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Efficiency Evaluation of Forest Carbon Sinks: A Case Study of Russia

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Abstract: Forest carbon sinks in Russia are an integral part of the national "Low-carbon development strategy". However, the influence of natural disasters and various land use policies in economic regions (ERs) raises the issue of forest carbon sink efficiency (FCSE). This study adopted a DEA-SBM model that considers undesirable outputs to measure FCSE, and the Malmquist index (MI) approach to analyze total factor productivity (TFP) of forest carbon sinks, using panel data from 2009 to 2021. The results show that the average FCSE was 0.788, with an improvement rate of 21.2%. Scale efficiency is the main factor constraining FCSE in Russia. In twelve ERs, forest carbon sinks are efficient only in the Kaliningrad and West Siberian ERs. In general, forest carbon sinks in Russia are inefficient mainly due to forest fires and other natural disturbances (82.33%); excessive logging activities (38.64%); and lack of carbon absorption capacity (31.70%). The average score of their TFP is 0.970, indicating a decline of 3% over the study period. This is primarily attributed to the decline of 1.6% in technological change. The productivity of forest carbon sinks remained static only in the Kaliningrad ER, while other economic regions performed deterioration trends. Therefore, Russia should enhance the efficiency of forest carbon sinks.

Keywords: forest carbon sink efficiency; SBM-undesirable output model; Malmquist index; Low-carbon development strategy; forest carbon offset projects; Russia

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1. Introduction

Russia has nearly 20% of the world's forests, which occupy 815 million hectares (49.8% of the total land area of the country) [1,2]. In addition to being a source of raw materials, forests are an important tool for climate change mitigation as they absorb carbon dioxide (CO_2) through photosynthesis [3]. Currently, Russia ranks fifth in the world in terms of CO_2 emissions [4]. Carbon sinks, which in the country consist mainly of forests, offseted about a quarter and slightly less than a third of national greenhouse gas (GHG) and CO_2 emissions in 2021, respectively [5]. Russia belongs to the Annex I countries of the United Nations Framework Convention on Climate Change (UNFCCC), which signed the Kyoto Protocol [6] in 1997 and the Paris Agreement [7] in 2015. The country annually publishes national inventory reports (NIRs) containing a section on GHG emissions and removals as a result of anthropogenic activities, in particular within the "land use, land use change, and forestry" (LULUCF) sector [8]. The parties included in Annex I of the UNFCCC are required to comply with the regulations of the guidelines for national greenhouse gas inventories of the Intergovernmental Panel on Climate Change (IPCC) [9].

Since reporting is formed independently by countries and takes into account national characteristics, the evaluation results in Russia differ significantly both methodologically and from the point of view of the quality and completeness of the data used [10]. The IPCC methodology consists of different hierarchical tiers (Tiers 1, 2, 3) [11]. To prepare NIRs for IPCC, Russia applies the third (highest) methodological tier that implies that the county has a detailed state forest registry (SFR) database and its own national methodologies based on regional experimental studies [12]. Since 2011, the system of the regional assessment of forest carbon budget (ROBUL) has been applied for compiling NIRs, complying with the IPCC guidelines [13]. After the reforms of the national forest management system related to the transition to annual data within the SFR, the “stock-difference” approach was almost totally replaced by the “gain–loss” method [12]. At the same time, a number of Russian experts [14] proposed to include reserve (remote) forests in the category of “managed” (consisting of exploitational and protective forests) and include these data in NIRs [15]. According to their findings, the value of carbon stock in the biomass of the country’s forests is expected to increase by 17%, annual absorption by 13%, and the net carbon sequestration of forest biomass in total by 13%. Noteworthy, this violates the key criterion of international climate reporting, stating that only managed forests may be included in carbon accounting practices [9]. Apart from that, the remote method of data collection during forest inventory, in comparison with ground surveys, also reveals significant discrepancies in estimates of carbon stock in Russia’s forests. According to the experts [16], remote sensing data showed that, in 2014, the growing stock in Russia’s forests was 39% higher than stated in the state forest register, and carbon sequestration in live biomass between 1988 and 2014 was 47% higher than reported in the NIR. Another study [17] on the assessment of carbon stock in Russian forests between 2001 and 2021 was carried out on the basis of satellite remote sensing data, selected ground observations, and prediction models. According to their findings [18], forest carbon stock (excluding soil carbon pool) in 2021 amounted to 55.8 billion tons (in comparison with 36.6 billion tons stated in the NIR for 1990–2021 [2]). Table 1 shows various estimations of the carbon sequestration potential of Russia’s forests in the long-term perspective.

Table 1. Estimates of changes in carbon sequestration potential of Russia’s forests in the long-term perspective (% for the projection period). Adapted from Vaganov et al. [10].

Projection Period (Years)			Drivers of Change	Reference
2010–2030	**2010–2035**	**2010–2050**		
−30. . . −52	−50. . . −68	−65. . . −83	Increased logging	[13]
−3. . . −13	−20. . . −40	−33. . . −60	Increased logging	[19]
n.d.	−15. . . −20	n.d.	Increased logging, fire protection	
−57. . . −62	n.d.	−58. . . −72	Increased logging, strengthening forest protection, reducing timber losses during logging, accounting for regrowth forests on abandoned agricultural lands	[20]
+7. . . +10	n.d.	n.d.	Increased logging, reduced forest damage, increased forest area	[21]

In general, the experts [12] point out that the currently applied ROBUL method is satisfactory for the estimation of carbon stocks and fluxes in managed forests of Russia. Moreover, it complies with the IPCC Guidelines and the results are comparable to other models, i.e., the carbon budget model of the Canadian forest sector (CBM-CFS3) of the Canadian Forest Service (CFS) [13,22]. Other carbon sequestration assessment techniques are not widely adopted and presented only as research alternatives that are not recognized by the experts from IPCC to become candidate solutions. However, the issue of choosing a particular method is primarily related to the accuracy and reliability of the national forest inventory on which estimations are based. According to the Accounts Chamber of the Russian Federation [23], for 2020, data for 84.4% of forests in Russia are more than 10 years out of date. Therefore, a more frequent update and quality improvement of related data is a must. In that case, the enhancement of international scientific cooperation could significantly contribute to the achievement of this goal.

Obviously, the discrepancies in the above-mentioned estimations on carbon stock and the sequestration potential of Russia's forests seriously complicate the formation of a reliable strategy for climate change mitigation. Nonetheless, in October 2021, Russia approved its "Strategy of the socio-economic development with low greenhouse gas emissions until 2050" [20] and submitted it to the UNFCCC on 5 September 2022 as its long-term climate strategy [24]. In the strategy, Russia has set a goal to achieve carbon neutrality no later than 2060. The strategy also includes a goal to reduce GHGs by 80% below 1990 levels by 2050, relying heavily on the carbon sequestration capacity of forests, which should be more than doubled between 2030 and 2050 (from 539 million tCO_2e to 1200 million tCO_2e), as stated in the target (intensive) scenario [20]. According to the document, forest–climatic projects (widely known as forest carbon offset projects) should be implemented to achieve this goal [25]. As of January 2024, only seven related projects have been implemented in Russia, and only two of them were added to the national carbon credit registry [26–28]. At the same time, the strategy does not limit the typology of such projects. They can include projects on afforestation; reforestation; protection of forests from fires, pests and diseases; and prevention of logging and conversion of forest lands. [26,29–32]. In general, the implementation of these projects should enhance the carbon sink capacity of managed forests. Moreover, forest carbon sinks in Russia are distributed highly unevenly, and their carbon absorption capacity depends on many factors, including the area, age structure, and species composition of the forests themselves; the land use policy of regions (wood harvesting or clear cutting due to agricultural expansion); and natural disturbance volumes (namely forest fires, pests, and disease outbreaks, etc.) [33–36].

Finally, Russia should urgently comprehend the importance of the climate role of its own forests, considering the fact that the climate in the country is warming about 2.5 times faster than the global average [37]. Given the largest area of forests and that the country is responsible for fulfilling the international commitments in climate change, there is a clear need to measure the efficiency of forest carbon sinks in Russia both from temporal and spatial perspectives. Therefore, this study aims to fill this research gap and provide recommendations for enhancing forest carbon sink efficiency (FCSE) in Russia.

2. Literature Review

The research topic of efficiency evaluation in forestry mainly focuses on the optimal allocation of resources and aims to improve production efficiency. The stochastic frontier approach (SFA) and data envelopment analysis (DEA) are both commonly used methods that measure the efficiency of forestry [38,39]. Based on the non-parametric nature, DEA is widely performed in efficiency measurement of input/output indicators [40]. FCSE refers to the obtaining of maximum forest carbon sink output with the least amount of forest resources utilized. Recently, several studies have focused on the efficiency performance of forest carbon sinks. Most scholars have focused on measuring FCSE by applying DEA. Long et al. [25] conducted an FCSE evaluation of Hangzhou and found out the spatial heterogeneity among counties and cities. Xue et al. [41] observed driving forces and the convergence of FCSE in four forest regions in China. Shu et al. [42] measured the FCSE of the Natural Forest Protection Project (NFPP). The results showed that the efficiency of forest carbon sinks in the state-owned forest areas of the project was higher. Yao et al. [43] and Zhao et al. [44] conducted similar research of FCSE in China, applying the traditional DEA models. Several studies adopted SFA regression in the three-stage DEA model as an extension to test the impact of uncontrollable environmental factors on the dependent variable. Ao et al. [45] proposed a three-stage DEA model combining SFA regression for the efficiency evaluation of bamboo forests, considering their carbon sequestration capacity. Lin and Ge [46] adopted SFA to adjust regional forest carbon sinks and forestry output slacks.

Moreover, a number of studies have investigated the factors that influence FCSE. Wei and Shen [47] adopted a DEA-SBM (slack-based measure) model to evaluate the efficiency of forest carbon sinks, and explored the influence of various natural and human factors within the pressure–state–response (PSR) framework model. Liu et al. [48] included socio-economic and meteorological factors to evaluate their impact on carbon sequestration by forest vegetation. Wang et al. [49] highlighted natural endowment, forest management, and social development factors, and performed a Tobit panel regression model to investigate their influence on FCSE. Yin et al. [50] pointed out that temperature, GDP per capita, urbanization, and length of highway network have significant positive impacts, and the total imports and exports have a significant negative impact.

In summary, most of the above-mentioned studies adopted a "stock-difference" approach for calculating forest carbon sink volumes. Moreover, there is a lack of quantitative analysis of FCSE, including various undesirable outputs during the forestry production process, e.g., forest fire rates and wood harvesting volumes, that hinder the development of forest carbon sinks. Therefore, this study proposed the DEA-SBM model considering undesirable outputs and the Malmquist index technique to evaluate the efficiency of forest carbon sinks in Russia both from temporal and spatial perspectives. Firstly, due to the "gain–loss" approach performed in Russia's NIRs, undesirable outputs are stated as "losses", which is more appropriated for examining FCSE under the proposed model. Secondly, ignoring the undesirable outputs may lead to exaggerated efficiency scores [51]. Thirdly, it can be possible to determine which kind of forest carbon offset projects should be implemented to increase FCSE in particularly inefficient regions.

3. Research Methodology

3.1. SBM-DEA Model Considering Undesirable Outputs

Originally, the DEA method was first proposed in 1978 by Charnes, Cooper, and Rhodes [52] (CCR model) based on the concept introduced by Farrell [53]. The CCR model assumes constant returns to scale (CRS), assuming that all decision-making units (DMUs) operate at the optimal scale. Alternatively, in 1984, Banker, Charnes, and Cooper [54] proposed a variable returns to scale (VRS) model (BCC model), in which DMUs do not operate at the optimal scale. However, neither model considers input or output slacks (namely input redundancy and output deficiency) or the impact (redundancy) of undesirable outputs. Tone [55,56] proposed a more advantageous non-radial SBM model that incorporates all slack variables into the objective function to solve the slackness problem and improve the efficiency measurement considering undesirable outputs. Based on the model's adjustments (namely slack movements), it is possible to provide some suggestions regarding inefficient DMUs becoming efficient. Given that the forest carbon sinks in Russia are affected by natural disasters, wood harvesting, and clear cutting, this study adopts a more suitable input-oriented SBM-DEA model that considers undesirable outputs. The specific model is as follows:

$$\rho^* = min\frac{1-\frac{1}{I}\sum_{i=1}^{I}\frac{S_i^-}{x_{i0}}}{1+\frac{1}{R+L}\left(\sum_{r=1}^{R}\frac{S_r^g}{y_{r0}^g}+\sum_{l=1}^{L}\frac{S_l^b}{y_{l0}^b}\right)}$$

$$s.t.\begin{cases} x_{i0} = \sum\limits_{j=1}^{n} x_{ij}\lambda_j + S_i^-,\ i = 1,\ldots,M \\ y_{r0}^g = \sum\limits_{j=1}^{n} y_{rj}^g\lambda_j - S_r^g,\ r = 1,\ldots,R \\ y_{l0}^b = \sum\limits_{j=1}^{n} y_{lj}^b\lambda_j + S_l^b,\ l = 1,\ldots,L \\ S_j^-, S_r^g, S_l^b \geq 0,\ \forall i, \forall r, \forall l \end{cases}, \quad (1)$$

where ρ^* is the efficiency value of forest carbon sinks of the j-th DMU; x_{ij}, y_{rj}^g, and y_{lj}^b represent input, expected output, and undesirable output variables, respectively; S_i^-, S_r^g, and S_l^b are the slack variables of input, expected output, and undesirable output, respectively; λ stands for the linear programming weight vector. When $\rho^* = 1$, it means that DMU is efficient under the condition that the slack variables of input, expected output, and undesirable output (S_i^-, S_r^g and S_l^b) are all 0. If $\rho^* < 1$, it means that DMU has low efficiency, and the slack variables of input, expected output, and undesirable output are larger than 0. Therefore, ineffective DMUs might be input redundant, expected output deficient, or undesirable output redundant. Subsequently, Equations (2)–(4) are used to compute the relevant rates in the case of their existence.

The formula for the redundancy rate of inputs is as follows:

$$\vartheta_{m0}^{-} = \frac{x_{i0} - S_i^{-}}{x_{i0}} \quad (2)$$

The formula for the deficiency rate of expected output is as follows:

$$\vartheta_{r0}^{g} = \frac{S_r^{g} - y_{r0}^{g}}{y_{r0}^{g}} \quad (3)$$

The formula for the redundancy rate of undesirable outputs is as follows:

$$\vartheta_{l0}^{b} = \frac{y_{l0}^{b} - S_l^{b}}{y_{l0}^{b}} \quad (4)$$

Since the research object of this study (forest carbon sinks) is a key climate mitigation tool in the "Low-carbon development strategy" (in terms of global (national) scope), the values of TE (constant returns to scale) are selected to measure FCSE in Russia. In an input-oriented model, TE defines the ability of a DMU to produce an output using the lowest possible quantity of inputs [57,58]. Furthermore, it can be decomposed into pure technical efficiency (PTE) and scale efficiency (SE). PTE implies that all resources are being efficiently utilized and allocated during the production process. SE reflects the gap between the actual and optimal production scales based on the combination of resources. The value of each indicator is ≤ 1, and $TE = PTE \times SE$. This decomposition also highlights the potential sources of inefficiency, whether they are caused by the management regime (in case of lower PTE value), disadvantageous conditions (in the case of lower SE value), or both [40,59].

3.2. Malmquist Index (MI)

Originally, the Malmquist index was developed by Sten Malmquist in 1953 [60]. Caves et al. [61] adopted this technique to measure total factor productivity (TFP), assuming the efficiency of the main productive factors, including capital, labor, land resources, and innovations. Färe et al. [62,63] decomposed TFP change into technical progress change (TC) and technical efficiency change (EC). Assuming variable returns to scale, EC can be divided into pure technical efficiency change (PEC) and scale efficiency change (SEC). Traditional DEA analysis only reflects the relative efficiency values of different DMUs in the same time period and is unable to track the changes of their efficiency over time. The Malmquist index technique improves drawbacks of the classical DEA model by measuring the dynamic changes of efficiency values both from spatial and temporal perspectives. Therefore, it provides a valuable tool for DMUs to track the improvements or deteriorations in efficiency during the whole production process. This study calculates the TFP of forest carbon sinks among DMUs in Russia by taking t period as the base period; the formula is as follows:

$$\begin{aligned} TFP^{t,t+1} &= MI^{t+1}\left(x^{t+1}, y^{t+1}, x^t, y^t\right) = EC^{t,t+1} \times TC^{t,t+1} \\ &= PEC^{t,t+1} \times SEC^{t,t+1} \times TC^{t,t+1} \\ &= \frac{D_v^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_v^{t}\left(x^{t}, y^{t}\right)} \times \left[\frac{D_c^{t+1}\left(x^{t+1}, y^{t+1}\right)/D_v^{t+1}\left(x^{t+1}, y^{t+1}\right)}{D_c^{t}\left(x^{t}, y^{t}\right)/D_v^{t}\left(x^{t}, y^{t}\right)}\right] \\ &\times \left[\frac{D_c^{t}\left(x^{t+1}, y^{t+1}\right)}{D_c^{t+1}\left(x^{t+1}, y^{t+1}\right)} \times \frac{D_c^{t}\left(x^{t}, y^{t}\right)}{D_c^{t+1}\left(x^{t}, y^{t}\right)}\right]^{\frac{1}{2}}, \end{aligned} \quad (5)$$

where x^t and x^{t+1} are the input vectors of units from t to t + 1; y^t and y^{t+1} are output vectors of units from t to t + 1, respectively. $D^t\left(x^t, y^t\right)$ and $D^{t+1}\left(x^{t+1}, y^{t+1}\right)$ are distance functions based on t and t + 1 period, respectively. The subscript v in the above formula is the VRS assumption, and c is the CRS assumption. If the Malmquist index is greater than 1, the productivity of forest carbon sinks is improved; if the Malmquist index is less than 1, the TFP of forest carbon sinks is decreased.

3.3. Variables Selection and Data Sources

3.3.1. Efficiency Evaluation Index System of Forest Carbon Sinks in Russia

The relative efficiency of each DMU can be evaluated by considering the input and output variables. This paper uses the production approach, including the main components of the Cobb–Douglas production function (namely land, labor, and capital) as the input variables. Among them, land is measured by the area of managed forests, labor is measured by the average number of forestry employees at the end of the year, and capital is measured by the number of expenditures on delegated commitments in forestry. The expected output variables in this study are represented by the net absorption volume of carbon by managed forests. The undesirable outputs include the area of forest loss due to forest fires and other natural disturbances and deforestation area due to logging activities. Table 2 shows the proposed efficiency evaluation index system of forest carbon sinks in Russia.

Table 2. Efficiency evaluation index system of forest carbon sinks in Russia.

Indicator Layer	Variable	Content of Measurement	Units
Input	Land	Area of managed forests including shrubs	1000 ha
	Labor	Average number of forestry employees at the end of the year	People
	Capital	Expenditures on delegated commitments in forestry	1000 rubles
Expected Output	Net absorption volume	Net balance of total carbon absorption by managed forests and carbon released due to clear cutting and forest degradation factors	1000 tC
Undesirable Outputs	Degradation	Forest degradation area due to forest fires and other disturbances	1000 ha
	Deforestation	Deforestation area due to clear cutting and wood harvesting activities	1000 ha

The sample size in this study was selected according to the "rule of thumb", as proposed by several researchers [64–67]. In order to maintain the discrimination power of DEA, the number of DMUs should be at least twice the number of inputs and outputs combined [58,64]. Since the more traditional division of regions in Russia into eight federal districts is inappropriate in this case, this study proposed a division into twelve economic regions (ERs) according to the classification established by the Ministry of Economic Development (Minekonomrazvitiya) [68]. The structure of ERs considers that, in 2018, the Republic of Buryatia and Zabaykalsky Krai were removed from the East Siberian ER and added to the Far Eastern ER.

Further, suitability verification of the selected input and output variables was conducted. Since one of the prerequisites of DEA is the "isotonic" relationship between input and output data, the selected variables should have a positive correlation [64]. Therefore, a Pearson correlation test was conducted to analyze this assumption for the selected data, and the results are presented in Table 3. The correlation coefficients between three input variables and three output variables are all more than 0.514. Therefore, the selected data satisfy the isotonic property for conducting the research.

Table 3. Pearson correlation test between input and output variables.

	Land	Labor	Capital	Net Absorption Volume	Degradation	Deforestation
Land	1					
Labor	0.664	1				
Capital	0.802	0.818	1			
Net absorption volume	0.872	0.796	0.772	1		
Degradation	0.880	0.514	0.724	0.642	1	
Deforestation	0.877	0.670	0.796	0.795	0.642	1

Note: all Pearson correlations are significant at the 0.01 level (2-tailed).

3.3.2. Data Sources

Data on the area of managed forests, degradation and deforestation areas and related net absorption volumes in Russia among regions were collected from the 2009–2021 NIRs [69]. Data on the expenditures of delegated commitments in forestry were obtained from the Unified Interagency Information and Statistical System (EMISS) [70]. Data on the average number of forestry employees at the end of the year were obtained from the Federal Forestry Agency (Rosleskhoz) upon request.

4. Results and Discussion

4.1. Forest Carbon Sink Efficiency (FCSE) in Russia

The efficiency of forest carbon sinks in managed forests of Russia from 2009 to 2021 was calculated using MaxDEA Ultra 8.0 software. Figure 1 and Table 4 show the average trend of FCSE in Russia and related values among ERs, respectively.

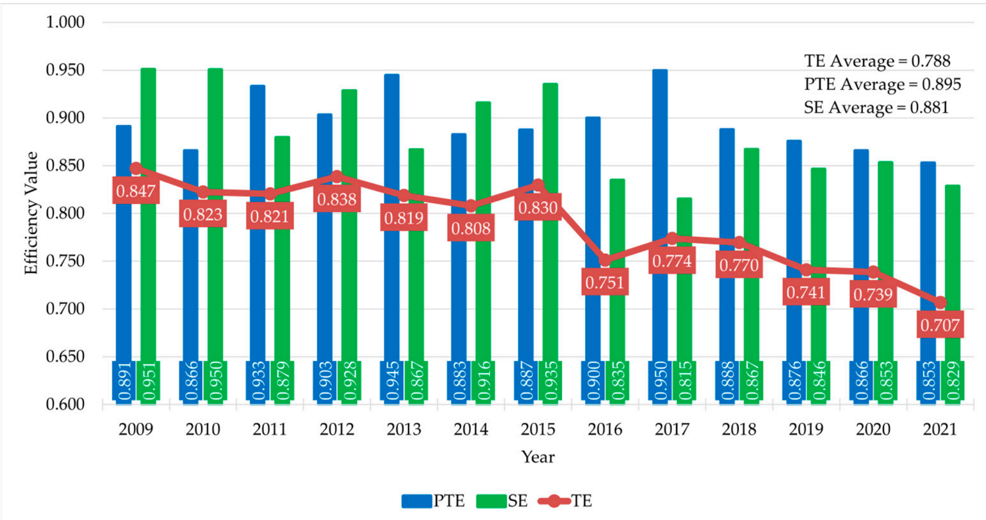

Figure 1. Average trend of forest carbon sink efficiency in Russia from 2009 to 2021.

As shown in Figure 1, FCSE and its decomposition had volatile, increasing, and decreasing trend intervals for the entire study period. In general, the average value of FCSE during the study period was 0.788, accounting for the gap of 21.2% between the actual FCSE and the efficiency frontier. In 2009, this gap was 15.3%, but, in 2021, it almost doubled (29.3%). The trends of FCSE can be divided into three stages. The first stage was from 2009 to 2015, forming a "W" shape structure. The second stage was from 2015 to 2017, forming a "V" shape on the graph. The third stage, after 2017, performed a downward trend. For the entire study period, FCSE did not reach the efficiency frontier. The minimal gap between the actual FCSE and the efficiency frontier was in 2009 (15.3%), and the largest one was in 2021 (29.3%). From the perspective of FCSE decomposition, there were two periods: 2009–2015 and 2016–2021. During the first period, except for 2011 and 2013, the values of PTE were lower than the related values of scale efficiency. During the second period, SE values were lower than the values of PTE. Correlation analysis was adopted to verify the explanatory ability of PTE and SE to FCSE. The correlation coefficients of TE with PTE and SE were 0.381 and 0.826, respectively, indicating that the correlation between scale efficiency and FCSE was stronger. Therefore, SE is the main factor constraining the efficiency of forest carbon sinks in Russia. This indicates the prevailing role of adverse conditions that hinder the efficient functioning of forest carbon sinks.

Table 4. Forest carbon sink efficiency among economic regions in Russia from 2009 to 2021.

Economic Region (ER)	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Average
Kaliningrad ER	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Northwestern ER	0.835	1.000	1.000	1.000	0.817	0.800	0.824	0.891	0.825	1.000	1.000	1.000	1.000	0.918
Northern ER	0.656	0.614	0.763	1.000	1.000	1.000	1.000	0.585	0.678	0.538	0.544	0.502	0.458	0.691
Central ER	1.000	1.000	1.000	1.000	0.947	0.877	0.845	1.000	1.000	1.000	1.000	1.000	0.806	0.957
Central Black Earth ER	1.000	1.000	0.495	0.496	0.553	0.418	0.439	0.518	0.542	0.565	0.555	0.563	0.541	0.570
North Caucasus ER	1.000	0.666	1.000	1.000	0.534	1.000	1.000	0.550	0.557	0.561	0.506	0.529	0.507	0.692
Volga ER	0.668	0.571	0.583	0.630	0.666	0.636	0.608	0.682	0.647	0.609	0.531	0.523	0.503	0.602
Volga-Vyatka ER	1.000	1.000	1.000	0.840	0.802	0.695	0.679	0.741	0.813	1.000	1.000	1.000	1.000	0.881
Ural ER	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.918	0.993
West Siberian ER	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
East Siberian ER	0.611	0.640	0.740	0.686	0.742	0.823	0.843	0.708	0.787	0.721	0.658	0.654	0.623	0.707
Far Eastern ER	0.611	0.642	0.571	0.671	1.000	0.724	1.000	0.609	0.660	0.576	0.513	0.516	0.532	0.648
National average	0.847	0.823	0.821	0.838	0.819	0.808	0.830	0.751	0.774	0.770	0.741	0.739	0.707	0.788

Table 4 shows forest carbon sink efficiency values among economic regions in Russia. It can be seen that only two DMUs are considered to be totally efficient, including the Kaliningrad and West Siberian ERs. Therefore, the remaining DMUs are inefficient. Economic regions in Russia can be conditionally divided into two groups considering their FCSE performance. The first group consists of high-efficient DMUs with values of 0.800 and above, meaning their gap in FCSE does not exceed 20%. Therefore, except for the absolutely efficient Kaliningrad and West Siberian ERs, there are also four DMUs, namely Northwestern, Central, Volga-Vyatka, and Ural ERs, with FCSE gaps of 8.2%, 4.3%, 11.9%, and 0.7%, respectively. The second group includes the low-efficient regions in terms of forest carbon sink efficiency. Their gap in FCSE value is more than 20%. The Northern, Central Black Earth, North Caucasus, Volga, East Siberian, and Far Eastern ERs account for the gaps in FCSE value at 30.9%, 43%, 30.8%, 39.8%, 29.3%, and 35.2%, respectively.

4.2. Redundancy of Input and Undesirable Outputs

The SBM model provides the incorporation of all slack variables into the objective function and proposes the adjustments for ineffective DMUs based on the redundancy of input and undesirable outputs and the deficiency of expected outputs. If a DMU is considered to be efficient, all its slack variables are equal to 0 and the efficiency value equals 1. On the contrary, if a DMU does not meet these conditions, then it is considered inefficient. Therefore, to be transformed into efficient ones, inefficient DMUs should reduce their redundancy levels of input and undesirable outputs and the deficiency level of expected output. It was found that the employed model proposes no adjustments to optimize the deficiency of expected output. It means that FCSE in Russia is not brought by a deficiency of expected outputs but by resource inputs and undesirable outputs. Obviously, to increase the net absorption volume of forest carbon sinks, forest degradation and deforestation should be reduced, and input should be better utilized to improve FCSE. Therefore, the proposed adjustments are only focused on the redundancy of inputs and undesirable outputs. Table 5 presents the calculated rates of related slack variables and their average values for each DMU from 2009 to 2021.

Table 5. Average redundancy rates of inputs and undesirable outputs of forest carbon sink efficiency in Russia among economic regions from 2009 to 2021.

Economic Region (ER)	FCSE Value	Slack Variables					
		Redundancy Rates of Inputs			Deficiency Rate of Expected Output	Redundancy Rates of Undesirable Outputs	
		Land	Labor	Capital	Net Absorption Volume	Degradation	Deforestation
Kaliningrad Economic Region	1.000	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Northwestern Economic Region	0.918	1.52%	12.51%	11.32%	0.00%	18.18%	8.30%
Northern Economic Region	0.691	53.64%	17.36%	25.19%	0.00%	0.00%	55.93%
Central Economic Region	0.957	0.00%	7.69%	5.80%	0.00%	18.91%	10.25%
Central Black Earth Economic Region	0.570	11.55%	77.99%	44.55%	0.00%	59.07%	63.00%
North Caucasus Economic Region	0.692	20.54%	52.00%	25.46%	0.00%	60.35%	8.44%
Volga Economic Region	0.602	4.51%	74.16%	43.20%	0.00%	75.93%	51.38%
Volga-Vyatka Economic Region	0.881	5.13%	10.25%	21.45%	0.00%	43.69%	27.83%
Ural Economic Region	0.993	1.98%	0.00%	0.13%	0.00%	4.51%	4.11%
West Siberian Economic Region	1.000	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
East Siberian Economic Region	0.707	40.73%	21.30%	27.39%	0.00%	81.68%	65.04%
Far Eastern Economic Region	0.648	47.36%	18.99%	41.04%	0.00%	91.62%	49.41%
National average	0.788	31.70%	21.26%	21.52%	0.00%	82.33%	38.64%

If an input factor is not fully utilized during the production process, this means the existence of its redundancy. In the case of land resources, it indicates the lack of carbon absorption capacity by forests due to their mature or overmature condition. In the case of labor, it means personnel are in an idle working or underutilized state. In the case of capital, it indicates that not all expenditures are properly consumed to maintain the effective functioning of forest carbon sinks. The redundancy of undesirable outputs means an excess of adverse factors out of their permissible level.

As noted before, there are two ERs with non-redundant inputs and undesirable outputs, indicating the efficient functioning of forest carbon sinks in these regions. In general, forest carbon sinks in Russia are inefficient mainly due to forest fires and other natural disturbances (82.33%); excessive logging activities (38.64%); and lack of carbon absorption capacity (31.70%). However, the redundancy rates of inputs and undesirable outputs in FCSE among inefficient economic regions are different. The highest redundancy rate of forest land is in Northern ER, meaning that more than half (53.64%) of forests are overmature with a lack of carbon absorption capacity. Also, the rates in East Siberian (40.73%) and Far Eastern (47.36%) ERs are relatively high. The highest redundancy rates of labor are in Central Black Earth (77.99%) and Volga (74.16%) ERs, indicating that forestry personnel is either idle working or underutilized. Nearly half (52%) of the labor in North Caucasus ER is also in the related status. Noteworthy is that forestry is not the key industry in these ERs, rather it is agriculture [71]. From the perspective of capital, above 40% of expenditures are improperly consumed to maintain the effective functioning of forest carbon sinks in the Central Black Earth, Volga, and Far Eastern ERs.

Forest carbon sinks in most of the inefficient economic regions are suffering from degradation processes and deforestation activities. It is possible to highlight three groups of inefficient DMUs in order to enhance their FCSE. The first group includes Ural, East Siberian, and Far Eastern ERs. Since the labor factor has the lowest and the land resource has the highest redundancy value in the structure of inputs, these regions should reallocate part of their expenditure for combatting forest fires and other natural disasters and reduce excessive logging activities; otherwise, the carbon absorption capacity of local forests will continue to decrease. First of all, this applies to East Siberian and Far Eastern ERs. The second group consists of Northwestern, Central, Central Black Earth, Volga, and Volga-Vyatka ERs. Since the land factor has the lowest redundancy value and the labor and capital resources have the highest redundancy values in the structure of inputs, these regions should mobilize forestry personnel and related expenditures for forest degradation mitigation and clear-cutting reduction. Except for Northwestern ER, other economic regions in this group presumably neglect this policy due to agricultural expansion. The third group includes Northern and North Caucasus ERs. Forest carbon sinks in these regions deserve a specific approach. In the case of the Northern ER, logging operations should be significantly reduced. Since the predominant natural area here is tundra, the restoration and reproduction of forests is hindered [72]. In the case of the North Caucasus ER, forestry personnel should be better mobilized to mitigate forest fires, pest and disease outbreaks, and other natural disasters. In terms of favorable climate and less man-made destruction, the high growth rates of local vegetation contribute to intensive carbon absorption [33]. Moreover, the recreational significance of the local forests in natural parks and reserves must be considered [73]. The proportion of overmature trees will continue to grow, while relatively low logging volumes and mountainous terrain will lead to scarce reforestation and afforestation activities. Therefore, these features should be comprehended in order to maintain the efficient functioning of forest carbon sinks in this region.

4.3. Temporal Changes in Total Factor Productivity of Forest Carbon Sinks in Russia

To further analyze the changes of FCSE in Russia, the Malmquist index technique was performed to reflect the improvements or deteriorations of total factor productivity and its decomposition. The results are presented in Figure 2.

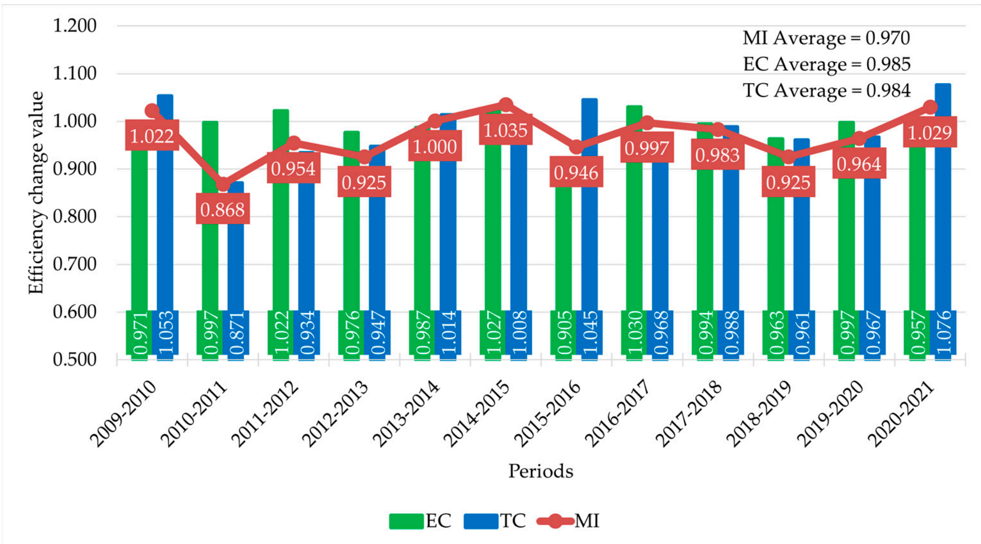

Figure 2. Total factor productivity and efficiency changes of forest carbon sinks in Russia from 2009 to 2021.

The average Malmquist index value of forest carbon sinks in Russia was 0.970, meaning that their productivity declined by 3% during the study period. The increase in TFP occurred only three times, reaching the maximal value of 3.5% in 2015. The increment of EC also occurred only three times, with the highest value of 3% in 2017. Technical progress during the study period was revealed five times, reaching the maximal value of 7.6% in 2021. Correlation analysis was adopted to verify the explanatory ability of EC and TC to TFP value. The correlation coefficients were 0.160 and 0.786, respectively, indicating that the correlation between technical progress change and TFP was stronger. It indicates that forestry departments in Russia did not adopt modern technologies or sustainable practices for the effective functioning of forest carbon sinks. Therefore, they should establish a technological advancement policy related to forest carbon sinks and strengthen the forest management regime in order to improve their efficiency.

Further decomposition of the technical efficiency change values is presented in Table 6. During the study period, the average value of scale efficiency change was lower than the value of pure efficiency change. That means that the comprehensive efficiency change of forest carbon sinks in Russia was primarily hindered by the deterioration of 1.1% in their returns to scale, as evidenced by the high-influenced disadvantageous conditions discussed in the previous subsection. As mentioned before, the increase in EC occurred only three times. The improvement in PEC was in 2011, 2013, and 2015–2017, reaching the maximal value of 7.8% in 2011. The increase in SEC occurred in 2012, 2014–2015, 2018, and 2020, reaching the highest value of 6.4% in 2018.

Table 6. Technical efficiency changes and their decomposition values in forest carbon sinks of Russia from 2009 to 2021.

Time Period	EC	PEC	SEC
2009–2010	0.971	0.972	0.999
2010–2011	0.997	1.078	0.925
2011–2012	1.022	0.968	1.056
2012–2013	0.976	1.046	0.934
2013–2014	0.987	0.934	1.056
2014–2015	1.027	1.006	1.021
2015–2016	0.905	1.014	0.893
2016–2017	1.030	1.055	0.976
2017–2018	0.994	0.935	1.064
2018–2019	0.963	0.986	0.976
2019–2020	0.997	0.989	1.008
2020–2021	0.957	0.985	0.971
National average	0.985	0.996	0.989

Note: EC stands for technical efficiency change; PEC stands for pure technical efficiency change; SEC stands for scale efficiency change.

4.4. Spatial Heterogeneity in Total Factor Productivity of Forest Carbon Sinks in Russia

Since the Malmquist approach provides assessment of productivity and efficiency changes not only from a temporal but also from a spatial perspective, this subsection aims to investigate the TFP changes in forest carbon sinks across the country to determine the most effective DMUs from 2009 to 2021. Figure 3 shows the dynamic performance of forest carbon sinks among ERs in Russia valued as an average from 2009 to 2021. During the study period, their productivity remained static only in the Kaliningrad ER, while other economic regions performed a deterioration trend. Since the national average reduction rate of TFP equals 3%, DMUs can be conditionally divided into two groups. The first group contains the regions with values that do not exceed the national average deterioration. Except for Kaliningrad ER, the group consists of Northwestern, Central, North Caucasus, West Siberian, and East Siberian ERs, with rates of 0.5%, 3%, 0.8%, 2.7%, and 2.5%, respectively. The second group includes the regions with TFP reduction rates more than 3%. These are the Northern, Central Black Earth, Volga, Volga-Vyatka, Ural, and Far Eastern ERs, with deterioration rates of 5.9%, 6.4%, 3.1%, 4.4%, 3.1%, and 3.9%, respectively. During the study period, only Northwestern and East Siberian ERs performed efficiency improvement in forest carbon sinks, accounting for 1.5% and 0.2%, respectively, while Kaliningrad, Volga-Vyatka, and West Siberian ERs remained stagnant. Efficiency deterioration occurred in mostly agricultural regions (namely Central, Central Black Earth, North Caucasus, and Volga) and became the main factor, while other DMUs performed a technological decline in forest carbon sink functioning, leading to productivity reduction. This decline ranged from 2% in the Northwestern ER to 4.4% in the Volga-Vyatka ER. Technical progress emerged only in the North Caucasus ER, accounting for 5%.

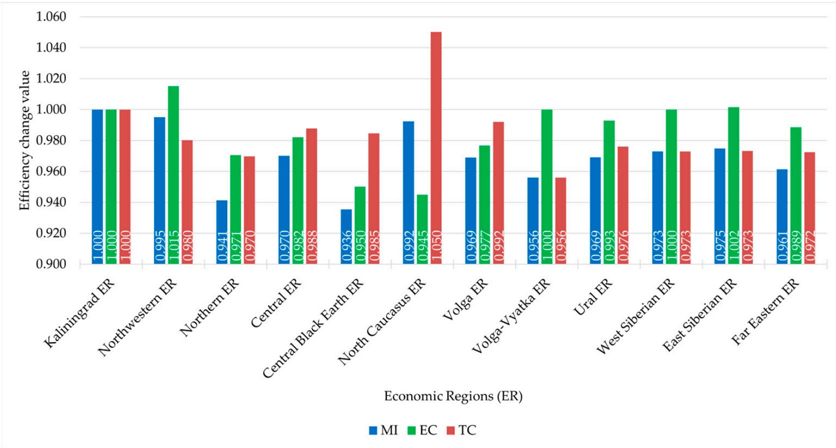

Figure 3. Average total factor productivity and efficiency changes of forest carbon sinks among economic regions in Russia from 2009 to 2021.

Further decomposition of the technical efficiency change values is presented in Figure 4. As mentioned before, three regions, namely Kaliningrad, Volga-Vyatka, and West Siberian ERs, did not perform any efficiency improvements, therefore their PTE and SE values remained unchanged. Along with them, six DMUs (namely Central, Central Black Earth, North Caucasus, Ural, and Far Eastern ERs) kept their management regimes (PTEs) unmodified. During the study period, related improvements occurred in Northwestern ER (1.4%) and East Siberian ER (0.1%), while Northern and Volga ERs deteriorated by 3.5% and 2.3%, respectively. Therefore, these changes made a significant contribution to their performance. As stated before, deterioration in terms of scale efficiency is the main factor hindering the productivity of forest carbon sinks in Russia. In particular, the related value sufficiently decreased in the predominantly agricultural regions of Central Black Earth and North Caucasus ERs, accounting for 5% and 5.5%, respectively. Meanwhile, Central, Volga, Ural, and Far Eastern ERs decreased only by 1.8%, 0.1%, 0.7%, and 1.1%, respectively. Noteworthy, the scale efficiency increment in forest carbon sinks occurred in the Russian North, namely in Northwestern (0.2%) and Northern (0.5%) ERs. As stated in the report [37] by the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet), high warming rates occurred in these territories, presumably contributing to local forests absorbing more carbon.

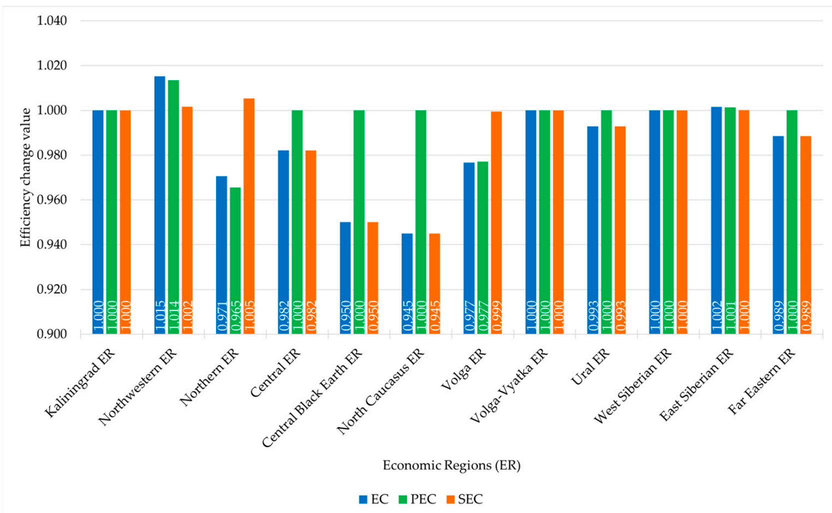

Figure 4. Average technical efficiency changes and their decomposition values in forest carbon sinks among economic regions of Russia from 2009 to 2021.

5. Conclusions

Russian forests are vital to climate change mitigation and play an important role in the national "Low-carbon development strategy". Being natural carbon sinks, they absorb atmospheric CO_2 and sequester carbon. Moreover, considering the largest area, forest carbon sinks in Russia should be responsibly managed in order to achieve the goal stated in the strategy. Forests are unevenly distributed across the country, caused by the diversity of climatic zones [36]. Along with logging activities and natural disasters (in particular, wildfires), forests in the majority of regions are mature or overmature, affecting their carbon absorption capacity [34,35]. In addition, considering the different land use policies, some regions in Russia perform deforestation due to the prevailing role of agriculture. Russia's "Low-carbon development strategy" [20] mostly relies on the implementation of forest carbon offset projects. Therefore, regional features and general performances of forest carbon sinks should be comprehended in order to introduce related projects in Russia.

This study employed an SBM-DEA model considering undesirable outputs to evaluate the efficiency of forest carbon sinks in Russia from 2009 to 2021. The results show that their average efficiency during the study period was valued at 0.788, indicating a space for improvement of 21.2%. In general, FCSE in Russia performed a downward trend and did not reach the efficiency frontier. In 2021, the related gap almost doubled in comparison with 2009. Forest carbon sinks are efficient only in two regions—the Kaliningrad and West Siberian ERs. The Central Black Earth and Volga ERs have the lowest FCSE values of 0.570 and 0.602, respectively, due to the predominant role of agriculture in terms of land use policy.

The SBM model also allowed to estimate the redundancy rates of inputs and undesirable outputs for ineffective DMUs to reveal the related adjustments. In general, forest carbon sinks in Russia are inefficient mainly due to forest fires and other natural disturbances (82.33%); excessive logging activities (38.64%); and lack of carbon absorption capacity (31.70%). Labor and capital inputs also should be better utilized. Therefore, fire protection, avoided conversion/deforestation, and improved forest management are the most demanded carbon offset projects for the forests in Russia, in general. However, local features of forest carbon sink functioning among ERs should be considered in order to implement the related projects.

The Malmquist productivity index (MI) of forest carbon sinks in Russia averaged 0.970 during the study period, reflecting a 3% decline in their productivity. Technical progress change (TC) was the main factor that hindered TFP. The decline in scale efficiency change (SEC) was the primary factor behind the technical efficiency (TE) decrease. The productivity of forest carbon sinks remained static only in Kaliningrad ER, while other economic regions performed deterioration trends. During the study period, only Northwestern and East Siberian ERs performed efficiency improvement of forest carbon sinks, accounting for 1.5% and 0.2%, respectively. The North Caucasus ER performed technical progress of forest carbon sinks, valued at 5%. Two-thirds of the regions did not modify their management regime (PTE). Only Northwestern and East Siberian ERs improved it by 1.4% and 0.1%, respectively. The scale efficiency of forest carbon sinks was slightly improved in the northern regions and significantly decreased in agricultural-related Central Black Earth and North Caucasus ERs.

Benchmarking techniques introduced in this study allowed to evaluate the performance of forest carbon sinks among different economic regions in Russia. It became possible to assess their efficiency both statically and dynamically, and from temporal and spatial perspectives. The findings of this study can be adopted by local forestry departments to develop new strategies and technological innovations to enhance the functioning of forest carbon sinks. The largest forest area in Russia lacks proper monitoring and is vulnerable to various natural disasters. In most regions, forest carbon sinks are inefficient. Therefore, the implementation of related carbon offset projects could create benefits both for their effective functioning and for their use as a valuable asset in carbon markets. Finally, several aspects of land use policy should also be considered in order to develop forest carbon sinks and launch related carbon offset projects in Russia. Firstly, regarding the growing demands of the logging industry, the possible implementation of logging restrictions can affect the related companies' revenues. Alternatively, along with the growing share of mature and overmature forests in Russia, their carbon absorption capacity also will decline. Therefore, the increment in logging volumes can be put on the agenda. Secondly, regarding the growing demands of agriculture, since the climate in Russia is warming 2.5 times faster than the global average, agriculture, in particular in the southern regions, will increasingly face drought and the spread of pests [37,74]. Such a scenario may cause the transition of agriculture to the northern territories, which will lead to clear-cutting activities. Thirdly, regarding the implementation features of forest carbon offset projects, the fulfillment of numerous quality criteria for launching these projects (including additionality, permanence, leakage avoidance, etc.) often hinders and postpones the issuing of related credits [75–77]. Therefore, for Russia it is extremely important to find a balance in the national land use policy to improve the efficiency of forest carbon sinks.

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