Трансформация экосистем
Ecosystem Transformation

ISSN 2619-0931 Online
www.ecosysttrans.com

DOI: https://doi.org/10.23859/estr-241119
EDN: https://elibrary.ru/oetvnf
UDC 631.433.3

Article

Carbon dioxide emission from the soil surface of secondary deciduous phytocenoses (South Timan, Komi Republic)

P.A. Arzubov[1, 2]*, N.M. Gorbach[2], A.F. Osipov[2], A.A. Dymov[2]

[1] *Pitirim Sorokin Syktyvkar State University, Oktaybrskiy Prospect St. 55., Syktyvkar, 167001 Russia*

[2] *Institute of Biology, Komi Science Centre, Ural Branch of the Russian Academy of Sciences, Kommynisticheskaya St. 28, Syktyvkar, 167982 Russian Federation*

**arzubov-2000@mail.ru*

Abstract. To understand the impact of clear-cutting on carbon dioxide emissions from the soil surface, it is necessary to obtain empirical data in various areas. This paper provides data on the evaluation of soil respiration dynamics from June to October 2024 on three plots: the background blueberry-green moss spruce forest, an 8-year-old clear-cut area, and an 18-year-old clear-cut area, all located in the middle taiga of the Komi Republic. The studied communities grow on typical podzolic soils, on developing dusty cover loams. A 1.4-fold increase in the rate of CO_2 flux from the soil surface of the 8-year-old clear-cut area was found compared to the stand, while no differences were found with the 18-year-old post-cut community. From the soil surface of skid roads (paths for logging equipment movement), CO_2 emissions are 2.3 times higher than in the blueberry spruce forest, and 1.1–1.4 times higher than in feling areas with a relatively undisturbed soil cover. A reliable positive relationship was established between soil temperature and carbon dioxide emission from the soil surface, at a depth of 5 cm (R^2 = 0.39–0.62) and 10 cm (R^2 = 0.20–0.56). The soil of the blueberry spruce forest emits 635−698 gC m^{-2} during the snowless period, felling areas 651−728 and 630−645 gC m^{-2}, for B8 and B18-year old felling, respectively, the same age 1089−1240; 1180−1341 gC m^{-2}. Large amplitudes of values – are observed on skid roads, which is most likely due to the presence of post-logging residues that lie at a depth of 10 cm.

Keywords: boreal forests, forest communities, the carbon cycle, soil respiration

Funding. The work was carried out within the frames of the most critical innovative project of national importance “Development of the terrestrial and remote sensing monitoring system of carbon pools and greenhouse gas flows on the territory of the Russian Federation, creation of the data recording system about the flows of climate-active substances and the carbon budget in forests and other terrestrial ecological systems” (reg. No. 123030300031-6) and the project No. 125021902454-1 “Soils and soil resources of the European North-East of Russia in the context of modern climate change, anthropogenic pressure and socio- economic challenges”.

ORCID:
P.A. Arzubov, https://orcid.org/0009-0006-4941-3799
N.M. Gorbach, https://orcid.org/0000-0002-5099-6868
A.F. Osipov, https://orcid.org/0000-0003-0618-9660
A.A. Dymov, https://orcid.org/0000-0002-1284-082X

To cite this article: Arzubov, P.A. et al., 2026. Carbon dioxide emission from the soil surface of secondary deciduous phytocenoses (South Timan, Komi Republic). *Ecosystem Transformation* **9** (1), 13–29. https://doi.org/10.23859/estr-241119

Received: 19.11.2024
Accepted: 07.02.2025
Published online: 13.02.2026

DOI: https://doi.org/10.23859/estr-241119
EDN: https://elibrary.ru/oetvnf
УДК 631.433.3

Научная статья

Дыхание почв вторичных сообществ на начальных стадиях восстановительной сукцессии (Южный Тиман, Республика Коми)

П.А. Арзубов[1, 2*], Н.М. Горбач[2], А.Ф. Осипов[2], А.А. Дымов[2]

[1] *Сыктывкарский государственный университет им. Питирима Сорокина, 167001, Россия, Республика Коми, г. Сыктывкар, Октябрьский пр-кт, д. 55*

[2] *Институт биологии Коми НЦ УрО РАН, 167982, Россия, Республика Коми, г. Сыктывкар, ул. Коммунистическая, д. 28*

**arzubov-2000@mail.ru*

Аннотация. Для понимания влияния сплошных рубок на эмиссию углекислого газа с поверхности почв требуется получение эмпирических данных на различных территориях. В работе приводятся сведения по оценке динамики дыхания почвы с июня по октябрь 2024 г. на трех участках: фоновый ненарушенный ельник чернично-зеленомошный, 8-летняя вырубка и 18-летняя вырубка, расположенные в средней тайге Республики Коми. Исследуемые сообщества произрастают на типичных подзолистых почвах, формирующихся на пылеватых покровных суглинках. Выявлено возрастание в 1.4 раза скорости потока CO_2 с поверхности почвы 8-летней вырубки по сравнению с фоновым насаждением, тогда как с 18-летним послерубочным сообществом различий не отмечено. С поверхности почвы волоков (путей движения лесозаготовительной техники) эмиссия CO_2 в 2.3 раза больше, чем в ельнике черничном, и в 1.1−1.4 раза выше, чем на пасечных участках с относительно ненарушенным почвенным покровом. Установлена достоверная положительная взаимосвязь между температурой почвы и выделением углекислого газа с поверхности почвы на глубине как 5 см (R^2 = 0.39−0.62), так и 10 см (R^2 = 0.20−0.56). Почва ельника черничного эмитирует за бесснежный период 635−698 гС·м$^{-2}$, пасечные участки – 651−728 и 630−645 гС·м$^{-2}$

для 8- и 18-летней вырубки соответственно, волока тех же возрастов – 1089−1240 и 1180−1341 гС·м$^{-2}$. На волоках наблюдаются большие амплитуды значений, что, по всей видимости, связано с наличием послерубочных остатков, которые залегают на глубину 10 см.

Ключевые слова: бореальные леса, лесные сообщества, цикл углерода

Финансирование. Работа выполнена в рамках реализации важнейшего инновационного проекта государственного значения (ВИП ГЗ) “Разработка системы наземного и дистанционного мониторинга пулов углерода и потоков парниковых газов на территории Российской Федерации, обеспечение создания системы учета данных о потоках климатически активных веществ и бюджете углерода в лесах и других наземных экологических системах» (рег. № 123030300031-6) и при финансовой поддержке бюджетной темы ИБ ФИЦ Коми НЦ УрО РАН № 125021902454-1 «Почвы и почвенные ресурсы Европейского Северо-Востока России в условиях современных климатических изменений, антропогенного пресса и социально-экономических вызовов».

ORCID:
П.А. Арзубов, https://orcid.org/0009-0006-4941-3799
Н.М. Горбач, https://orcid.org/0000-0002-5099-6868
А.Ф. Осипов, https://orcid.org/0000-0003-0618-9660
А.А. Дымов, https://orcid.org/0000-0002-1284-082X

Для цитирования: Арзубов, П.А. и др., 2026. Дыхание почв вторичных сообществ на начальных стадиях восстановительной сукцессии (Южный Тиман, Республика Коми). *Трансформация экосистем* **9** (1), 13–29. https://doi.org/10.23859/estr-241119

Поступила в редакцию: 19.11.2024
Принята к печати: 07.02.2025
Опубликована онлайн: 13.02.2026

Introduction

The territory of the Russian Federation includes about 20% of the world’s forest area (FAO, 2010), the majority of which belongs to boreal forests. These ecosystems are significant carbon stocks, 30–60% of which is accumulated in soils indicating how important soils are in the global carbon cycle (Kurganova and Kudeyarov, 2012; Osipov et al., 2021). The intensity of carbon dioxide emission from the soil surface is among the most crucial indicators of carbon balance in ecosystems (Schlesinger and Andrews, 2000). Soil respiration (SR) is a product of heterotrophic (organic matter decomposition of (aboveground and underground) plant litterfall, previous-year plant litter in form of forest floor and soil organic matter) and autotrophic respiration of tree and shrub roots (Bond-Lamberty et al., 2024; Kudeyarov et al., 2007). The role each component plays in the process depends on biotic and abiotic factors (Bond-Lamberty and Thomson, 2010; Kurganova et al., 2012). Accumulation of the bank of zonal models on soil emission long-term dynamics and research of factors determining its spatial dispersion is a strategic task (Kurganova et al., 2024). Having solved this task, we will be able to identify not only the role forest ecosystem plays as sink or source of atmospheric carbon but also to gain detail information on the carbon cycle on the territory of the Russian Federation (Kudeyarov et al., 2015).

The carbon cycle is significantly affected by human economic activities (Dymov, 2020), in particular, clearcutting that disturbs the carbon balance (Zamolodchikov et al., 2013). Clearcutting is a widespread forest management practice in which more than 75% (72% carbon) of all trees in an area are uniformly cut down (Kutyavin et al., 2024; Dymov et al., 2024). A clearcut is then a heterogeneous landscape or a combination of poorly disturbed cutting areas, in which trees are felled, and skid trails used by logging equipment to remove logs from a timber stand. The skid trail normally becomes covered with logging residues to make its surface strong and take 15–25% of the whole timber harvesting area (Dymov, 2020; Osipov, 2022). The studies on the impact, clearcutting inserts on greenhouse gas fluxes between the Earth’s surface and the atmosphere, are extremely important as greenhouse gases affect not only biological cycling but also local and regional climatic conditions (Korkiakoski et al., 2019; Molchanov et al., 2017; Pridacha et al., 2021).

According to the Ministry of Natural Resources and Ecology of the Russian Federation[1], the timber logging volume changed from 193.26 to 194.59 million m^3 in the last decade. In the Komi Republic[2] at the same time period, the volume of felled timber varied from 8.5 to 9.1 million m^3. Analyzed data indicates significant impact of industrial deforestation on carbon stock dynamics, including studies involving the process of restoration succession and taking into account the spatial heterogeneity of postlogging communities.

The dynamics of soil respiration (SR) of postmortem communities at different stages of successional recovery compared to unbroken communities is clearly not studied enough (Korkiakoski et al., 2019; Molchanov et al., 2017; Osipov, 2022, 2023; Prydacha and Semin, 2024). A.F. Osipov (2022, 2023) in his work, conducted in clearcuts of blueberry pine forests, that the peak of seasonal soil respiration is in July or August depending on weather conditions in different study years but the intensity of fluxes differs clearly between postcutting communities and undisturbed stands. A.G. Molchanov with co-authors (2017), a newly felled spruce forest area in the south taiga subzone has significantly higher carbon dioxide emission values than the exact same but undisturbed forest area. M. Korkiakoski et al. (2019) conducted their work in drained peat soils in Finland and found a decrease in soil respiration in 1–3 years after clearcutting. V.B. Pridacha and D.E. Semin (2024) reported a reduced contribution of soil emissions to the atmospheric CO_2 flux in a 10-year-old clearcut, in contrast to an undisturbed stand of blueberry pine forest.

Assessing the effects of clearcutting on CO_2 fluxes between forest ecosystems and the atmosphere is a critical task for improving the quality of climate prediction and developing sustainable land-use strategies (Aguilos et al., 2014; Pongratz et al., 2009). As clearcutting became a dominant tree harvesting procedure in the recent decades, secondary stands developed instead of felled forests occupy large territories and are at different stages of regenerative succession. Therefore, the assessment of soil respiration at these territories will enable researchers to determine the long-term effect of clearcuttings on the carbon cycle and reduce uncertainties in characterising the role of human economic activities in this process (Osipov, 2023).

The aim of this work was to determine the effect of clearcutting on CO_2 emission from the surface of podzolic soils of blueberry-green-moss communities at the initial stages of regenerative succession.

Materials and methods

The study was carried out in the Ust-Kulom District of the Komi Republic (Fig. 1), which is characterized by a temperate-continental temperate-cold climate with short and cool summers, long and cold winters with a stable snow cover (Atlas respubliki Komi..., 1997). According to the data for the period of 1990–2019, the average temperature in January was −14.9 °C, July – +17.1 °C, annual temperature – +0.9 °C. Precipitation volume was 615 mm, 60% of which fell in the warm period from May to October. According to the data from the Ust-Kulom[3] meteorological station the average daily air temperature for the study period (June-October) reached +12.7°C and the amount of precipitation was 292 mm. Comparing with the mean perennial data, the study period was prominent through warmer weather conditions but similar precipitation volume.

The study area is located in the middle taiga subzone on the southern edge of the Timan Range. The southern part of the Timan Range consists the so-called parmas – of a series of dissected high ridges and hills covered with spruce forests, with absolute heights of 250–350 m.

According to the soil-geographical zoning of the central and eastern parts of the European USSR (Rudneva et al., 1981), the study area is located in the South Timan region of the Vychegda province of the middle taiga subzone of typical podzolic soils. In the conditions of hilly relief, typical podzols dominate among other soil types.

---

[1] State report on the state and protection of the environment of the Russian Federation in 2022, 2023. Ministry of Natural Resources and Environment of Russia, Lomonosov Moscow State University, Moscow, Russia, 687 p.

[2] State report on the state of the environment in the Komi Republic in 2023, 2024. Ministry of Natural Resources of the Komi Republic, Syktyvkar, Russia, 162 p.

[3] Weather in Ust-Kulom. Web page. URL: http://www.pogodaiklimat.ru/history/23803.htm (accessed: 20.12.2024).

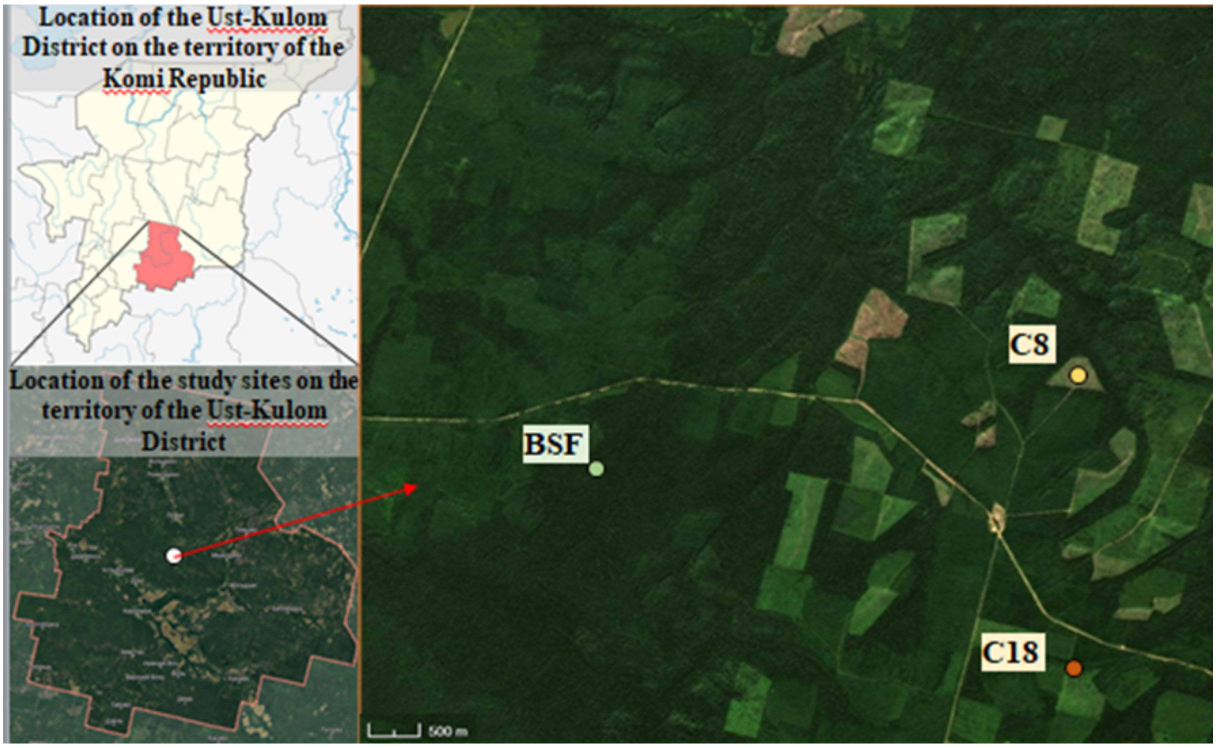

Fig. 1. Location of the study sites. BSF – blueberry spruce forest, C8 – 8-year-old clearcut, C18 – 18-year-old clearcut. The sketch-map was prepared using the public cadastral map https://egrp365.ru/map/https://egrp365.ru/map/.

The impact of clearcutting on soil respiration was assessed in two after-cut communities, which are at different stages of regenerative succession formed instead of blueberry spruce forests in typical podzolic soils. In one area of 11 hectares of wood harvesting was conducted in 2016 (C8 – blueberry-fern-green moss birch forest), in the other area 17 ha – in 2006 (C18 – fern birch forest). At present, both sites are grown with birch young trees of I and II age classes. The old-growth stand of blueberry spruce forest formed on typical podzolic soil (according to the international classification WRB[4] – Stagnic Albic Dystric Retisol Alumic Cutanic Loamic) was chosen as a control plot.

The tree layer of the blueberry spruce forest is dominated by spruce and fir with some birch and mountain ash. Natural reforestation at clearcuts proceeds *via* deciduous species, mainly birch. The herbaceous-dwarf shrub layer of the study sites is dominated by *Vaccinium myrtillus*, *Dryopteris carthusiana* and *Gymnocarpium dryopteris*, while the moss-lichen cover – by *Hylocomium splendens* and *Polytrichum commune*.

Any of three study sites got installed 10 foundations made of nontransparent PVC pipes being 110 mm in diameter (Kurganova et al., 2024). In after-cut communities, the foundations were installed as follows: 5 foundations immediately at the cutting area and 5 foundations in the skid road at a distance of 5–10 meters from each other. The cutting process elements are arable plots with relatively little disturbance of soil cover and fibres, along which machinery was moved. The foundations were buried to a depth of 4 cm, whereas the chamber volume varied from 1.7 to 2.7 liters (depending on the length of tubes). Measurements were made between tree crowns. The soil ground vegetation was removed. Soil respiration was measured fortnightly from June to October 2024 using a portable CO_2, CO, temperature and humidity logger VENTpro II (Russia). It has been established that the arable

[4] World Reference Base. Web page. URL: https://www.fao.org/soils-portal/data-hub/soil-classification/world-reference-base/en/ (accessed: 06.10.2025).

land covers 80% of the deforestation area. The exposure time was 7 minutes with one measurement taken per one foundation. Totally, 300 CO_2 flux rate determinations were made, 100 at each site. Simultaneously, we measured soil temperature (ST) at depths of 5 and 10 cm, using an electronic thermometer CHECKTEMP 1 HANNA instruments (USA).

A linear equation was used to evaluate the relationship between SR and ST:

$$lnSR = \alpha X + \beta \quad ,$$

where *lnSR* – logarithmised soil respiration data, *α* and *β* – equation coefficients, *X* – soil temperature at a depth of 5 or 10 cm.

Logarithmisation of initial SR data before regression analysis was performed in order to achieve the normality of distribution of linear model's residuals and the homogeneity of variance of linear model's errors (Osipov, 2022). As the literature data inform about correlations of SR with temperature at 5- or 10-cm depths (Kurganova et al., 2012; Kuznetsov, 2014; Osipov, 2022 et al.), we derived the equations for accessing the relationship between ST and SR for both depths in order to examine the C–CO_2 removal using soil dynamics data for different depths.

The coefficient α from the previous equation was used to calculate the temperature coefficient Q_{10}, showing the change in rate of SR at a temperature change of 10 °C, according to the following equation (Davidson et al., 2006):

$$Q_{10} = e^{\alpha \times 10}$$

Carbon removal in CO_2 emission from the soil surface (C–CO_2) was calculated using the daily mean soil temperature values measured with autonomous loggers according

$$SR_{period} = \sum_{n=1}^{n} SR_{10} Q_{10}^{\frac{T-10}{10}} \quad ,$$

where SR_{period} – C–CO_2 removal per time interval, $gC \cdot m^{-2}$, SR_{10} – SR value at 10 °C, Q_{10} – temperature coefficient, T – mean daily soil temperature at a depth of 5 or10 cm.

We performed descriptive statistics with calculation of mean values, mean errors and variation coefficient. For pairwise comparisons, the Student's t-criterion was used due to a small number of pairs analysed. The effect of clearcutting was assessed by comparing the soil respiration rate between blueberry spruce forest and cutting areas (as a technological element of clearcuts opposite to skid trails) of secondary communities. Also separately performed a comparison between the technological elements of the cut-off (cutting areas and skid trails). The regression analysis was used to characterise the relationship between soil respiration and soil temperature. All calculations were performed using Microsoft Excel 2010 and R programming environment at 95% significance level.

Results and discussion

Seasonal dynamics of soil respiration

As shown in Fig. 2, the seasonal dynamics of podzolic soil respiration in blueberry spruce forest are characterized by maximum values in July and August, and minimum in October. This corresponds to the available literature data on the SR curve of dark coniferous forests in the boreal belt (Ivanov et al., 2020; Kukumägi et al, 2017; Mashika, 2006; Osipov et al., 2024).

No significant differences in mean monthly soil respiration values were observed during summer months in cutting areas (as part of a clearcut opposite to skid trails) of secondary communities (p_t > 0.05), in spite of relatively high values in August. Young birch forests demonstrate a wide diapason of the obtained data that is expressed by high (coefficients of variation 22–74%) associated with the heterogeneity of spatial location of birch undergrowth, as well as stumps of felled trees.

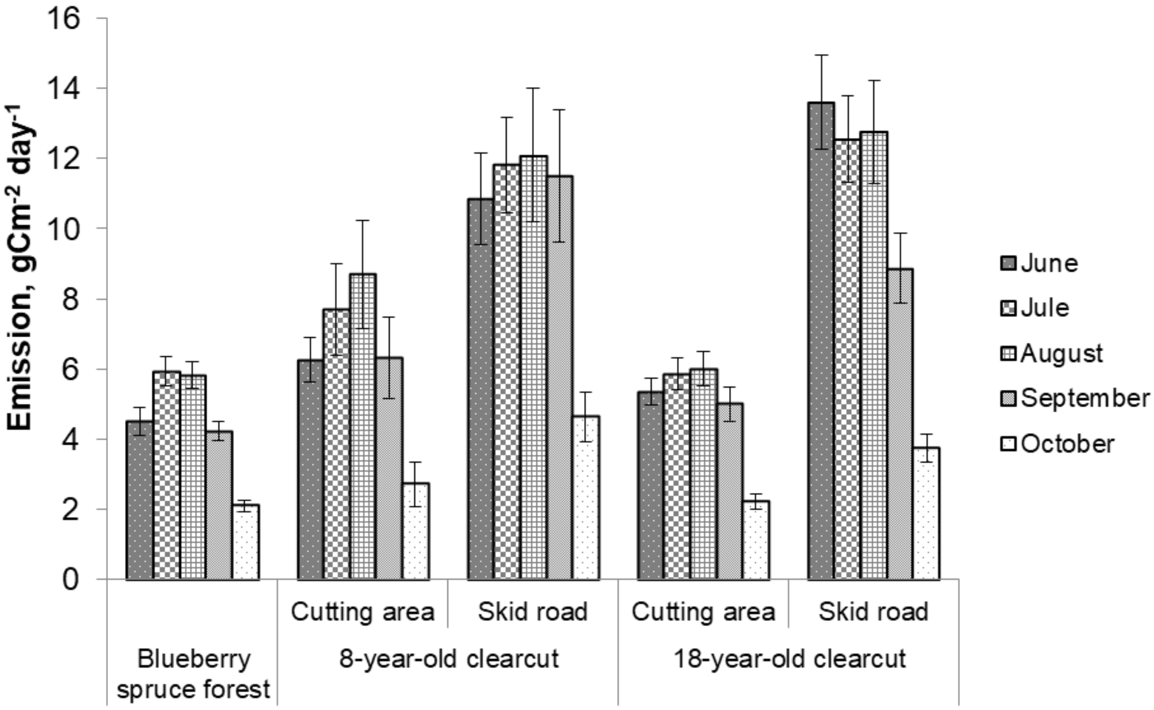

Fig. 2. Soil respiration dynamics of blueberry spruce forest and technological elements of clearcuts (cutting areas and skid trails) in June–October 2024. Error bars – mean error.

We did not identify any significant effect of clearcutting on SR through all months ($p_t > 0.05$), except for June when the CO_2 emission rate was by 1.4 higher ($p_t = 0.036$) in the cutting areas of 8-year-old clearcut. However, the mean SR rate analysis over the entire observation period revealed a higher (by 1.3–1.5; $p_t < 0.05$) value in 8-year-old clearcut, which is probably due to active decomposition of underground organs of dead plants and respiration of root of renewing birch trees. The mean CO_2 flux rate from the soil surface of undisturbed spruce forest and 18-year-old clearcut from June to October was comparable ($p_t = 0.190$).

When analyzing CO_2 emission from the surface of technological elements of clearcuts (cutting area and skidding track), we fixed a higher SR rate (by 1.4–2.1; $p_t < 0.05$) in tracks compared to the cutting areas, the flow rate is also characterized by a fairly high (31–52%) variation. The intensive emission in the logging machinery paths is related not only to the active regeneration of small-leaved woody vegetation, decomposition of fallen wood and root respiration, which are involved in CO_2 formation, but also to the presence of decomposing felling residues, put onto the skidding roads to make the soil compact.

For the observation period, the seasonal dynamics are less pronounced in tracks of the 8-year-old clearcut, which is indicated by the comparable values of mean monthly emission from June to September ($p_t > 0.05$), whereas the 18-year-old clearcut is found for a decrease in September after maximum values during summer.

The obtained patterns of SR from June to October coincide with the published results. According to A.F. Osipov et al. (2024), high values of CO_2 flux in the snow-free period were also observed in July-August 2022 and reached 3.90–5.62 gC·m^{-2} per day and 2.3–2.5 gC·m^{-2} per day in the control and clearcut sites, respectively, which corresponds to the seasonal dynamics we obtained. The work of A.G. Molchanov et al. (2017) highlights exactly the same pattern as the maximum CO_2 emission is in July-August and then decreases in October from 4.67 to 1.81 gC·m^{-2} per day in the background plot of spruce forest, and from 8.29 to 1.76 gC·m^{-2} per day in the cutting areas of mixed herbaceous spruce forest clearcut. In trails, the flow rate is by 30% higher than that in the cutting areas. V.V. Mamkin et al. (2019) showed CO_2 emission from the soil surface in different observation years after clearcutting in the south taiga subzone varying from 4 to 16 gC·m^{-2} per day. The mean daily dynamics of CO_2 flux in blueberry pine forest in July-August in Karelia were 6.12 gC·m^{-2} per day, which was by 1. times higher than in same clearcut (Pridacha and Semin, 2024). The authors note that soil and air temperature and illumination have a significant effect on soil respiration.

Relationship between soil respiration and soil temperature

Soil temperature is one of the main abiotic factors affecting carbon dioxide emission (Bond-Lamberty and Thomson, 2010). The regression analysis showed a significant ($p < 0.001$) positive correlation between soil respiration and soil temperature, both from the soil surface of blueberry spruce forest and particular technological elements of spruce forest clearcut in all study periods and at both depths (Table 1). However, the degree of correlation in the studied communities differs. For example, blueberry spruce forest is identified for a higher correlation at a 5-cm depth (R^2 = 0.54 vs R^2 = 0.45) against similar values of the coefficients of the dependence equations. The cutting areas of the 8-year-old clearcut demonstrate a decrease in the coefficient of determination for the relationship between SR and ST10 from 0.39 to 0.20. The interrelationships between skidding tracks' respiration are similar at both depths with higher values of the regression equation coefficients observed for a depth of 10 cm.

The respiration response of cutting areas and skidding tracks in 18-year-old clearcut is similar to that in undisturbed spruce forest, as expressed by approximately equal equation parameters, but with a medium correlation at a 5-cm depth and a low correlation with ST10 (R^2 = 0.37 vs R^2 = 0.22 for cutting areas and R^2 = 0.41 vs R^2 = 0.28 for skidding tracks). The medium correlations at 5-cm depth are probably due to the fact that leaf waste decomposition proceeds just in this layer. Leaf litter is the main soil fraction at this depth in after-felling communities where the tree layer is dominated by small-leaved species.

Table 1. Characteristics of equations (lnSR = αX + β) of CO_2 emission dependence on soil temperature (ST). ST5 – dependence on soil temperature at a depth of 5 cm; ST10 – dependence on soil temperature at a depth of 10 cm; coefficient errors are given in brackets.

Community		Factor	Coefficient α	Coefficient β	R^2	p-value	Q_{10}	SR_{10}, g·C/(m^2× day)
Blueberry spruce forest		ST5	0.143(0.013)	−0.097(0.142)	0.54	< 0.001	4.18	3.79
		ST10	0.162(0.018)	−0.187(0.180)	0.45	< 0.001	5.03	4.17
8-year-old clearcut	Cutting area	ST5	0.148(0.026)	−0.111(0.322)	0.39	< 0.001	4.37	3.91
		ST10	0.133(0.039)	0.255(0.409)	0.20	< 0.001	3.80	4.90
	Skidding road	ST5	0.112(0.020)	0.701(0.267)	0.40	< 0.001	3.06	6.18
		ST10	0.161(0.028)	0.324(0.331)	0.40	< 0.001	4.99	6.90
18-year-old clearcut	Cutting area	ST5	0.122(0.014)	0.132(0.161)	0.62	< 0.001	3.39	3.86
		ST10	0.146(0.019)	−0.024(0.208)	0.54	< 0.001	4.31	4.20
	Skidding road	ST5	0.125(0.014)	0.693(0.180)	0.61	< 0.001	3.49	6.98
		ST10	0.177(0.022)	0.292(0.250)	0.56	< 0.001	5.84	7.82

When comparing the SR and ST relationship at different depths, the temperature coefficient is higher (by 1.2–1.7) at a 10-cm depth in most cases, except for cutting areas in C8 (Table 1). This is probably due to the vertical distribution of woody plant roots, most of which are distributed in the lower layers of forest floor and upper mineral horizons of the soil profile. Heterotrophic respiration is known to be less sensitive to changes in soil temperature compared to autotrophic respiration (Yang et al., 2022), as a consequence of which we observe higher Q_{10} values calculated for 10-cm depth. In general, clearcutting reduces SR-ST relationship that is associated with a decrease in weight and respiration rate intensity of roots compared to undisturbed spruce forest, as discussed above.

In the work of A.F. Osipov (2022) are given values close to our calculated Q_{10}, which varied depending on moisture conditions during the warm period. For example, in the middle taiga subzone of the Komi Republic in different years of observations Q_{10} reached 7.95–5.62 in undisturbed blueberry pine forest, 4.28–3.29 in cutting areas of 3–5-year-old clearcut of blueberry pine forest, in skidding tracks 5.70–2.33. The Q_{10} coefficient in different years of observation was 1.78–4.88 in the average coniferous plantation and 1.50–1.98 at its harvest (Osipov et al., 2024), in blueberry spruce forest – from 2 to 6.9 (Mashika, 2006). Low values of the temperature coefficient (1.60–2.12) in different years are also shown by V.V. Mamkin et al. (2019). For the 10-year harvest of Q_{10} blueberry pine forest was equal to 2.68–3.73 on arable plots and 2.04–3.87 on fibers depending on weather conditions in years of study (Osipov, 2023). The influence of air temperature and precipitation during the warm year period on the value of temperature response of soil respiration was revealed by I. Kurganova et al. (2022) by the results of long-term observations. Smaller values of Q_{10} in stands growing in the south taiga subzone and in mixed forests are largely associated with a better temperature sensitivity of soil respiration in high latitude ecosystems under conditions of heat deficiency (Kudeyarov and Kurganova, 2005).

Soil temperature dynamics

By the analysis of the results obtained for the dynamics of soil temperature from June to October, the undisturbed cutting area of logged plot had the soil temperature in early summer and September, in October, there was a decline. The maximum temperature was recorded in the first decade of July. We also identified local peaks in the second decade of June, the first decade of August, and the second decade of September due to weather conditions. In blueberry spruce forest, at the beginning of observations (5-cm depth) the soil warmed to 9.1 °C. The maximum temperature was 14.4 °C in the first decade of July, by the end of October they dropped to 2.8. In C8 cutting areas, the soil warmed up from 11 °C in June to 13.7 °C towards the end of the first decade of July with a decrease to 4.8°C in mid-October. On the skid roads, the values of the same periods were similar to those of the cutting areas and were 11.9, 15 and 4.8 °C, respectively. In the first decade of June, ST in cutting areas of C18 was 10.9 °C, then warmed up to 14.6 °C in early July and decreased to 2.6 °C in October; in skid trail, ST reached 11.2, 14.8 and 3 °C, respectively (Fig. 3). Thus, in clearcuts a more favorable temperature regime was observed in the cuttings compared to the unbroken blueberry spruce forest.

Similar data on the impact of clearcuttings on the soil temperature regime are given for stands formed after clearfelling of spruce, pine and coniferous-deciduous stands in the Komi Republic (Dymov and Startsev, 2016; Osipov, 2022; Osipov et al., 2024), as well as south taiga spruce (Mamkin et al., 2019) and pine forests (Zenkova and Stabrovskaya, 2022).

The soil temperature dynamics at a depth of 5 cm were characterised by greater amplitude of indicators, less than 10 cm. The highest values of 13.7–15 °C were found in the first decade of July. It is worth noting that the soil temperature in skid tracks of 8-year-old clearcuts is always higher than in other technological elements of logged forest area because the soil warms up faster there due to the thin tree canopy (Osipov, 2022). You can also notice that during the summer, as well as warm September at a depth of 5 cm the soil is warmer than at a depth of 10 cm. In October, the trend is reversed: at a depth of 10 cm, the average temperature is 1 °C higher.

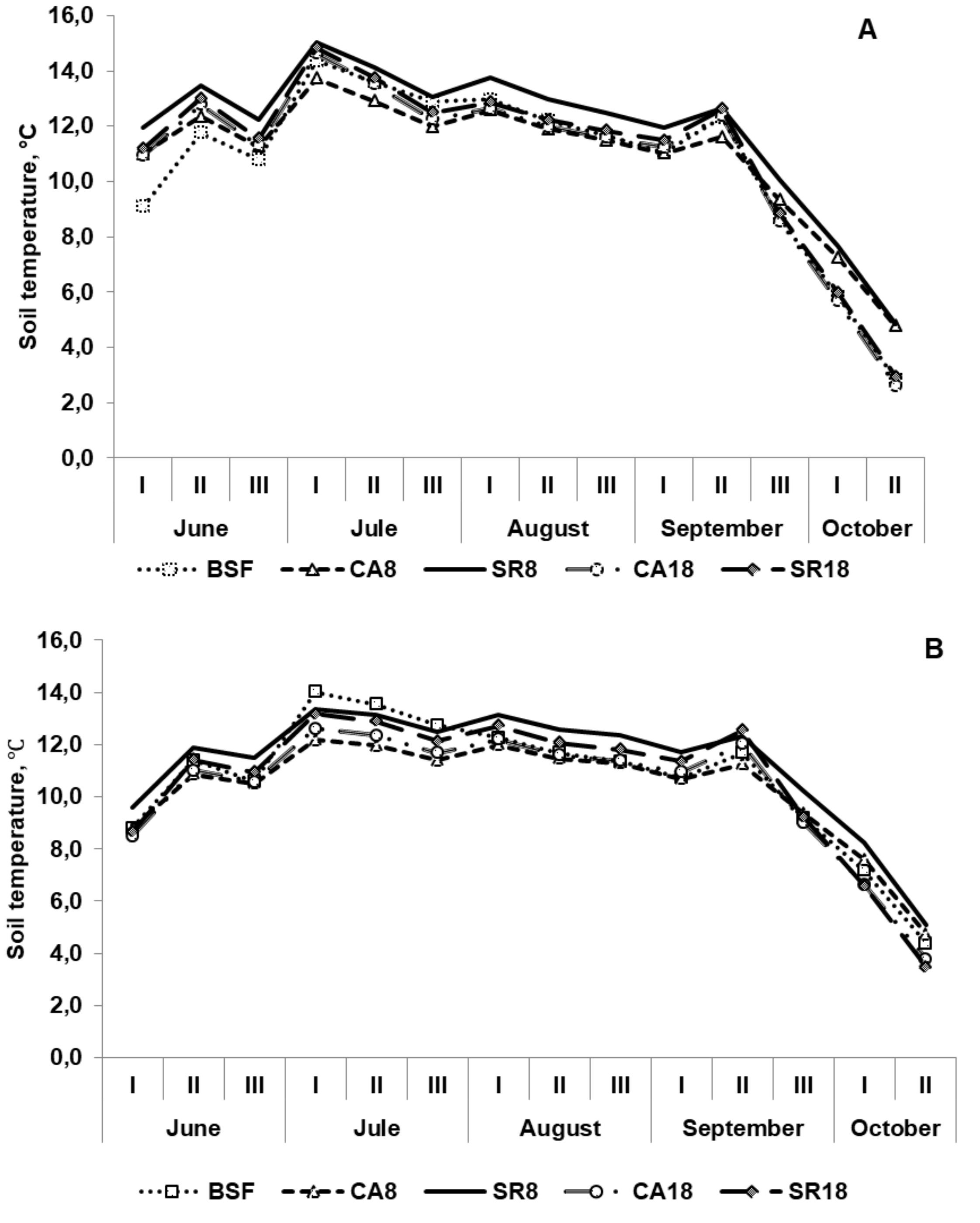

Fig. 3. Fig. 3. Soil temperature dynamics in blueberry spruce forest and clearcuts of different years in June-October 2024. **A** – soil temperature at 5-cm depth; **B** – soil temperature at 10-cm depth; BSF – blueberry spruce forest; CA8 – 8-year-old cutting area (opposite to skid road); SR8 – 8-year-old skid road; CA18 – 18-year-old cutting area; SR18 – 18-year-old skid road; I, II, III – decades.

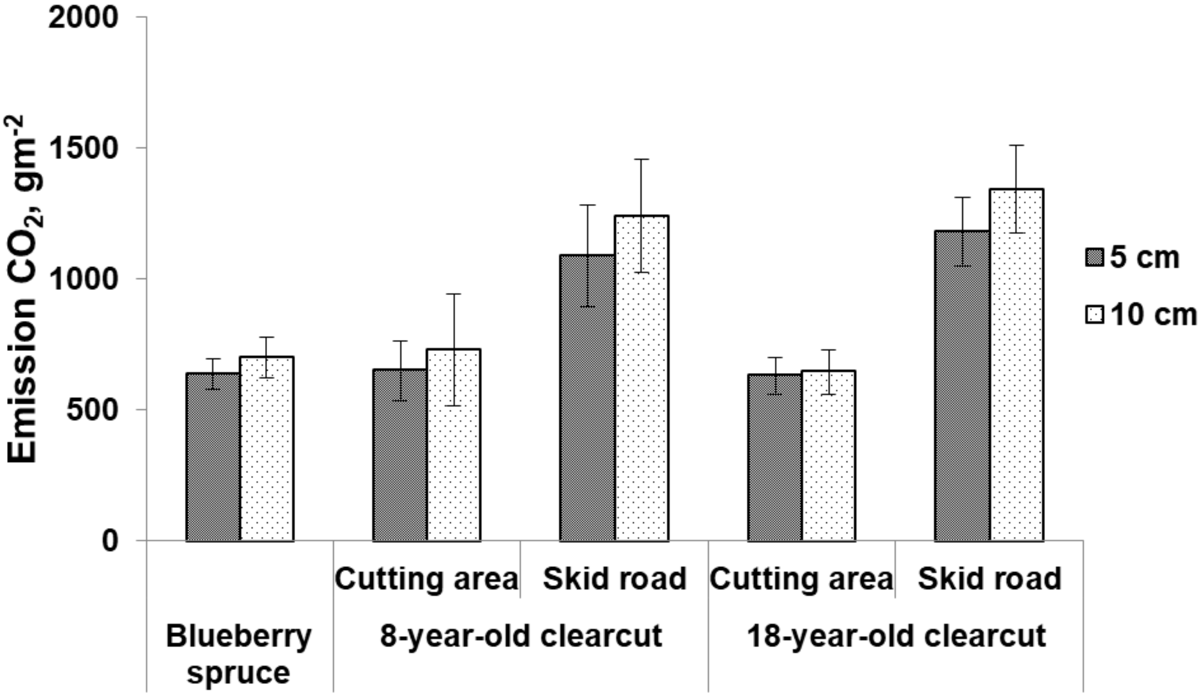

Fig. 4. Carbon C–CO_2 flux during the observation period in blueberry spruce forest and clearcuts at different soil depths in June-October 2024. Error bars indicate the mean error.

Carbon removal with soil respiration

For June-October 2024, 635–698 gC·m^{-2} emitted from the soil surface of the control blueberry spruce forest depending on the depth used to calculate the removal C–CO_2 (Fig. 4). At 10 cm a higher value is observed, but no reliable differences have been found. The higher value for the deeper layer is associated to the high value of Q_{10}, the mechanism of which was above-discussed (showing the change in SR speed at a temperature change of 10 °C).

The clearcutting does not affect the CO_2 flux from the surface of cutting areas (opposite to skid roads) in felled plots. C8 cutting areas emit 651–728 gC·m^{-2} and C18 cutting areas – 630–645 gC·m^{-2} from the soils surface. However, the skidding trails are characterised by a more active C-CO_2 emission. For instance, C8 skid roads emitted 1089–1240, C18 – 1190–1341 gC·m^{-2} during June-October 2024, which is by 1.67–2.08 times more than cutting areas. The intensive carbon flux with soil respiration in skid trail is due to felling residues left after logging to strengthen the soil surface. Decomposition of logging residues in combination with respiration of roots of actively growing small-leaved species and the presence of easily decomposable leaf litter affect the increase of C–CO_2 emission.

Using the soil respiration data at the particular technological elements of clearcut, we accessed the C–CO_2 emission from the surface of the entire timber harvesting area. Cutting areas take 80% of the total harvesting area, with the rest occupied by skid trails. From the soil surface of the 8-year-old clearcut (S=11 ha), 336 tCO_2/ha (8.3 tC/ha) entered the atmosphere from June to October, with the contribution of trails accounting for 30%. The 18-year-old clearcut (S = 17 ha) emitted 495.9 tCO_2/ha (7.8 tC/ha), of which 34% was from skid roads. Carbon flux from blueberry spruce forest was 6.4–7.0 tCO_2/ha, which was by 1.2 less than that from the 8-year-old clearcut and by 1.1 times less than from the 18-year-old clearcut.

When comparing the obtained data on C–CO_2 flux from the soil surface of spruce forests, we identified higher values than the results presented by A.V. Mashika (2006) for blueberry spruce and M.A. Kuznetsov (2014) for blueberry-sphagnum spruce forests. Similar data were published in a number of works. For example, 373–681 gC·m^{-2} emits from the soils of wet peatland south taiga spruce forests in summer months (Ivanov et al., 2020) and 522–804 gC·m^{-2} in an Estonian mature spruce forest (Kukumagi et al., 2017). From the soil surface of a coniferous-deciduous forest stand during the snow-free period in different years, 400–746 gC·m^{-2} is emitted. As a clearcut, it emits 337–442 gC·m^{-2} (Osipov et al., 2024). The annual C–CO_2 flux from the waterlogged gley organo-mineral soil of spruce clearcut in England varied within 243–322 gC·m^{-2} (Yamulki et al., 2021). 210–379 gC·m^{-2} emit from the soils of blueberry pine forest cuts being at different development stages and 296–573 gC·m^{-2} – from tracts in these clearcuts from May to October (Osipov, 2022, 2023). Pine forest clearcuts in Finland emit 267–286 gC·m^{-2} (Korkiakoski et al., 2019). Thus, the analysis of the literature allows concluding that the CO_2 emission of undisturbed forest and their clearcuts varies widely and largely depends on the growing conditions, stages of development after disturbance, weather conditions in the years of research.

Conclusion

The data on soil respiration of plant communities formed after clearcutting of blueberry spruce forest and being at different stages of regenerative succession are similar to the data obtained for an undisturbed spruce forest on the typical podzolic soil, which indicates that there is no reliable impact of clearcutting on soil respiration in 8 and 18 years after the logging procedure, whereas initially we observed a 1.4-fold increase in the rate of CO_2 flux from the soil surface. The combination of logging residues and this-year leaf litterfall decomposition with root respiration of actively regenerating woody plants caused an intensive soil respiration in skid roads that was by 1.4–2.1 times higher compared to undisturbed cutting areas within a clearcut. During the observation period, skid trails in 8-year-old clearcut had no signs of seasonal dynamics, which is expressed in comparable values of average monthly emissions from June to September. The highest CO_2 emission occurs in July-August and attains its minimum in October in all studied communities. SR positively correlates with soil temperature. When analyzing the correlation for 5- and 10-cm depths, we identified that the relationship became higher with depth, the same for the temperature response (Q_{10} coefficient) of CO_2 emission. From June to October, 635–698 gC·m^{-2} was emitted from the soil of blueberry spruce forest, 651–728 gC·m^{-2} from the soil of 8-year-old clearcut, and 630–645 gC·m^{-2} from the soil of 18-year-old clearcut. The skidding roads are characterized by a more intensive (by 1.7–2.1) carbon flux, compared to the cutting areas. It is calculated that 336–495.9 tCO_2 with a skid trails of 30–34% enters the atmosphere from the surface of all the B8 (11 ha) and B18 (17 ha).

References

Aguilos, M., Takagi, K., Liang, N., Ueyama, M., Fukuzawa, K. et al., 2014. Dynamics of ecosystem carbon balance recovering from a clear-cutting in a cool-temperate forest. *Agricultural and Forest Meteorology* **197**, 26–39. https://doi.org/10.1016/j.agrformet.2014.06.002

Atlas Respubliki Komi po klimatu i gidrologii [Atlas of the Komi Republic on climate and hydrology], 1997. Taskaev, A.I. (ed.). Nauka, Moscow, Russia, 116 p. (In Russian).

Bobkova, K.S., Zagirova, S.V., 2014. Uglerod v lesnykh i bolotnykh ekosistemakh osobo okhranyayemykh prirodnykh territoriy Respubliki Komi [Carbon in forest and wetland ecosystems of specially protected natural areas of the Komi Republic]. IB FRC Komi SC UB RAS, Syktyvkar, Russia, 202 p. (In Russian).

Bond-Lamberty, B., Thomson, A.M., 2010. Temperature-associated increases in the global soil respiration record. *Nature* **464**, 579–582. https://doi.org/10.1038/nature08930

Bond-Lamberty, B., Ballantyne, A., Berryman, E., Fluet-Chouinard, E., Jian, J. et al., 2024. Twenty years of progress, challenges, and opportunities in measuring and understanding soil respiration. *Journal of Geophysical Research: Biogeosciences* **129** (2), e2023JG007637. https://doi.org/10.1029/2023JG007637

Davidson, E.A., Janssens, I.A., Luo, Y., 2006. On the variability of respiration in terrestrial ecosystems: moving beyond Q_{10}. *Global Change Biology* **12**, 154–164. https://doi.org/10.1111/j.1365-2486.2005.01065.x

Dymov, A.A., 2020. Suktsessii pochv v boreal'nykh lesakh Respubliki Komi [Soil successions at boreal forests of the Komi Republic]. GEOS, Moscow, Russia, 336 p. (In Russian). https://doi.org/10.34756/GEOS.2020.10.37828

Dymov, A.A., Startsev, V.V., 2016. Changes in the temperature regime of podzolic soils in the course of natural forest restoration after clearcutting. *Eurasian Soil Science* **49** (5), 551–559. https://doi.org/10.1134/S1064229316050021

Dymov, A.A., Osipov, A.F., Startsev, V.V., Gorbach, N.M., Severgina, D.A. et al., 2024. Carbon pools and fluxes in mixed coniferous–small-leaved forests and clearcut areas. *Eurasian Soil Science* **57** (11), 1867–1878. https://doi.org/10.1134/S1064229324601847

FAO, 2010. Global forest resources assessment. FAO, Rome, 122 p.

Ivanov, D., Tatarinov, F., Kurbatova, J., 2020. Soil respiration in paludified forests of European Russia. *Journal of Forest Research* **31**, 1939–1948. https://doi.org/10.1007/s11676-019-00963-4

Korkiakoski, M., Tuovinen, J-P., Penttilä, T., Sarkkola, S., Ojanen, P. et al., 2019. Greenhouse gas and energy fluxes in a boreal peatland forest after clear-cutting. *Biogeosciences* **16**, 3703–3723. https://doi.org/10.5194/bg-16-3703-2019

Kudeyarov, V.N., Kurganova, I.N., 2005. Respiration of russian soils: database analysis, long-term monitoring, and general estimates. *Eurasian Soil Science* **38**, 983–992.

Kudeyarov, V.N., Zavarzin, G.A., Blagodatskiy, S.A., Borisov, A.V., Voronin, P.Yu., et al., 2007. Puly i potoki ugleroda v nazemnyh ekosistemakh Rossii [Pools and fluxes of carbon in terrestrial ecosystems of Russia]. Nauka, Moscow, Russia, 315 p. (In Russuan).

Kukumägi, M., Ostonen, I., Uri, V., Helmisaari, H.-S., Kanal, A., Kull, O., Lõhmus, K., 2017. Variation of soil respiration and its components in hemiboreal Norway spruce stands of different ages. *Plant and Soil* **414**, 265–280. https://doi.org/10.1007/s11104-016-3133-5

Kurganova, I.N., Kudeayrov, V.N., 2012. Ekosistemy Rossii i global'nyy byudzhet ugleroda [Russian ecosystems and the global carbon budget]. *Nauka v Rossii [Science in Russia]* **5**, 25–32. (In Russian).

Kurganova, I.N., Lopez de Guerenu, V.O.L., Gallardo Lancho, J.F.G., Em, K.T., 2012. Evaluation of the rates of soil organic matter mineralization in forest ecosystems of temperate continental, mediterranean, and tropical monsoon climates. *Eurasian Soil Science* **45** (1), 68–79.

Kurganova, I., Lopes de Gerenyu, V., Khoroshaev, D., Myakshina, T., Sapronov, D., Zhmurin, V., 2022. Temperature sensitivity of soil respiration in two temperate forest ecosystems: the synthesis of a 24-year continuous observation. *Forest* **13**, 1374. https://doi.org/10.3390/f13091374

Kurganova, I.N., Goncharova, O.Yu., Zamolodchikov, D.G., Karelin, D.V., Kuznetsov, M.A. et al., 2024. Opredeleniye ehmissii CO_2 iz pochv kamernym metodom v razlichnykh tipakh ekosistem [Determination of CO_2 emissions from soils using the chamber method in different types of ecosystems]. Center for Forest Ecology and Productivity RAS, Moscow, Russia, 28 p. (In Russian).

Kutyavin, I.N., Manov, A.V., Startsev, V.V., Dymov, A.A., 2024. Vliyaniye lesozagotovitel'noy tekhniki na dinamiku yestestvennogo vozobnovleniya lesa posle rubki khvoyno-listvennogo nasazhdeniya sredney taygi [The influence of logging equipment on the dynamics of natural forest regeneration after felling of coniferous-deciduous stands of the middle taiga]. *Teoreticheskaya i prikladnaya ekologiya [Theoretical and Applied Ecology]* **3**, 123–132. (In Russian). https://doi.org/10.25750/1995-4301-2024-3-123-132

Mamkin, V.V., Avilov, V.K., Ivanov, D.G., Olchev, A.V., Kurbatova, Yu.A., 2019. Potoki CO_2 na sploshnoy vyrubke v yuzhnoy tayge yevropeyskoy territorii Rossii [CO_2 fluxes at the dear-cut in the southern taiga of European Russia]. *Sibirskiy ekologicheskiy zhurnal [Contemporary Problems of Ecology]* **5**, 598–611. (In Russian). https://doi.org/10.15372/SEJ20190509

Mashika, A.V., 2006. Carbon dioxide emission from the surface of podzolic soils. *Eurasian Soil Science* **39** (12), 1312–1317.

Molchanov, A.G., Kurbatova, Yu.A., Olchev, A.V., 2017. Vliianie sploshnoi rubki lesa na emissiiu SO2 s poverkhnosti pochvy [Effect of clear-cutting on soil CO_2 emission]. *Biology Bulletin* **44** (2), 218–223. (In Russian). https://doi.org/10.7868/S0002332916060126

Osipov, A.F., 2016. Carbon emission from the soil surface in a mature blueberry pine forest of the middle taiga (Republic of Komi). *Eurasian Soil Science* **49** (8), 926–933. https://doi.org/10.1134/S1064229316080093

Osipov, A.F., 2022. Vliyaniye sploshnoy rubki na dykhaniye pochvy srednetayezhnogo sosnyaka chernichnogo Respubliki Komi [Clear cuttings affecting the soil respiration of the middle taiga blueberry pine forest in the Komi Republic]. *Lesovedeniye [Russian Journal of Forest Science]* **4**, 395–406. (In Russian). https://doi.org/10.31857/S0024114822030111

Osipov, A.F., 2023. Carbon dioxide emission from the soil surface of the 10-year felled area of the pine forest in the European North-East of Russia. *Eurasian Soil Science* **56** (9), 1223–1231. https://doi.org/10.1134/s106422932360118x

Osipov, A.F., Bobkova, K.S., Dymov, A.A., 2021. Carbon stocks of soils under forest in the Komi Republic of Russia. *Geoderma Regional* **27**, e00427. https://doi.org/10.1016/j.geodrs.2021.e00427

Osipov, A.F., Startsev, V.V., Dymov, A.A., 2024. Influence of clear felling on CO_2 emission from surface of podzolic soil of coniferous–deciduous forest (middle taiga, Komi Republic). *Eurasian Soil Science* **57** (5), 806–813. https://doi.org/10.1134/S1064229323603700

Pongratz, J., Reick, C.H., Raddatz, T., Claussen, M., 2009. Effects of anthropogenic land cover change on the carbon cycle of the last millennium. *Global Biogeochemical Cycles* **23** (4), GB4001. https://doi.org/10.1029/2009GB003488

Pridacha, V.B., Sazonova, T.A., Novichonok, E.V., Semin, D.E., Tkachenko, Y.N. et al., 2021. Clear-cutting impacts nutrient, carbon and water exchange parameters in woody plants in an east Fennoscandia pine forest. *Plant and Soil* **476**, 317–336. https://doi.org/10.1007/s11104-021-05058-w

Pridacha, V.B., Semin, D.E., 2024. Clear-cutting effects on components of the carbon balance in a bilberry-type pine forest in southern Karelia. *Ecosystem Transformation* **7** (3), 64–83. https://doi.org/10.23859/estr-230505

Rudneva, E.N., Zaboeva, I.V., Urusevskaya, I.S., 1981. Pochvenno-geograficheskoye rayonirovaniye tsentral'noy i vostochnoy chastey yevropeyskoy territorii SSSR. Podzolistyye pochvy tsentral'noy i vostochnoy chastey yevropeyskoy territorii SSSR [Soil-geographical zoning of the central and eastern parts of the European territory of the USSR. Podzolic soils of the central and eastern parts of the European territory of the USSR] Nauka, Leningrad, USSR, 200 p. (In Russian).

Schlesinger, W.H., Andrews, J.A., 2000. Soil respiration and the global carbon cycle. *Biogeochemistry* **48**, 7–20. https://doi.org/10.1023/A:1006247623877

Yang, L., Qin, J., Geng, Y., Zhang, C., Pan, J., Niu, S., Wang, J., 2022. Long-term effects of forest thinning on soil respiration and its components in a pine plantation. *Forest Ecology and Management* **513**, 120189. https://doi.org/10.1016/j.foreco.2022.120189

Yamulki, S., Forster, J., Xenakis, G., Ash, A., Brunt, J., Perks, M., Morison, J.I.L., 2021. Effects of clear-fell harvesting on soil CO_2, CH_4, and N_2O fluxes in an upland Sitka spruce stand in England. *Biogoescoence* **18**, 4227–4241. https://doi.org/10.5194/bg-18-4227-2021

Zamolodchikov, D.G., Chestnykh, O.V., Grabovsky, V.I., Shulyak, P.P., 2013. The impacts of fires and clear-cuts on the carbon balance of Russian forests'. *Contemporary Problems of Ecology* **6** (7), 714–726.

Zenkova, I.V., Shtabrovskaya, I.M., 2022. Vliyaniye gidrotermicheskikh usloviy na podstilochnykh bespozvonochnykh vyrubok i garey Khibin [Hydrothermal conditions affecting the forest litter invertebrates in the cuttings and burnt areas of Khibiny mountains]. *Lesovedeniye [Russian Journal of Forest Science]* **4**, 364–380. (In Russian). https://doi.org/10.31857/S0024114822030123

Список литературы

Атлас Республики Коми по климату и гидрологии, 1997. Таскаев, А.И. (ред). Наука, Москва, Россия, 116 с.

Бобкова, К.С., Загирова, С.В., 2014. Углерод в лесных и болотных экосистемах особо охраняемых природных территорий Республики Коми. ИБ Коми НЦ УрО РАН, Сыктывкар, Россия, 202 с.

Дымов, А.А., 2020. Сукцессии почв в бореальных лесах Республики Коми. Издательство ГЕОС, Москва, Россия, 336 с. https://doi.org/10.34756/GEOS.2020.10.37828

Дымов, А.А., Старцев, В.В., 2016. Изменение температурного режима подзолистых почв в процессе естественного лесовозобновления после сплошных рубок. *Почвоведение* **5**, 599–608. https://doi.org/10.7868/S0032180X16050038

Замолодчиков, Д.Г., Грабовский, В.И., Шуляк, П.П., Честных, О.В., 2013. Влияние пожаров и заготовок древесины на углеродный баланс лесов России *Лесоведение* **5**, 36–49.

Зенкова, И.В., Штабровская, И.М., 2022. Влияние гидротермических условий на подстилочных беспозвоночных вырубок и гарей Хибин. *Лесоведение* **4**, 364–380. https://doi.org/10.31857/S0024114822030123

Кудеяров, В.Н., Заварзин, Г.А., Благодатский, С.А., Борисов, А.В., Воронин, П.Ю. и др., 2007. Пулы и потоки углерода в наземных экосистемах России. Наука, Москва, Россия, 315 с.

Курганова, И.Н., Кудеяров, В.Н., 2012. Экосистемы России и глобальный бюджет углерода. *Наука в России* **5**, 25–32.

Курганова, И.Н., Лопес де Гереню, В.О., Галлардо Ланчо, Х.Ф., Ем, К.Т., 2012. Оценка скорости минерализации органического вещества почв в лесных экосистемах внутриконтинентального умеренного, средиземноморского и тропического муссонного климата. *Почвоведение* **1**, 82–94.

Курганова, И.Н., Гончарова, О.Ю., Замолодчиков, Д.Г., Карелин, Д.В., Кузнецов, М.А. и др., 2024. Определение эмиссии CO_2 из почв камерным методом в различных типах экосистем. ЦЭПЛ РАН, Москва, Россия, 28 с.

Кутявин, И.Н., Манов, А.В., Старцев, В.В., Дымов, А.А., 2024. Влияние лесозаготовительной техники на динамику естественного возобновления леса после рубки хвойно-лиственного насаждения средней тайги. *Теоретическая и прикладная экология* **3**, 123–132. https://doi.org/10.25750/1995-4301-2024-3-123-132

Мамкин, В.В., Авилов, В.К., Иванов, Д.Г., Ольчев, А.В., Курбатова, Ю.А., 2019. Потоки CO_2 на сплошной вырубке в южной тайге европейской территории России. *Сибирский экологический журнал* **5**, 598–611. https://doi.org/10.15372/SEJ20190509

Машика, А.В., 2006. Эмиссия диоксида углерода с поверхности подзолистой почвы. *Почвоведение* **12**, 1457–1463.

Молчанов, А.Г., Курбатова, Ю.А., Ольчев, А.В., 2017. Влияние сплошной рубки леса на эмиссию CO_2 с поверхности почвы. *Известия РАН. Серия биологическая* **2**, 190–196. https://doi.org/10.7868/S0002332916060126

Осипов, А.Ф., 2016. Выделение углерода с поверхности почвы спелого сосняка черничного средней тайги Республики Коми. *Почвоведение* **8**, 982–990. https://doi.org/10.7868/S0032180X16080098

Осипов, А.Ф., 2022. Влияние сплошной рубки на дыхание почвы среднетаежного сосняка черничного Республики Коми. *Лесоведение* **4**, 395–406. https://doi.org/10.31857/S0024114822030111

Осипов, А.Ф., 2023. Эмиссия CO_2 с поверхности почвы на 10-летней вырубке среднетаежного сосняка черничного на Европейском севере-востоке России. *Почвоведение* **9**, 1049–1058. https://doi.org/10.31857/S0032180X23600087

Придача, В.Б., Семин, Д.Е., 2024. Влияние сплошной рубки на составляющие углеродного баланса сосняка черничного Южной Карелии. *Трансформация экосистем* **7** (3), 64–83. https://doi.org/10.23859/estr-230505

Руднева, Е.Н., Забоева, И.В., Урусевская, И.С., 1981. Почвенно-географическое районирование центральной и восточной частей европейской территории СССР. Подзолистые почвы центральной и восточной частей европейской территории СССР. Наука, Ленинград, СССР, 200 с.

Aguilos, M., Takagi, K., Liang, N., Ueyama, M., Fukuzawa, K. et al., 2014. Dynamics of ecosystem carbon balance recovering from a clear-cutting in a cool-temperate forest. *Agricultural and Forest Meteorology* **197**, 26–39. https://doi.org/10.1016/j.agrformet.2014.06.002

Bond-Lamberty, B., Thomson, A.M., 2010. Temperature-associated increases in the global soil respiration record. *Nature* **464**, 579–582. https://doi.org/10.1038/nature08930

Bond-Lamberty, B., Ballantyne, A., Berryman, E., Fluet-Chouinard, E., Jian, J. et al., 2024. Twenty years of progress, challenges, and opportunities in measuring and understanding soil respiration. *Journal of Geophysical Research: Biogeosciences* **129** (2), e2023JG007637. https://doi.org/10.1029/2023JG007637

Davidson, E.A., Janssens, I.A., Luo, Y., 2006. On the variability of respiration in terrestrial ecosystems: moving beyond Q_{10}. *Global Change Biology* **12**, 154–164. https://doi.org/10.1111/j.1365-2486.2005.01065.x

Dymov, A.A., Osipov, A.F., Startsev, V.V., Gorbach, N.M., Severgina, D.A. et al., 2024. Carbon pools and fluxes in mixed coniferous–small-leaved forests and clearcut areas. *Eurasian Soil Science* **57** (11), 1867–1878. https://doi.org/10.1134/S1064229324601847

FAO, 2010. Global forest resources assessment. FAO, Rome, 122 p.

Ivanov, D., Tatarinov, F., Kurbatova, J., 2020. Soil respiration in paludified forests of European Russia. *Journal of Forest Research* **31**, 1939–1948. https://doi.org/10.1007/s11676-019-00963-4

Korkiakoski, M., Tuovinen, J-P., Penttilä, T., Sarkkola, S., Ojanen, P. et al., 2019. Greenhouse gas and energy fluxes in a boreal peatland forest after clear-cutting. *Biogeosciences* **16**, 3703–3723. https://doi.org/10.5194/bg-16-3703-2019

Kudeyarov, V.N., Kurganova, I.N., 2005. Respiration of russian soils: database analysis, long-term monitoring, and general estimates. *Eurasian Soil Science* **38**, 983–992.

Kukumägi, M., Ostonen, I., Uri, V., Helmisaari, H.-S., Kanal, A., Kull, O., Lõhmus, K., 2017. Variation of soil respiration and its components in hemiboreal Norway spruce stands of different ages. *Plant and Soil* **414**, 265–280. https://doi.org/10.1007/s11104-016-3133-5

Kurganova, I., Lopes de Gerenyu, V., Khoroshaev, D., Myakshina, T., Sapronov, D., Zhmurin, V., 2022. Temperature sensitivity of soil respiration in two temperate forest ecosystems: the synthesis of a 24-year continuous observation. *Forest* **13**, 1374. https://doi.org/10.3390/f13091374

Osipov, A.F., Bobkova, K.S., Dymov, A.A., 2021. Carbon stocks of soils under forest in the Komi Republic of Russia. *Geoderma Regional* **27**, e00427. https://doi.org/10.1016/j.geodrs.2021.e00427

Osipov, A.F., Startsev, V.V., Dymov, A.A., 2024. Influence of clear felling on CO_2 emission from surface of podzolic soil of coniferous–deciduous forest (middle taiga, Komi Republic). *Eurasian Soil Science* **57** (5), 806–813. https://doi.org/10.1134/S1064229323603700

Pongratz, J., Reick, C.H., Raddatz, T., Claussen, M., 2009. Effects of anthropogenic land cover change on the carbon cycle of the last millennium. *Global Biogeochemical Cycles* **23** (4), GB4001. https://doi.org/10.1029/2009GB003488

Pridacha, V.B., Sazonova, T.A., Novichonok, E.V., Semin, D.E., Tkachenko, Y.N. et al., 2021. Clear-cutting impacts nutrient, carbon and water exchange parameters in woody plants in an east Fennoscandia pine forest. *Plant and Soil* **476**, 317–336. https://doi.org/10.1007/s11104-021-05058-w

Schlesinger, W.H., Andrews, J.A., 2000. Soil respiration and the global carbon cycle. *Biogeochemistry* **48**, 7–20. https://doi.org/10.1023/A:1006247623877

Yang, L., Qin, J., Geng, Y., Zhang, C., Pan, J., Niu, S., Wang, J., 2022. Long-term effects of forest thinning on soil respiration and its components in a pine plantation. *Forest Ecology and Management* **513**, 120189. https://doi.org/10.1016/j.foreco.2022.120189

Yamulki, S., Forster, J., Xenakis, G., Ash, A., Brunt, J., Perks, M., Morison, J.I.L., 2021. Effects of clear-fell harvesting on soil CO_2, CH_4, and N_2O fluxes in an upland Sitka spruce stand in England. *Biogoescoence* **18**, 4227–4241. https://doi.org/10.5194/bg-18-4227-2021