УДК 631.4+551.583+613.1:610.2
DOI 10.29003/m3555.0514-7468.2023_45_3/389-397

# A MODEL FOR CALCULATING THE IMPACT OF FORESTS ON THE BALANCE OF C-$CO_2$ IN THE EARTH'S ATMOSPHERE

**G.A. Bulatkin, Dr. Sci (Biol.)**
*Institute of Basic Biological Problems of Russian Academy of Sciences*

*A new three-stage method for assessing the $CO_2$ balance in plant communities was formulated. The methodology includes not only taking into account the absorption of C-$CO_2$ during plantation vegetation, but also the processes occuring when using wood. In managed forests, when calculating the carbon balance, it is necessary to take into account the release of $CO_2$ not only at direct, but also at indirect consumption of technical energy for laying plantations, caring for them, and felling for final use. As a model, the consumption of technical energy in cultivating natural and genetically modified forms of aspen Populus tremula L. was calculated. The large role of indirect expenditure of technical energy in the C-$CO_2$ balance in forest plantations is shown. The use of a genetically modified clone of aspen significantly increases the productivity of plantations and $CO_2$ absorption from the atmosphere compared to its natural form. On a long time scale 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 of using wood. There is a highly effective way of using forest plantations to regulate the carbon dioxide content in the atmosphere, which is currently little paid attention, namely, the so-called substitution effect. Replacing energy-intensive materials (reinforced concrete, plastic, metal, and brick) with wood may be one of the main ways for the positive impact of forests on the $CO_2$ content in the atmosphere. The use of wood biomass from thinning, wood processing wastes, short-rotation forests for heat and power generation is a great reserve for replacing fossil hydrocarbons. The forest area needs to be expanded to increase wood production to replace energy-intensive building materials and generate biofuels.*

***Keywords:*** *managed forests, renewable energy sources, technical energy consumption, Populus tremula L., substitution effect, methodology for assessing the impact of forests and wood use on $CO_2$ balance in the atmosphere.*

***For citation:*** Bulatkin, G.A., "A model for calculating the impact of forests on the balance of C-$CO_2$ in the Earth´s atmosphere", *Zhizn Zemli* [Life of the Earth] **45**, no 3, 389–397 (2023) (in Engl., abstr. in Russ.). DOI: 10.29003/m3555.0514-7468.2023_45_3/389-397.

## МОДЕЛЬ РАСЧЁТА ВЛИЯНИЯ ЛЕСОВ НА БАЛАНС С-$CO_2$ В АТМОСФЕРЕ ЗЕМЛИ

**Г.А. Булаткин***

*Сформулирована новая трёхступенчатая методика расчёта влияния лесов на баланс С-$CO_2$ в атмосфере Земли. Методика включает не только учёт поглощения С-$CO_2$ при вегетации насаждений, но и процессы, происходящие при использовании древесины. В модельных экспериментах изучались затраты технической энергии, её энергетическая эффективность и потоки С-$CO_2$ в плантациях природной и генетически модифицированной формах осины Populus tremula L. Использование генетически модифицированного клона осины значительно повышает продуктивность и поглощение $CO_2$ из атмосферы по сравнению с его природной формой. В управляемых лесах при расчёте баланса $CO_2$ необходимо*

* Булаткин Геннадий Александрович – д.б.н., в.н.с., Институт фундаментальных проблем биологии РАН, г. Пущино Московской области, ORCID 0000-0003-2322-1597, *genbulatkin@yandex.ru*.

*учитывать не только прямые, но и косвенные вложения технической энергии при закладке плантации, выращивании деревьев и рубке главного пользования. Окончательные размеры стока из атмосферы под влиянием лесов зависят не только от площади насаждений и их продуктивности, но и от способов использования древесины. Основное значение леса в регулировании содержания углекислого газа в атмосфере, на который мало обращают внимания, – так называемый эффект замещения. Замена энергоёмких материалов (железобетона, кирпича, металла, пластика) на древесину будет одним из главных путей положительного влияния лесов на содержание C-$CO_2$ в атмосфере. Использование биомассы древесины рубок ухода, отходов деревопереработки, лесов с короткой ротацией для получения тепла и выработки электроэнергии является большим резервом для замещения ископаемых углеводородов. Необходимо расширять площадь лесов для увеличения производства древесины с целью замены энергоёмких строительных материалов и выработки биотоплива.*

***Ключевые слова:*** *управляемые леса, возобновляемые источники энергии, затраты технической энергии, Populus tremula L., эффект замещения, новая методика расчёта влияния лесов и использования древесины на баланс C-$CO_2$ в атмосфере Земли.*

***Ссылка для цитирования:*** *Булаткин Г.А.* Модель расчёта влияния лесов на баланс C-$CO_2$ в атмосфере Земли // Жизнь Земли. 2023. Т. 45, №3. С. 389–397 (in Engl.,). DOI: 10.29003/m3555.0514-7468.2023_45_3/389-397.

*Поступила 29.07.2023 / Принята к публикации 06.09.2023*

**Introduction.** According to FAO [7], 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 about 20 % of global anthropogenic $CO_2$ emissions every year [3]. The proper solution to the problem of the negative impact of an increased temperature of the surface layer of the atmosphere on natural ecosystems and the life of mankind largely depends on the cause of this change [13]. 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 its emissions due to direct and indirect consumption of technical energy [6]. The generally accepted calculation of C-$CO_2$ fluxes in forests leads to the conclusion that the carbon dioxide runoff from the atmosphere increases sharply with an increase in the planting area and their productivity. Based on this approach, country-by-country carbon balances are compiled and emission trading is proposed. However, further, deeper consideration of the fate of wood in time leads to a different conclusion. The objective results of assessing the impact of tree plantations on $CO_2$ flows in the atmosphere largely depend on the duration of the analysis of natural and anthropogenic transformations of wood.

**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.) – its natural and genetically modified forms [5]. To assess the consumption of technical energy in the experiment and the value of C-$CO_2$ flows, we analyzed all technological operations for growing, starting with aspen seedlings production in a nursery. The technical energy expenditure was calculated using the following methods. The direct consumption of technical energy (fuel for tractors, vehicles, and labor costs) was taken into account. The indirect energy consumption includes depreciation deductions for the manufacture and overhaul of equipment. The expenses for the household needs of workers and the production of mineral fertilizers were also taken into account [4, 12].

The 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 phenotype, namely: accelerated growth, changes in the ratio of leaf and root biomass to stem wood biomass [14].

A model experiment was carried out by the author on the example of the soil and climatic conditions of the north-west of the Leningrad region (Russian Federation). The growth of plantations with a short turnover of felling (30 years), established on a 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.

**Results and discussion.** The results of our simulation experiments show that the use of 2 thinnings 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 thinnings [10]. 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 2 plantation rotations.

Fertilizers are proven to be a significant factor in increasing the productivity of all types of forest stands. Thus, the productivity with 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 options without fertilizers.

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

However, large direct and indirect investments of technical energy are associated with the use of nitrogen fertilizers. The total consumption of technical energy in the option with the transgenic clone and the introduction of ammonium nitrate amounted to 46.8 GJ/ha, including the indirect energy consumption due to fertilizers (for their production, delivery to the farm warehouse and application) – 45.2 GJ/ha, which is 85 % of the total energy expenditure. The $CO_2$ emissions into the atmosphere due to the indirect consumptions 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 our 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, the soil carbon reserves were significantly reduced (from 9 to 7 kg/$m^2$). Such a sharp drop was observed mainly in the first 5–7 years. This is due to the intense decomposition of forest litter accumulated in previous spruce plantings. During the second rotation of the plantation, the intensity of depletion of forest litter and the reduction of carbon stocks in soils decreased and the losses amounted to about 1 kg C /$m_2$ for 30 years. Due to the loss of soil carbon, $CO_2$ is emitted into the atmosphere at the 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, 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 non-renewable fossil energy and thus reduces the release of $CO_2$ into the atmosphere.

**Table 1.** C-$CO_2$ balance in plantations of natural and genetically modified forms of aspen *Populus tremula* L. (2nd rotation of the plantation) [6].

**Таблица 1.** Баланс C-$CO_2$ в плантациях природной и генетически модифицированной формах осины *Populus tremula* L. (вторая ротация) [6].

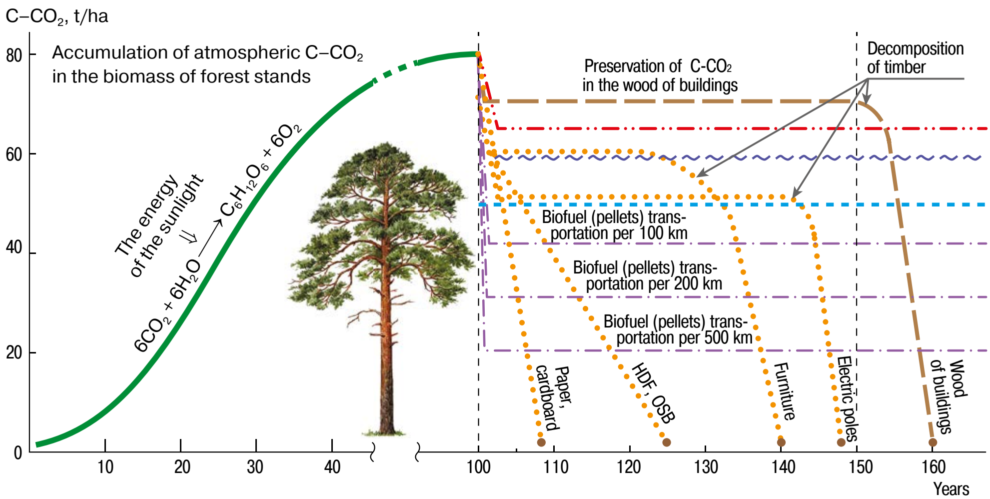
| Unit of Measurement | Aspen form | | |
|---|---|---|---|
| | Natural | Natural with N Fertilizers | Genetically Modified with N Fertil-izers |
| stem wood | | | |
| t/ha* | 75.7 | 89.4 | 91.0 |
| technical energy consumption in wood production | | | |
| GJ/ha | 9.4 | 55.2 | 55.2 |
| C-CO2 emissions 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.* [10]

Aspen tree plantations with a short felling rotation (up to 30 years), taking into account the total (direct and indirect) consumption 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 one. The total C-$CO_2$ emissions 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 therefrom 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 the time of use, our conclusions will not be so optimistic.

**A new three-stage methodology for assessing the impact of forests on the $CO_2$ balance in the atmosphere.** 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 cultivation period of 30–120 years, depending on the forest-forming species and the period of felling for 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 materials), 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, accumulative landscapes).

The usage mode of industrial wood is essential in the carbon dioxide release into the atmosphere. The service life of buildings made of wood fluctuates slightly and averages about 50 years. After this period of time, buildings are usually dismantled, the remains of wood are either burned or partially used for a short time on the farm (**Figure**). Thus, the positive impact of forest planting on reducing the carbon dioxide concentration in the atmosphere when wood is used only in construction will not be significant due to the short period of operation of structures.




Reducing the emission of C-$CO_2$ into the atmosphere:

- during construction when cement, concrete, metal, plastic are replaced by wood
- when replacing reinforced concrete electric poles with wooden ones
- during construction of furniture
- due to the replacement of hydrocarbons with biofuel

Sediments of woody biomass residues

HDF – High density fiberboard

OSB – Oriented strand board

**Figure.** Scheme of our three-stage method for calculating the C-$CO_2$ balance in the atmosphere, when growing forests and using wood.

**Рисунок.** Схема трёх ступенчатой модели расчёта баланса C-$CO_2$ в атмосфере при выращивании лесов и использовании древесины.

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 lifetime. First of all, paper and cardboard are consumed. Furniture usually lasts no more than 25 years (see Figure). Thus, the initial large carbon sink with industrial wood leads to a temporary (up to 150–160 years) removal of $CO_2$ from the atmosphere. During this period, various wood products are gradually destroyed, decomposed by microorganisms, and the carbon dioxide absorbed by green plants re-enters the atmosphere. The long-term C-$CO_2$

cycle in the system "*atmosphere – green plants – industrial wood – man-made buildings and things – dust – atmosphere*" ends only with 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 [1, 11].

The bulk of the buried dispersed organic matter is concentrated in the sediments of the continents and the oceanic vector (**Table 2**).

**Table 2.** Dead organic matter in the ancient Earth biospheres [2].
**Таблица 2.** Мёртвое органическое вещество древних биосфер Земли [2].

| Object | C, $10^{12}$ t | % |
|---|---|---|
| Continental sediments | 10,000 | 66.5 |
| Ocean vector sediments | 5,000 | 32.3 |
| Coal | 30.0 | 0.20 |
| Oil | 2.5 | 0.04 |
| Oil shale | 10.0 | 0.08 |
| Hydrocarbon gases | 2.0 | 0.02 |
| Groundwaters | 2.5 | 0.04 |
| Dissolved hydrocarbon gases in groundwaters | 1.4 | 0.02 |
| Total | 15,048 | 100 |

Concentrated organic reserves of the ancient biospheres are found in deposits of coal, hydrocarbon gases and oil. Their intense extraction and use in the modern period leads to a sharp release of carbon dioxide into the atmosphere. However, there is a highly effective way of using forest plantations to regulate the carbon dioxide content in the atmosphere, which is currently paid little attention – the so-called substitution effect [9].

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

Indeed, when wood is used for energy generation, 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 in the cycle "atmosphere – green plants – wood – atmosphere".

When processing plant biomass into a commercial energy carrier (e.g., pellets), about 6.5 kg of $CO_2$ is emitted into the atmosphere per 1,000 MJ of energy contained in the fuel [5].

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. E.g., the transportation of pellets by road for 200 km reduces the overall energy efficiency from 6 to 3, and carbon dioxide emissions increase by 10.8 kg per 1,000 MJ of energy content in biofuels. When transporting along 500 km, the energy efficiency drops to 1.7. The release of $CO_2$ into the atmosphere from transport reaches 17.6 kg per 1,000 MJ [5]. Thus, from the ecological viewpoint, biofuels should be considered as a local source of energy, since transportation over considerable distances almost nullifies their effect in the sink of $CO_2$ from the atmosphere.

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

Ref. [15] shows that the global consumption of wood pellets could reach 93 million tons by 2028, which in terms of calorific value corresponds to 10.7 million tons of oil equivalent. In the Russian Federation, 9/10 of wood waste remains in the forest and landfills every year. Our country could 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.

The Russian Federation annually produces about 3 million tons of wood pellets. About 95% of the production is exported, 90% to Europe [17]. On July 9, 2022, EU sanctions came into force prohibiting the import of Russian wood pellets. In Europe, there is already a serious rise in prices. So, if earlier a 15-kilogram bag of pellets in Finland was sold for €2, now it costs €5.

At the same time, the volume of the domestic biofuel market in the Russian Federation is only 100–200 thousand tons.

In our country, there are currently about 70–80 million hectares of unproductive and overgrown agricultural land suitable for forestry. The areas not occupied by crops make up about one tenth of the total forest area of the country. If even half of vacant arable land energy forests with a short felling rotation (about 30 years) is grown by fast-growing tree species, then 4,000 million tons of biomass with a total bioproductivity (trunks + thinning wood) of about 100 t/ha could be obtained. Per year, the productivity will be about 130 million tons (**Table 3**).

**Table 3.** Possible impact of the Russian energy forests on $CO_2$ sink from the Earth's atmosphere.
**Таблица 3.** Возможное влияние энергетических лесов России на сток $CO_2$ из атмосферы Земли.

| Indicator | Unit of measurement | Value |
|---|---|---|
| Abandoned arable land | mln ha | 80 |
| Area of forest plantations on vacant arable land | mln ha | 40 |
| Forest biomass (with a productivity of 100 t/ha) | | |
| for 30 years | mln t | 4,000 |
| on average for 1 year | mln t | 130 |
| Renewable energy received/year | mln GJ | 2,340 |
| Energy consumption for growing forests and producing pellets/year | mln GJ | 414 |
| Energy costs for the transportation of pellets over a distance of 100 km/year | mln GJ | 200 |
| Amount of additional energy received/year | mln GJ | 1,726 |
| Substitution of hydrocarbon fuel/year in oil equivalent | mln t | 40,4 |
| Reduction of $CO_2$ emissions of hydrocarbons when using pellet/year | mln t | 142 |

This amount of biomass corresponds to 2,340 million GJ of renewable energy per year. Taking into account the costs of growing forests, logging and production of biofuel in the form of pellets, the amount of additional energy will be 1,726 million GJ per year, which can replace about 40.4 million tons of hydrocarbon fuel in oil equivalent per year, or about 26 % of the annual oil consumption in the Russian Federation. As a result of replacing hydrocarbons with biofuels, the $CO_2$ emissions into the atmosphere will be reduced by 142 million tons per year. The total emission of $CO_2$ equivalent is currently 1.6 billion tons per year [16].

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

In the Russian Federation, artificial reforestation is beginning to increasingly prevail over natural one. 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 for the restoration of clearings only with coniferous, in rare cases, hardwood species, even if softwood trees were harvested in this clearing [17]. The planting of energy forests in the Russian Federation is associated with the nursery system development, and the production of fuel pellets is associated with the construction of processing plants. But, most importantly, there is a need for comprehensive propaganda among the population, industrialists and entrepreneurs of the idea of widespread use of a type of fuel that is almost new for our country. It also requires the development, regional discussions 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.

**Conclusions.** 1. During the growing season, trees absorb $CO_2$ from the atmosphere many times more than it is emitted when using technical energy for growing forests. However, then the wood gradually decomposes and carbon dioxide re-enters the atmosphere.

2. A significant $CO_2$ reduction effect can be achieved by using wood products instead of products made from other materials such as reinforced concrete, plastic or steel, and petroleum-based fibers.

3. The use of wood from thinning, wood-processing residue, and biomass from forests with a short felling rotation to produce heat and power is a big reserve to reduce the carbon dioxide concentration in the Earth's atmosphere with the help of forests.

4. Biofuel from wood should be a local source of energy, since its transportation over long distances nullifies its energy and environmental efficiency.

5. There is a need to expand the area of forests on Earth, as this will provide an opportunity to obtain more commercial wood used to replace energy-intensive building materials and to produce biofuel.

**Funding.** The work was supported by Ministry of Science and Higher Education of the Russian Federation, project #122041200035-2.

**REFERENCES**

1. Alpatiev, A.M., *Development, transformation and protection of the natural environment* (Leningrad: Nauka, 1983) (in Russian).

2. Bazilevich, N.I., "Productivity, biogeochemistry of current biosphere and functional models of ecosystem", *Pochvovedenie* [Soil Science] **2**, 79-94 (1979) (in Russian).

3. Bellassen, V, le Maire, G., Dhôte, J.F., Viovy, N., Ciais, P., "Modelling forest management within a Global Vegetation Model (ORCHIDEE)". https://agritrop.cirad.fr › document_548099]

4. Bulatkin, G.A., *Ecological and energy bases for optimizing the productivity of agroecosystems* (Moscow: NIA-Priroda, 2008) (in Russian).

5. Bulatkin, G.A., "Study of the effectiveness of energy crops on the example of miscanthus sinensis (*Miscanthus sinensis* Anderss.), Ecological and economic problems", *Ecological Bulletin of Russia* **10**, 36–41 (2018) (in Russian).

6. Bulatkin, G.A., "A new Model for Calculating the Impact of Forests and Wood Use on the Balance of C-$CO_2$ in the Earth's Atmosphere", *Environ. Sci. Proc.* **22** (1), 28 (2022). https://doi.org/10.3390/IECF2022-13040.

7. *Global Forest Resources Assessment 2020*. Main report. Rome, Italy: FAO, 2021.

8. Grigoriev, I., Kunitskaya, O., Davtyan, A., "Energy forest plantations", *Forest industry"* **9** (137), 24–29 (2019) (in Russian).

9. Knauf, M., Kohl, M., Mues, V., Olschofsky, K., Fruhwald, A., "Modeling the $CO_2$-effects of forests management and wood usage on a region basis", *Carbon Balance and Management* **10**, 1–11 (2015).

10. Komarov, A.S., Chertov, O.G., Bykhovets, S.S., Priputina, I.V., Shanin, V.N., Vidyagina, E.O., Lebedev, V.G., Shestibratov, K.A., "Influence of aspen plantations with a short turnover felling on the

biological cycle of carbon and nitrogen in forests of the boreal zone: a model experiment", *Mathematical biology and informatics* **10**, 398–415 (2015) (in Russian).

11. Kovda, V.A., *Fundamentals of the soil studies.* Book. 1 (Moscow: Nauka, 1973) (in Russian).
12. Mindrin, A.S., *Energy-economic evaluation of agricultural products.* Diss. Dr. Sci. (Moscow, 1997) (in Russian).
13. Snakin, V.V., "Dynamics of Global Natural Processes and V.I. Vernadsky´s teaching of the biosphere", *Zhizn Zemli* [Life of the Earth] **45** (1), 27–38 (2023). DOI: 10.290003/m3147.0514-7468.2023_45_1/27-38 (in Russian).
14. Shestibratov, K., Lebedev, V., Podrezkov, A., Salmova, M., "Transgenic aspen and birch trees for Russian plantation forests", *BMC Proc.* **5** (Suppl. 7), 124 (2011).
15. Sidorova, M., Gorchilina, K., "Demand for pellets will grow three times", *Forest Industry* **9** (137), 17–23 (2019) (in Russian).
16. *Strategy for socio-economic development of the Russian Federation withlow greenhouse gas emissions until 2050*, http://static.government.ru/media/files.
17. Tikhomirov, A., "There are no alternatives yet" The EU has closed another market for Russia", *LesPromInform* **5** (167) (2022) (in Russian).

## ЛИТЕРАТУРА

1. *Алпатьев А.М.* Развитие, преобразование и охрана природной среды. Л.: Наука. 1983. 239 с.
2. *Базилевич Н.И.* Продуктивность, биогеохимия современной биосферы и функциональные модели экосистем // Почвоведение. 1979. №2. С. 79–94.
3. *Bellassen V, le Maire G., Dhôte J.F., Viovy N., Ciais P.* Modelling forest management within a Global Vegetation Model (ORCHIDEE). https://agritrop.cirad.fr › document_548099
4. *Булаткин Г.А.* Эколого-энергетические основы оптимизации продуктивности агроэкосистем. М.: НИА-Природа, 2008. 366 с.
5. *Булаткин Г.А.* Исследование эффективности энергетических культур на примере мискантуса китайского (Miscanthus sinensis Anderss.). Экологические и экономические аспекты // Экологический вестник России. №10. 2018. С. 36–41.
6. *Bulatkin G.A.* A new Model for Calculating the Impact of Forests and Wood Use on the Balance of C-$CO_2$ in the Earth's Atmosphere // Environ. Sci. Proc. 2022 (1) 28. https://DOI: org/10.3390/IEECF2022-13040
7. Global Forest Resources Assessment 2020. Main report. FAO: Rome, Italy, 2021. 184 p.
8. *Григорьев И., Куницкая О., Давтян А.* Энергетические лесные плантации // Лесная индустрия. 2019. №9. 9 (137). С. 24–29.
9. *Knauf M., Kohl M., Mues V., Olschofsky K., Fruhwald A.* Modeling the $CO_2$-effects of forests management and wood usage on a region basis // Carbon Balance and Management. 2015. V. 10. P. 1–11.
10. *Комаров А.С., Чертов О.Г., Быховец С.С., Припутина И.В., Шанин В.Н., Видягина Е.О., Лебедев В.Г., Шестибратов К.А.* Воздействие осиновых плантаций с коротким оборотом рубки на биологический круговорот углерода и азота в лесах бореальной зоны: модельный эксперимент // Математическая биология и биоинформатика. 2015. № 10. С. 398–415.
11. *Ковда В.А.* Основы учения о почвах. Книга 1. М.: Наука, 1973. 447 с.
12. *Миндрин А.С.* Энергоэкономическая оценка сельскохозяйственной продукции. Дис. докт. экон. наук. М., 1997. 291 с.
13. *Снакин В.В.* Динамика глобальных процессов и учение о биосфере В.И. Вернадского // Жизнь Земли. 2023. Том 45, №1. С. 27–38.
14. *Schestibratov R., Lebedev V., Podrezkov A., Salmova M.* Transgenic aspen and birch trees for Russian plantation forests // BMC. Proc. 2011. V. 5. Suppl. 7. P. 124.
15. *Сидорова М., Горчилина К.* Спрос на пеллеты вырастет в три раза // Лесная индустрия. Сентябрь 2019. № 9 (137). С. 17–23.
16. Стратегия социально-экономического развития Российской Федерации с низким уровнем выбросов парниковых газов до 2050 года. // Распоряжение правительства РФ от 29 октября 2021 г. № 3052-р. http://static.government.ru/media/files/ADKkCzp3fWO32e2yA0BhtIpyzWfHaiUa.pdf
17. *Тихомиров А.* «Альтернатив пока нет»: ЕС закрыл ещё один рынок для России // ЛесПромИнформ. 2022. № 59 (167). С. 110–112.