boreal forests are characterized by high soil carbon stocks. The change in these stocks in forests occurs, among other things, at depths below the first 30 cm. Apparently, the specification of data on these pools can cause an increase in total net carbon sequestration in forests by −30–−40 million tons of CO_2.
- Considering that estimates for forest lands are based on state statistics data, this study does not include forests on overgrown agricultural lands, which may lead to an underestimation of up to −90–−160 million tons of CO_2 uptake in stand biomass alone (expert assessment by Bartalev S.A. [56]). Carbon storage by soils of abandoned arable lands is accounted for in the inventory under the land use change category;
- Pyrogenic carbon (includes soot, char, black carbon, and biochar) that is produced by the incomplete combustion of organic matter during landscape fires and burning of plant residues and buried in soils. It forms an important part of the carbon cycle [57] but is not included in our quantification. There is great uncertainty in estimates of the reserves of pyrogenic carbon fractions, which have varying stability. Moreover, it remains unclear what proportion of carbon can be buried in stable forms. Inclusion of pyrogenic carbon in the estimates requires additional research and the development of special models;
- Estimates of the harvested wood products (HWP) carbon pool are missing. According to Zhao et al. [58], HWPs are some of the major contributors to the mitigation of greenhouse gas effects. According to Russia's GHG inventory, HWP's carbon pool was a net source of CO_2 emissions: 10.0 ± 2.1 million tons CO_2 year^{-1} in 2016 and 2.4 ± 0.5 million tons CO_2 year^{-1} in 2021. Shvidenko A. and Schepaschenko D. [12] estimated carbon emission due to harvesting and use of forest products in Russia to be as much as 42.3 million tons C per year (155 million tons CO_2 per year).

However, substantial changes in the management of short-lived HWPs (such as paper and paperboard) in recent years may result in changes to the default half-lives for these products. Preliminary results indicate that updating the half-lives of paper and paperboard will result in HWP becoming a net sink in the 2020s. For clarification, it is necessary to develop country-specific coefficients;

- Relatively high values of N_2O emissions in tundras. A much smaller estimate of N_2O emission in this zone is found in the scientific literature. Hence, according to Voigt et al. [59], on average, for permafrost soils, the specific global emission of N_2O for 1993–2019 is two orders of magnitude lower. In terms of comparable units, it is about 0.57 g C-CO_2 m^{-2} per year lower than the 21.7 g C-CO_2 m^{-2} per year that was obtained by Korotkov et al. [20]. At the same time, the overall assessment of the tundra zone as a weak net source or territory with zero GHG balance corresponds to the IPCC assessment obtained later [60,61]. It seems then that carbon uptake [20] may also be somewhat overestimated for tundra ecosystems, which, together with compensatory estimates of N_2O emission, shows consistent results with those of other authors;
- The areas of small and temporary freshwater bodies are likely to be underestimated on the basis of state statistics and, consequently, GHG emissions from them as well. Deeper thawing of permafrost soils during the warm period of the year may be accompanied by the formation of temporary shallow reservoirs, which are characterized by high methane emissions. It is necessary to conduct further studies to estimate the areas of small lakes, streams, and ponds on the tundra territory using remote sensing data for a more accurate estimation of the annual emission of methane and CO_2 into the atmosphere.

It is advisable to continue working on clarifying the GHG balance in managed and unmanaged grassland ecosystems.

Figure 3 shows the GHG flux balance of natural ecosystems on the territory of Russia. It can be seen from Figure 3 that CO_2 net flux is characterized by a negative value, i.e., the absorption of carbon dioxide prevails over its emissions and corresponds to -2.7 ± 1.7 billion tons of CO_2 per year. This estimate corresponds to the data of other authors [9,10,17,62,63]. In accordance with the Biomass Carbon Monitor global service data on changes in aboveground biomass carbon stocks, Russia absorbed about -2.14 billion tons of CO_2 in 2016, which also matches the obtained data on carbon dioxide in the study by Korotkov et al. [20]. In the study by Deng et al. [4], the mean value of CO_2 net uptake by ecosystems in the Russian Federation according to inversion modeling data was estimated on average as a smaller value, equal to -1.6 billion tons of CO_2, with a range of estimates by different models from -3.0 to -0.7 billion tons of CO_2.

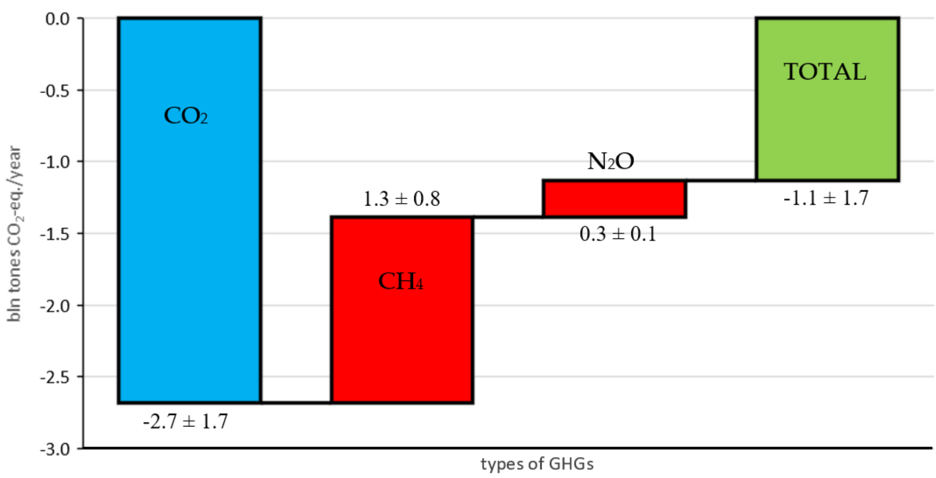

Figure 3. Net GHG uptake on the territory of natural ecosystems of Russia, billions of tons of CO_2-eq. per year: negative values (in blue) are net absorption; positive values (in red) are emissions; in green is the final GHG balance of all inland ecosystems in Russia.

Methane and nitrous oxide have net emissions to the atmosphere totaling 1.6 ± 0.8 billion tons of CO_2-eq. per year, which offsets more than 60% of CO_2 uptake. There are not much data in the literature on emission estimates of non-CO_2 gases, and their variation is relatively large. Considering this, Denisov et al. [5] found the natural methane flux in the Russian Federation to be nearly five times lower than the estimate provided by Korotkov et al. [20]. Methane emissions to the atmosphere from wetlands obtained in our study are almost 1.4 times higher than the maximum estimate from GOSAT satellite monitoring data [6]. It should also be noted that information on methane emissions from tundras is apparently absent in GOSAT and other satellite data.

The total GHG flux balance of all studied ecosystems in Russia corresponds to a net uptake of −1.1 ± 1.7 (±161%) billion tons of CO_2-eq. High uncertainty is primarily determined by the uncertainty of flows in wetlands and tundra.

Publications suggest that several factors may lead to increased GHG fluxes to the atmosphere from Russia in the second half of the 21st century, potentially turning its natural ecosystems into a net source of GHGs [5]. These factors include an expected increase in methane emissions from permafrost soils, along with a growth of methane emissions from the shelf. Additionally, further temperature changes and redistribution of precipitation will likely cause the gradual decrease in the productivity of forests and other ecosystems.

3.2. Balance of Anthropogenic and Natural GHG Fluxes in Russia

Considering the anthropogenic GHG fluxes already partially included in the above estimates, for a full assessment of the total net flux (anthropogenic and natural) from the ecosystems of Russia, it is necessary to add the contribution of agrocenoses, changes in land use, and changes in the carbon balance in the forest product pool. These estimates are available in the inventory [19]. Therefore, the total GHG net flux from the ecosystems of Russia is estimated to be equal to the absorption of −1064 ± 1820 thousand tons of CO_2-eq.

Figure 4 shows estimates of the total GHG balance taking into account anthropogenic emissions from fossil fuel combustion, industry, livestock, the waste sector, and the net uptake of ecosystems in Russia, according to this study and Romanovskaya et al. [19].

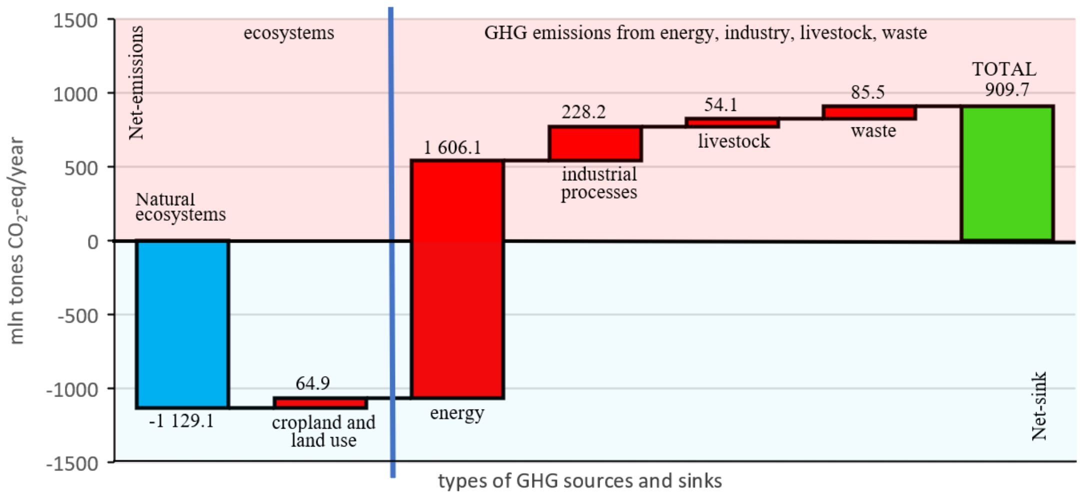

Figure 4. GHG balance (including F-containing gases) on the territory of Russia for 2016, million tons of CO_2-eq. per year: negative values (in blue) are net absorption; positive values (in red) are emissions; in green is the final GHG balance on the territory of Russia, taking into account natural and anthropogenic fluxes.

The obtained total balance of anthropogenic and natural GHG fluxes on the territory of Russia corresponds to the value of the net emission of 910 million tons of CO_2-eq. According to Romanovskaya et al. [19], the pooled uncertainty values excluding the contribution of the LULUCF sector in the base (1990) and reporting (2016) years were 4.4% and 5.5%, respectively [19], Volume 2. Using the higher value for 2016, we obtain a total uncertainty in the resulting estimate of ±171%. Thus, as of 2016, the overall GHG balance on the territory of Russia is likely to be positive, i.e., it is characterized by net emissions of 0.91 ± 1.8 billion tons of CO_2-eq.

The total GHG balance, taking into account net fluxes from ecosystems and anthropogenic emissions by types of major gases (excluding F-gases), is presented in Table 4.

Table 4. GHG balance on the territory of Russia taking into account natural and anthropogenic fluxes by GHG types as of 2016, millions of tons of CO_2-eq (emissions "+"/absorption "−") *.

GHGs	Natural Fluxes	Anthropogenic Fluxes According to Romanovskaya et al. [19]	GHG Balance in the Russian Federation
CO_2	−2685.9	1633.9	−1052.0
CH_4	1299.5	293.1	1592.6
N_2O	257.3	81.4	338.7

* excluding F-containing GHGs.

According to the data in Table 4, the Russian Federation can be considered a "donor" only for CO_2, net absorption of which is approximately −1.05 billion tons of CO_2. Thus, the Russian Federation already has the carbon neutrality that the IPCC [64] recommends achieving to meet the trajectory of keeping warming within 1.5 °C by 2050 when considering the sum of anthropogenic and natural fluxes. However, given the emissions of non-CO_2 gases, Russia is likely to be a net emitter of GHGs into the atmosphere.

4. Discussion

The available bottom-up satellite estimates for the CO_2 flux are in accordance with our results. Satellite information is an independent source of information for the verification of bottom-up data derived from ground observation and modeling data. For instance, according to Byrne et al. [3], the average of five datasets analyzed by the Orbiting Carbon Observatory (OCO-2) inversion model comparison project, including in situ CO_2 measurements and a combination of these data, showed the net uptake between the land surface and the atmosphere within the Russian Federation to be just under 1 billion tons of CO_2 on average over the period of 2015–2020. This value corresponds to the sum of ecosystem fluxes of carbon dioxide and anthropogenic CO_2 emissions in Russia, which is estimated in our study as −1.05 billion tons of CO_2 (see Table 4) for 2016. We estimate that natural ecosystems in the Russian Federation absorb approximately −2.7 billion tons of CO_2-eq, which also correlates well with the ΔCloss value [3] corresponding to the mean of the five datasets. Although the ΔCloss variable also includes international trade in grain and timber, in the case of Russia, the resultant for these fluxes is practically zero and does not significantly affect the comparison between our results and those of Byrne et al. [3].

Total methane fluxes in Russia obtained in our study are estimated to be about 2 times higher than in the study by Denisov et al. [5] and 1.4 times higher than those obtained by Bondur et al. [18]. According to the latest study, Russia's contribution to natural global methane emissions does not exceed 10% and amounts to 13.3 million tons of CH_4 per year for the bottom-up assessment and 11.7 million tons of CH_4 per year for the top-down assessment. At the same time, the contribution of wetlands dominates the intensity of all-natural sources, accounting for about one-third of all CH_4 emissions from the territory of Russia into the atmosphere. The intensity of anthropogenic sources of methane emissions is also not more than 10% (23.5 million tons of CH_4 per year and 19.8 million tons of CH_4 per year for the bottom-up and top-down assessments, respectively) [18]. It should be noted that, according to the inventory data, anthropogenic methane emissions without taking into account the LULUCF sector had a lower value of 11.6 million tons in 2016, and with its inclusion, it was 12.5 million tons of CH_4 [19]. According to EDGAR (Emissions Database for Global Atmospheric Research), anthropogenic methane emissions in Russia were about

16 million tons of CH_4 in 2016 (18 million tons of CH_4 in 2021). Other data, such as the CEDS (Community Emissions Data System) database, show about 25 million tons of CH_4 in 2017. The spread of bottom-up data for anthropogenic emissions in Russia ranges from 16 to 28 million tons of CH_4, while top-down data ranges from 11 to 26 million tons of CH_4 [6].

According to Bondur et al. [18], the share of anthropogenic emissions in the total methane emissions in Russia is close to two-thirds. Approximately the same 2:1 ratio between anthropogenic methane emissions and natural emissions is given by Denisov et al. [5]. International databases show a ratio close to 1:1 [6]. According to our data, natural methane emissions from the territory of Russia exceed anthropogenic emissions in the ratio of 4:1. Despite the possibility of some overestimation of natural fluxes and/or underestimation of anthropogenic methane emission in our study and in the National GHG inventory [19], given the presence of significant sources in tundra and wetland ecosystems, the excess of total natural methane emission over anthropogenic emission looks more logical for the territory of the Russian Federation than vice versa.

Anthropogenic nitrous oxide emissions can be compared with EDGAR database data, which show a lower value of anthropogenic N_2O emissions for 2016 than in the inventory, where it comprises 76 million tons CO_2eq (85 million tons CO_2-eq for 2021). For natural N_2O emissions on a nationwide scale, only modeling data have been found in scientific publications. However, a comparison of assessment results from 10 terrestrial ecosystem models—including DLEM, LM3V-N, ORCHIDEE, ORCHIDEE with nitrogen and phosphorus cycles (ORCHIDEE-CNP), O-CN, Lund–Potsdam–Jena General Ecosystem Simulator (LPJ-GUESS), LPX-Bern, TRIPLEX-GHG, and a model with a vegetation block for the estimation of small gas constituents (VISIT))—revealed quite similar results of nitrous oxide emissions from natural ecosystems of Russia. On average, for the period of 2001–2015, it amounts to about 0.26–0.28 Tg N-N_2O [65,66]. This value corresponds to 126.4 million tons CO_2-eq, which is two times lower than the 254.1 million tons CO_2-eq in our study. Doubts about the estimates of N_2O emission intensity from tundra and its possible overestimation by Korotkov et al. [20] are discussed above.

Managed and Unmanaged Lands in GHG Reporting

To structure the work of countries in combating anthropogenic climate change, only anthropogenic GHG fluxes of both emissions and removals need to be isolated and accounted for. The latter is not an easy task, but it is required. Accounting for large, unmanaged fluxes in nationally determined contributions (NDCs) under the Paris Agreement would lead to inefficient allocation of country efforts and could completely eliminate incentives to reduce emissions and increase national uptake.

Historically, the negotiations of the Parties to the UNFCCC have produced the following concepts of anthropogenic sinks: "land management" and "managed lands". In the first case, the action-by-action approach allows for only those fluxes that are modified by the direct impact of human activities to be considered. For instance, plowing land as part of cropland management results in losses of soil organic carbon. Direct impacts also include actions such as the cutting and planting of forests, flooding and draining of lands, etc. The most controversial issue is the management of existing forest lands. It is practically impossible to identify the effect of only anthropogenic activities on them, given that actions to protect and conserve forests prevent an unknown amount of GHG emissions into the atmosphere per year. In this case, it is necessary to introduce the concept of "managed lands". For example, the IPCC Good Practice Guidance for LULUCF [49] established the following definition of two management approaches for forest land:

"Forest management is the process of planning and implementing practices for stewardship and use of the forest aimed at fulfilling relevant ecological, economic and social functions of the forest. A managed forest is a forest subject to forest management".

The following 2006 IPCC Methodological Guidelines [43] define managed lands as "lands where human intervention and practices have been applied to fulfil productive, environmental or social functions. All land definitions and classifications should be specified at the national level, described in a transparent manner, and be applied consistently over time". For unmanaged land, it is recommended to consider only its area in country reporting.

The IPCC also distinguishes the concept of "indirect anthropogenic effects" on GHG fluxes in ecosystems due to anthropogenic changes in the environment (e.g., changes in atmospheric CO_2 concentration, deposition of nitrogen compounds of anthropogenic origin, changes in temperature or precipitation regimes) that affect plant growth, mortality of individuals in populations, decomposition rates of dead organic matter, and natural disturbance regimes in ecosystems.

According to IPCC guidelines [43,49], all GHG emissions and removals within managed land boundaries are to be reported, accounted for, and taken as an approximation of anthropogenic fluxes (e.g., wildfires caused by natural causes within managed forests are counted as anthropogenic, but any fires within unmanaged land are not). Thus, the concept of managed land is a kind of indirect indicator of anthropogenic effects on the territory of natural ecosystems.

The shortcomings of approximating anthropogenic effects on the climate system through the managed land approach were discussed in detail at a separate IPCC expert meeting in 2008 [67]. In particular, the complexity of applying the approach to wetlands and flooded lands, accounting for changes in forest age structure, and natural disturbances on managed lands, as well as the indirect positive effects of increasing atmospheric CO_2 concentration, etc., were pointed out. It is evident that estimating carbon stock changes across all pools of managed land, according to IPCC guidance [43,49], takes into account both management effects and natural processes together. However, no other approach was developed at the meeting to separate these factors, and the "managed land" approximation was confirmed as the most pragmatic approach for national reporting. It is still relevant today within the framework of the Paris Agreement.

It should be noted that the "managed lands" approach also does not work in the case of scaling up activities to reduce or prevent GHG emissions in previously unmanaged ecosystems, such as efforts that prevent the thawing of permafrost soils. However, fully accounting for all GHG fluxes on newly managed lands would result in an absolute increase in anthropogenic emissions in national reporting and remove incentives to increase such important climate change activities.

Given the difference in approaches used in scenario modeling of the required levels of emission reductions in the Assessment Reports of the IPCC and national reports under the UNFCCC [53,68], there are recommendations in the literature that GHG fluxes from all ecosystems of countries should be fully accounted for in their reporting [1]. However, it is impossible to accept this. As stated above, the inclusion of any large GHG flux (either positive or negative) in reporting could negate any efforts to reduce emissions or increase sequestration, as these efforts would "disappear" in the face of large unmanaged fluxes. For the Russian Federation, such an effect may be related to the inclusion in the reporting of total fluxes of unmanaged wetland and tundra ecosystems. The presence of large emissions that cannot be reduced may eliminate the sense of managing others, including forest ecosystems and, for example, reducing the area of forest fires. Despite the cost of these measures, the total GHG net flux in the national reporting will not change much. It is also inappropriate to consider unmanaged uptake in the forest and grassland ecosystems of the country, which can have a similar effect on the efficiency of management decisions (presence of large uptake despite emissions from forest fires will not stimulate activity on their extinguishing). Unfortunately, approaches to separate natural and managed uptake in the remaining forests have not yet been developed. An attempt to isolate anthropogenic effects is present in the IPCC Wetland Supplement [33], where, in carbon-rich coastal ecosystems, it is suggested that only the impact of management activities on the carbon stock of the ecosystem should be considered rather than accounting for it completely. This approach should be developed accordingly.

Evidently, it is the clear delineation of anthropogenic fluxes on managed lands that is the most accurate approach for reporting GHGs, and countries should aim for it, rather than extending their reporting entirely to all GHG fluxes within natural ecosystems, as suggested by Nabuurs et al. [1].

5. Conclusions

Despite possible errors in GHG emission and uptake estimates in the study by Korotkov et al. [20] and in our study, they appear to largely offset each other. The relatively high uncertainty of the resulting estimate for the natural ecosystems of Russia as a whole, determined at almost 200%, is due to the difference of two large values of differently directed emission and absorption fluxes. However, it can be assumed at the expert level that the accuracy of the resulting estimate is higher and ranges of about ±50%. This range corresponds to the average spread of modeling results from dynamic vegetation models and inversion modeling from remote sensing data. In such a case, there is no doubt about the GHG balance mark.

In our study, we obtained the following three main conclusions about the GHG flux balance on the territory of the Russian Federation:

- Net absorption of carbon dioxide on the territory of the terrestrial ecosystems of Russia corresponds to a value of more than −2.5 billion tons of CO_2. The contribution of forest ecosystems to the carbon balance is only about 35%. Taking into account the anthropogenic emission of carbon dioxide (1.6 billion tons of CO_2), Russia's territory is likely to be a net absorber, i.e., a "donor" when assessed by CO_2 alone. Therefore, the Russian Federation already has the carbon neutrality necessary to match the trajectory of keeping warming within 1.5 °C by 2050, when considering the sum of anthropogenic and natural fluxes;
- Taking into account emissions of non-CO_2 GHGs (methane and nitrous oxide), the net absorption of GHGs in the natural ecosystems of Russia is reduced by more than two times and amounts to about −1 billion tons of CO_2-eq. At the same time, forests account for almost 80% of the total GHG balance on the territory of Russia. The greatest contribution to emissions of non-CO_2 gases comes from the wetland and tundra ecosystems of Russia. For the latter, the estimation uncertainty is extremely high, and the data in the publications are fragmentary, while satellite information seems to be practically absent;
- GHG balance of natural and anthropogenic fluxes on the territory of Russia is most likely positive, i.e., corresponds to net emissions into the atmosphere in the amount of 1 billion tons of CO_2-eq. The estimated net balance for anthropogenic GHG fluxes in the National Inventory for 2016 is 1.56 billion tons of CO_2-eq emissions to the atmosphere [19]. Hence, it is most likely that the Russian Federation is not a "climate donor" when all GHGs are fully accounted for.

Russia's natural ecosystems, especially forest ecosystems, which comprise more than 20% of the global forest area, play a significant role in climate change mitigation. Main efforts should be concentrated on forest fire prevention, improved forest management, reforestation and afforestation, and conservation of intact forest landscapes. Started in 2022, the most important innovative project of national importance, the "Russian Climate Monitoring System", aims to intensify research on the fluxes of greenhouse gases in natural ecosystems, which clarify the country's significance in global environmental conservation efforts and provide valuable insights for future policy formulation and action.

In terms of improving reporting under the Paris Agreement, countries should endeavor to include only anthropogenic (manageable) GHG fluxes on managed land, rather than extending their reporting entirely to all-natural ecosystems. Only such an approach will incentivize action by countries to reduce emissions and increase removals on their territory.

Further scientific research should be devoted to the collection of more complete information on changes in carbon stocks and non-CO_2 GHG fluxes for the territory of Russia and to the correct assessment of the inter-annual variability of these fluxes. A significant lack of data, both ground-based experimental observational data and satellite and modeling estimates, is noted for the tundra ecosystem zone. Several factors contribute to the high variability in aggregate estimates of tundra's impact on climate change obtained by different methods. These factors include high spatial variability in tundra ecosystems, a small number of experimental measurements, low coverage by satellite systems, and the high cloudiness of northern territories. While carbon estimates are built on more reliable data (ecosystem carbon stocks) that are suitable for periodic observation, CH_4 and N_2O emissions require continuous measurements and cannot be reliably interpolated between point-in-time measurements, whether ground-based or remote. These features should be considered in future studies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15040707/s1, Figure S1: Net GHG fluxes from ecosystems by types of gases and by Russian territorial subjects, million tons of CO_2-eq. per year (negative values are absorption, positive values are emissions) (according to Korotkov et al. [20]): (a) CO_2; (b) CH_4; (c) N_2O; (d) all GHGs.

Author Contributions: Conceptualization, A.R. and V.K.; methodology, A.R. and V.K.; formal analysis, A.R. and V.K.; investigation, A.R. and V.K.; resources, A.R. and V.K.; data curation, A.R. and V.K.; writing—original draft preparation, A.R. and V.K.; writing—review and editing, A.R. and V.K.; visualization, A.R.; supervision, A.R.; project administration, A.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Russian Hydrometeoservice, research theme number 3.3 in the Research and Technical Work Plan for 2020–2024.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors are grateful to D.G. Schepaschenko and S.V. Fedorov for consultation and help with the results of the first cycle of the State Forest Inventory.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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