Proceeding Paper

A New Model for Calculating the Impact of Forests and Wood Use on the Balance of C-CO$_2$ in the Earth's Atmosphere [†]

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Abstract: An original methodology was formulated and a new three-stage method for assessing the CO$_2$ balance in plant communities was developed. In managed forests, when calculating the carbon balance, it is necessary to take into account the release of CO$_2$ and not only direct but also indirect costs of technical energy for laying plantations, caring for plantings, and felling for final use. As a model, the costs of technical energy for the cultivation of natural and genetically modified forms of aspen *Populus tremula* L. are calculated. The large role of indirect costs of technical energy in the balance of C-CO$_2$ in forest plantations is shown. The final amount of CO$_2$ runoff from the atmosphere depends not only on the area of forests and their productivity but also on the way the wood is used.

Keywords: managed forests; renewable energy sources; Paris Climate Agreement; technical energy costs; *Populus tremula* L.; methodology for assessing the impact of forests and wood use on CO$_2$ balance in the atmosphere

1. Introduction

According to the FAO [1], the world's forests store 662 billion tons of carbon, of which 44.5% is biomass, 10.3% is dead wood and litter, and 45.2% is in the soil. Forests have an essential carbon function, removing approximately 20% of global anthropogenic CO$_2$ emissions each year [2]. In the Paris Climate Agreement, forests play a major role in reducing CO$_2$ levels in the atmosphere. During the growing season, managed forest stands absorb a huge amount of CO$_2$, ten times greater than emissions due to direct and indirect costs of technical energy [3]. The generally accepted calculation of C-CO$_2$ fluxes in forests leads to the conclusion that with an increase in planting area and productivity, the runoff of carbon dioxide from the atmosphere increases sharply. Based on this approach, carbon balances are compiled for each country, and emissions trading is proposed. However, further, deeper consideration of the fate of wood over time leads to a different conclusion. The objective results of assessing the impact of tree plantations on CO$_2$ fluxes in the atmosphere largely depend on the duration of the analysis of natural and anthropogenic transformations of wood.

2. Methodology

To calculate the CO$_2$ balance in the atmosphere during forest cultivation, we used the results of a model experiment on the creation of forest plantations based on aspen (*Populus tremula* L.) and its natural and modified forms [4]. To assess the cost of technical energy in the experiment and the value of C-CO$_2$ flows, we analyzed all technological operations for growth, starting with the production of aspen seedlings in the nursery. The calculation of technical energy costs was performed using the methods outlined in [5,6].

A transgenic clone was created in the forest biotechnology laboratory of the Institute of Bioorganic Chemistry of the Russian Academy of Sciences and contains the sp-Xeg1b recombinant xyloglucanase gene from the fungus *Penicilium canescens*. According to experimental

data, this clone is characterized by a complex modification of the plant's phenotype: Accelerated growth and changes in the ratio of leaf and root biomass to stem wood biomass [7].

The model experiment was carried out by the authors in the context of the soil and climatic conditions of the north-west of the Leningrad Oblast (Russia). The growth of plantations with a short turnover of felling (30 years) established on the site of cut-down spruce forests was modeled.

In order to accelerate the growth of the forest stand and reduce the loss of soil fertility, nitrogen mineral fertilizers were applied in the experiment at a dose of 150 kg of active substance per 1 ha at planting, 10 years after planting, and 5 years before the main felling.

3. Results and Discussion

The results of simulation experiments show that the use of two iterations of thinning leads to an increase in the formation of economically valuable biomass up to 100–120 t/ha compared to 70 t/ha in the scenario without thinning [4]. At the same time, on genetically modified plantations, an additional 16.3–22.6 t/ha of dry matter of woody biomass is obtained due to thinning on average for two plantation rotations.

Fertilizers proved to be a significant factor in increasing the productivity of all types of forest stands. Thus, the productivity regarding the application of nitrogen fertilizers for planting unmodified forms of aspen was 5% higher during the first rotation of the plantation and 18% higher during the second rotation compared to the variants without fertilizers.

The use of a genetically modified clone of aspen with the introduction of nitrogen fertilizer significantly increases the productivity of plantations compared to its natural form. At the same time, the C-CO_2 sink in stem wood increased by 24.8%. The total runoff of C-CO_2 in the synthesized woody biomass in the fast-growing form of aspen increased by 14.2 t/ha or 23.9%.

However, large direct and indirect investments in technical energy are associated with the use of nitrogen fertilizers. The indirect cost of technical energy in the variant with a transgenic clone and the introduction of ammonium nitrate amounted to 46.8 GJ/ha, including indirect energy costs due to fertilizers (for the production of fertilizers, delivery to the farm warehouse and application)—45.2 GJ/ha, which is 85% of the total energy investment. Emission of CO_2 into the atmosphere due to indirect costs of technical energy amounted to 3.4 t/ha of CO_2 and are estimated at 1.4% of the runoff with wood. Table 1 presents the results of the analysis of the influence of growing various forms of aspen on the emission and sink of C-CO_2 in plantations.

After the establishment of model plantations, soil carbon reserves are significantly reduced (from 9 to 7 kg/m^2). Such a sharp drop is observed mainly in the first 5–7 years. This is due to the intensive decomposition of forest litter accumulated in previous spruce plantings. During the second rotation of the plantation, the intensity of the depletion of forest litter and the reduction of carbon stocks in soils decrease and the losses amount to approximately 1 kg/m^2 C for 30 years. Due to the loss of soil carbon, C-CO_2 is emitted into the atmosphere at a level of 10 t/ha.

Logging residues are an important source of carbon dioxide runoff from the atmosphere. However, the final effect largely depends on the further use of logging residues. Under production conditions, logging residues usually remain on the forest plot in heaps, and in a short period of time they rot or are burned on the spot and carbon dioxide is completely returned to the atmosphere. However, it is energetically and environmentally expedient to use the entire biomass of logging residues for the production of fuel pellets, briquettes, etc. In this case, solar energy stored in biomass replaces fossil non-renewable energy and thus reduces the release of CO_2 into the atmosphere.

Table 1. Balance in plantations of natural and genetically modified forms of aspen *Populus tremula* L. (second rotation of plantation).

Unit of Measurement	Aspen Shapes		
	Natural	Natural with N Fertilizers	Genetically Modified with N Fertilizers
stem wood			
t/ha *	75.7	89.4	91.0
technical energy costs in wood production			
GJ/ha	9.4	55.2	55.2
C-CO$_2$ emissions from wood production			
t/ha from technical energy	0.22	1.2	1.2
t/ha from loss of soil humus	9.0	9.0	10.0
C-CO$_2$ sink in stem biomass			
t/ha	37.9	44.7	45.5
thinning wood			
t/ha *	12.3	14.4	19.3
C-CO$_2$ runoff in the wood of thinnings			
t/ha	6.2	7.2	9.7
total C-CO$_2$ emissions from wood production			
t/ha	9.22	10.2	11.2
stem wood and thinnings			
t/ha *	88.0	103.8	110.3
total C-CO$_2$ sink in woody biomass			
t/ha	44.1	51.9	55.2

* according to Komarov et al. (2015) [4].

Aspen tree plantations with a short felling rotation (up to 30 years), taking into account the total (direct and indirect) costs of technical energy, are large net absorbers of atmospheric carbon dioxide. The content of C-CO$_2$ in commercial aspen wood fluctuated from 47.7 to 62.5 t/ha in the first rotation of the plantation and from 37.9 to 45.5 t/ha in the second. The total emissions of C-CO$_2$ from the use of technical energy in the cultivation of aspen amounted to no more than 1.2 t/ha. Such calculations and conclusions drawn from them usually inspire great hope in researchers and international organizations for the decisive positive role of forests in the sink of carbon dioxide from the Earth's atmosphere and in reducing the greenhouse effect. However, if we trace the further fate of wood and its transformation during its time of use, the conclusions are not as optimistic.

A new three-stage methodology for assessing the impact of forests on the balance of CO$_2$ in the atmosphere is proposed. The objective results of assessing the impact of tree plantations on the CO$_2$ balance in the atmosphere largely depend on the duration of the analysis of the natural and anthropogenic transformation of wood. We have developed a methodology and proposed a new three-stage method for calculating the C-CO$_2$ balance when growing forests and using wood: (1) Biocenotic balance (for a period of 30–120 years of cultivation, depending on the forest-forming species and the period of felling for the main use), (2) natural and economic balance (for 170–200 years from the moment of forest renewal to the completion of the service of wooden structures), and (3) biogeochemical C-CO$_2$ balance (associated with the cultivation of tree plantations and the use of wood and culminating in the entry of residual organic matter into the earth's crust and accumulative landscapes).

The mode of use of industrial wood is essential in the release of carbon dioxide into the atmosphere. The service life of buildings made of wood fluctuates slightly and averages approximately 50 years. After this period of time, buildings are usually dismantled, and the remains of wood are either burned or partially used for a short time on the farm (Figure 1). Thus, the positive impact of forest planting on reducing the concentration of carbon dioxide in the atmosphere when wood is used only in construction will not be significant due to the short period of operation of structures.
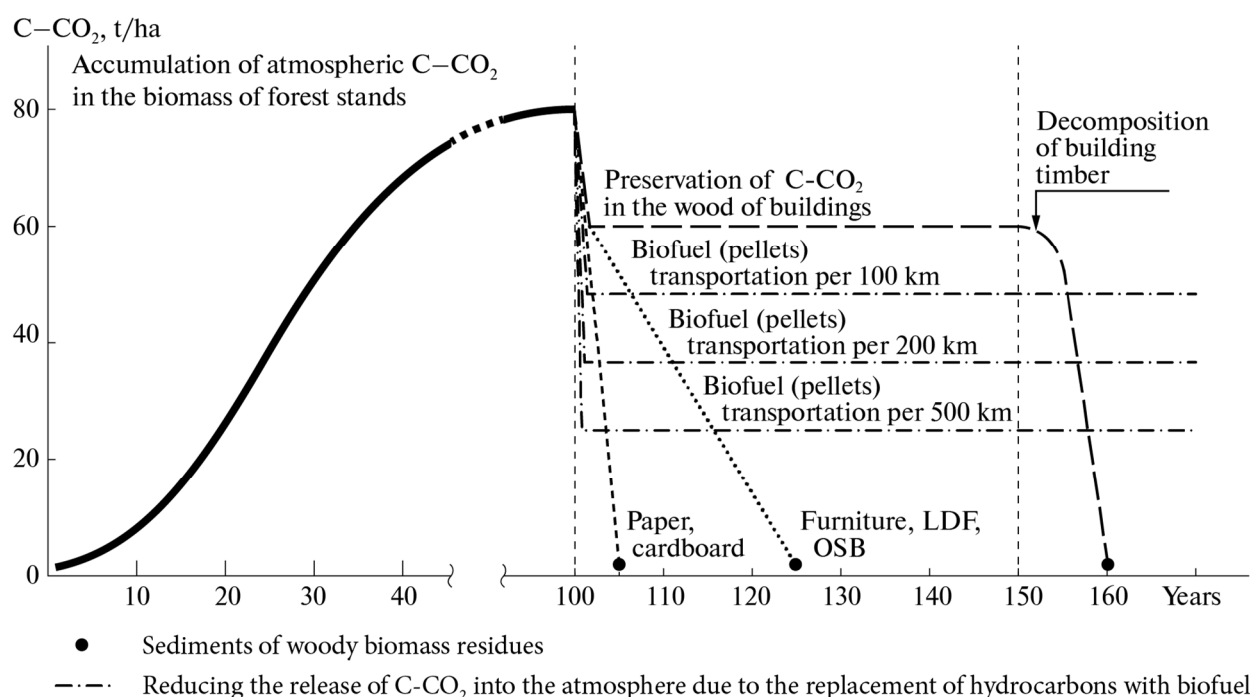
Figure 1. Scheme of a three-stage method for calculating the balance of C-CO$_2$ in the atmosphere when growing forests and using wood.

Eventually, the former timber will rot and turn back into CO$_2$. Part of the wood is used to make paper, cardboard, plywood, and furniture. However, these materials and products have a short life span. First of all, paper and cardboard are consumed. Furniture usually lasts no more than 25 years. Thus, the initially large carbon sink with industrial wood leads to the temporary (up to 150–160 years) removal of CO$_2$ from the atmosphere. During this period, various wood products are gradually destroyed and decomposed by microorganisms, and carbon dioxide absorbed by green plants re-enters the atmosphere. The long-term cycle of C-CO$_2$ in the system is as follows: atmosphere–green plants–industrial wood–man-made buildings and things–dust–atmosphere, which ends only gains a small positive balance. It is known that only a small part—0.8–1.0%—of the organic matter synthesized by plants enters the large geological cycle, transforms, and is preserved for millions of years [8,9].

The bulk of the buried dispersed organic matter is concentrated in the sediments of the continents and the oceanic vector [10]. Concentrated organic reserves of ancient biospheres are found in deposits of coal, hydrocarbon gases, and oil. Their intensive extraction and use in modern society lead to a sharp release of carbon dioxide into the atmosphere. However, there is a highly effective way of using forest plantations to regulate the content of carbon dioxide in the atmosphere, which is currently paid little attention—the so-called substitution effect [11].

This path constitutes the use of part of the wood for energy production and the replacement of fossil hydrocarbons used by mankind.

Indeed, when wood is used for energy, biomass carbon burns out and also enters the atmosphere in the form of CO_2. In this case, carbon dioxide does not replenish the pollutant pool. C-CO_2 simply recirculates into the atmosphere–green plants–wood–atmosphere system.

When processing plant biomass into a commercial energy carrier (for example, pellets), approximately 6.5 kg of CO_2 is emitted into the atmosphere per 1000 MJ of energy contained in the fuel [12].

At the same time, it is important to take into account that the transportation of biofuel from wood over long distances significantly reduces its efficiency and increases C-CO_2 emissions into the atmosphere. Thus, the transportation of pellets via road for 200 km reduces the overall energy efficiency from 6 to 3, and carbon dioxide emissions increase by 10.8 kg per 1000 MJ of energy content in biofuels. When transporting biofuel from wood 500 km, the energy efficiency drops to 1.7. The release of CO_2 into the atmosphere from transport reaches 17.6 kg per 1000 MJ [12]. Thus, from the perspective of ecology, biofuels should be considered a local source of energy since transportation over considerable distances decreases its effect on the sink of CO_2 from the atmosphere to almost "none".

The use of wood for the production of heat and electricity is currently growing at a rapid pace.

Previous work [13] shows that the global consumption of wood pellets by 2028 may reach 93 million tons, which, in terms of calorific value, corresponds to 10.7 million tons of oil equivalent. In Russia, 90% of the wood waste remains in the forest and in landfills every year. Our country can increase the volume of wood biofuel production by 10 times if woodworking waste is included in the trade turnover, as well as logging residues, which are often simply left in the forest and burned at logging sites.

Russia produces approximately 3 million tons of wood pellets annually. Approximately 95% of the production is exported, with 90% going to Europe [14]. On 9 July 2022, EU sanctions came into force prohibiting the import of Russian wood pellets. In Europe, there has already been a serious increase in prices. Therefore, if a 15-kg bag of pellets in Finland was once sold in a store for €2, it now costs €5.

At the same time, the volume of the domestic biofuel market in Russia is only 100,000–200,000 tons. In Russia, there are currently approximately 70–80 million hectares of unproductive and overgrown agricultural land suitable for forestry. Areas not occupied by crops make up approximately one-tenth of the total forest area of the country. If even half of these areas contain a forest with a short felling rotation (approximately 30 years) grown using a fast-growing tree species, then with a total bioproductivity (trunks + thinning wood) of approximately 100 t/ha, 3500–4000 million tons of biomass can be obtained. In terms of 1 year, productivity will be approximately 115–130 million tons. This amount of biomass corresponds to 2070–2340 million GJ per year of renewable energy. Taking into account the costs of growing forests, logging, and the production of biofuel in the form of pellets, the amount of additional energy will be 1656–1926 million GJ per year, which can replace approximately 38.8–45.1 million tons of hydrocarbon fuel in oil equivalent per year, or approximately 22–26% of the annual oil consumption in the Russian Federation. As a result of replacing hydrocarbons with biofuels, CO_2 emissions in the atmosphere will be reduced by 122–142 million tons per year. The total emission of CO_2 equivalent is currently 1.6 billion tons per year [15].

However, in connection with the great tension in food security across the world, the planting of forests on empty arable land in Russia can hardly be fully implemented. Therefore, the most promising and realistic strategy for reducing the content of C-CO_2 in the atmosphere with the help of forests at present is the use of logging residues, wood processing waste, and partial energy forests for the production of biofuels in order to obtain heat and electricity.

In Russia, artificial reforestation is beginning to increasingly prevail over natural methods. The number of forest nurseries producing planting material with a closed root system is increasing every year. However, there are a number of problems. No nursery produces planting material for fast-growing softwoods. Forest development projects

at the leased bases of timber industry enterprises provide the restoration of clearings only for coniferous, and in rare cases, hardwood species, even if softwood trees were harvested in this clearing [16]. The planting of energy forests in Russia is associated with the development of a nursery system, and the production of fuel pellets is associated with the construction of processing plants. However, most importantly, there is a need for comprehensive propaganda among the population, industrialists, and entrepreneurs regarding the idea of the widespread use of a type of fuel that is practically new to our country. It also requires development, discussion by region, and approval of the Federal Program for the cultivation of energy forests as a new and highly efficient source of renewable energy and the most important mechanism for the sink of CO_2 from the Earth's atmosphere by replacing hydrocarbon fuels.

4. Conclusions

1. The influence of forests on the sink of carbon dioxide from the atmosphere on a long-term scale when wood is used only in construction and the production of paper, chipboard, fiberboard, etc., is not significant.
2. The use of wood from thinning, wood-processing residue, and biomass from forests with a short felling rotation to produce heat and electricity is the main reserve to reduce the concentration of carbon dioxide in the Earth's atmosphere with the help of forests.
3. Biofuel from wood should be a local source of energy since transportation over long distances nullifies its energy and environmental efficiency.
4. The energy and environmental efficiency of all renewable energy sources must be assessed taking into account the total cost of technical energy for the construction of installations, the production of equipment and its depreciation, the costs of further disposal, and the costs of the logistics of a new energy carrier.

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