

CO₂ FLUXES BETWEEN CLEAR-CUT SURFACE AND ATMOSPHERE IN THE PROTECTIVE ZONE OF THE CENTRAL FOREST STATE NATURE BIOSPHERE RESERVE

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АННОТАЦИЯ

Лесозаготовки в настоящее время являются одной из основных причин нарушения естественного цикла углерода в лесных экосистемах. Оценка связанных с этим изменений потоков CO₂ может быть осложнена гетерогенностью растительности на естественно возобновляющихся вырубках. В данной работе представлены результаты экспериментальных измерений потоков CO₂ на вырубке на юго-западе Валдайской возвышенности (европейская часть России) с травянистой растительностью и очаговым возобновлением осины, окруженной елово-берёзово-осиновым лесом. Измерения газообмена CO₂ почвы с травянистой растительностью проводились с помощью статической камеры. Результаты камерных измерений сопоставлялись с общим экосистемным дыханием, полученным методом турбулентных пульсаций на той же вырубке. Параллельные измерения проводились в различных растительных сообществах вырубки, а также в прилегающем к ней лесном массиве, аналогичном вырубленному. Показано, что эмиссия CO₂ на вырубке была достоверно ($p = 0,001$) выше, чем в прилегающем лесу. Например, средняя дневная эмиссия CO₂ из почвы в середине лета составила 8,3 и 10,7 мкмоль·м⁻²·с⁻¹ в лесу и на вырубке соответственно. За три года наблюдений эмиссия CO₂ из почвы на вырубке увеличивалась из года в год с 6,9 до 12,3 мкмоль·м⁻²·с⁻¹. Эмиссия CO₂ на вырубке статистически значимо выше на участках с луговой растительностью по сравнению с участками, заросшими древесной растительностью, с медианными значениями за последний год 11,5 и 7,5 мкмоль·м⁻²·с⁻¹ соответственно. Наблюдалась линейная зависимость эмиссии CO₂ из почвы с общим экосистемным дыханием ($r^2=0,52$). Таким образом, проведенное исследование показало, что оценку интеграционных потоков на вырубке с использованием камерных методов наблюдений необходимо проводить с учетом неоднородности растительного покрова.

Ключевые слова: выбросы углерода, камерный метод, вырубка лесов, травянистая растительность, почвенное дыхание.

ABSTRACT

Timber harvesting is currently one of the main reasons for the alteration of the natural carbon cycle in forest ecosystems. The evaluation of the related changes in CO₂ fluxes can be complicated by the heterogeneity of vegetation in naturally regrowing clear-cut areas. This study presents the results of experimental measurements of CO₂ fluxes at a clear-cut site in the southwest of the Valdai Upland (European Russia) with herbaceous vegetation and patchy aspen regeneration surrounded by spruce-birch-aspen forest. The measurements of CO₂ flux from soil with herbaceous vegetation were made by the static chamber method. Estimates of total primary production, balance, and CO₂ emissions from undisturbed soils were obtained. The parallel measurements were carried out in various plant communities of the clear-cut area, as well as in a forest stand adjacent to it and similar to the cut one. It is shown that CO₂ emission in the clear-cut was significantly ($p = 0.001$) higher than in the adjacent forest. For instance, mean daytime midsummer soil CO₂ efflux was 8.3 and 10.7 $\mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$ in the forest and clear-cut area, respectively. During three years of observation soil CO₂ efflux in the clear-cut increased from year to year from 6.9 to 12.3 $\mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$. The emission fluxes in the clear-cut site are statistically significantly higher in areas with meadow vegetation compared to areas overgrown with woody vegetation, with median values in the last year 11.5 and 7.5 $\mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$, respectively. The

assessment of integration fluxes in the clear-cut area using chamber methods of observation must be carried out considering the heterogeneity of the vegetation cover.

Key words: carbon emission, chamber method, deforestation, herbaceous vegetation, soil respiration.

INTRODUCTION

More than 80% of the world's forests have been affected by natural or anthropogenic disturbances [Bjornlund, 2010]. The number of experimental studies that assess the anthropogenic impact on the transformation of biogeochemical processes in forest ecosystems has been increasing in recent years [Keenan, Kimmins, 1993; Lytle, Cronan, 1998; Machimura et al., 2005; Lavoie et al., 2013; Kuznetsov, 2017; Molchanov et al., 2017; Molchanov, Tatarinov, 2017; Lindroth et al., 2018; Mamkin et al., 2019a; Vestin et al., 2020]. In Russia studies aimed at evaluating carbon dioxide exchange between atmosphere and anthropogenically disturbed ecosystems by direct experimental measurements remain rare [Kuznetsov, 2017; Molchanov, Tatarinov, 2017; Mamkin et al., 2019a].

Clear-cutting of mature and overmature stands is the most significant forest management practice, which affects the carbon cycle of the forest ecosystems. As a result of felling, a large number of photosynthetic plants are removed from the forest ecosystem. At the same time the decay of roots of harvested trees, as well as the residues of aboveground biomass remained after harvesting increases ecosystem respiration. This has a significant impact on the ecological, meteorological and hydrological conditions of the area [Lytle, Cronan, 1998; Amiro et al., 2010; Williams et al., 2014].

Due to deforestation the carbon balance changes – the ecosystem becomes net CO₂ source for the atmosphere for a period ranging from several years to decades. In general, this occurs due to a significant decrease in gross primary production (GPP) with small changes in ecosystem respiration, given that after removal of forest trees a decrease in autotrophic respiration is compensated by an increase in heterotrophic respiration due to decomposition of dead organic matter [Pumpanen et al., 2004]. The spatial and temporal variability of CO₂ fluxes in a naturally regenerating clear-cut is associated not only with its climatic zone, but also with a number of other factors: microrelief, moisture regime, composition and age of the previous stand, the structure of the understory of the felled area, the degree of preservation of undergrowth, soil organic matter contents etc., – all of which determine the pattern of felled area flora [Pumpanen et al., 2004; Giasson et al., 2006; Humphreys et al., 2006]. Some of these factors, e.g., microrelief or preserved undergrowth, can considerably vary within the felling area. Consequently, the vegetation can also vary. E.g., in some parts of the felling area the trees regeneration can start short time after the harvesting, whereas in other parts dense layer of tall grasses can prevent the regeneration for several years [Petrov, 1985]. In their turn, the ecosystem fluxes can also highly vary within the felling area. Hence, when evaluating the effect of felling vegetation on the energy and mass exchange with atmosphere this variability should be also taken into account.

The study area is the object of comprehensive long-term research conducted by A.N. Severtsov Institute of Ecology and Evolution of the Russian Academy of Sciences in the protective zone of the Central Forest State Nature Biosphere Reserve (CFSNBR) [Kurbatova et al., 2008; Mamkin et al., 2019a]. The study focused on the assessing the climate-regulating functions of the natural and anthropogenically disturbed ecosystems in southern taiga of the European part of Russia (EPR) based on observations made by the eddy covariance method [Burba, 2013]. Ecosystem level CO₂ flux measurements (total primary production, ecosystem respiration, net ecosystem exchange) in the first three years of regeneration after the harvest have been presented by Mamkin et al. [2019a, 2019b]. These studies have shown that, in general, clear-cuts in the southern taiga of the EPR are CO₂ sources for the atmosphere in the first years of regeneration. However, the eddy covariance method [Aubinet et al., 1999; Baldocchi, 2014] does not allow to assess the spatial variability of CO₂ fluxes at the disturbed site connected with the heterogeneity of the soils and vegetation within the area of interest. The present study was conducted in order to address the gap in understanding of biogeochemical processes at the clear-cut site and to evaluate a range of spatial and temporal variability of CO₂ fluxes between the soil with undisturbed ground vegetation and the atmosphere in a clear-cut site in CFSNBR, considering the pattern of vegetation cover. The design of the experiment was to obtain data that would answer the following questions: (1) How high can be the variability of soil CO₂ fluxes among different plant communities within the felling area. (2) What is the temporal variability of soil CO₂ fluxes within the vegetation season. (3) What is the partitioning between photosynthesis and respiration in the ground vegetation CO₂ fluxes in the felling. (4) How much differ soil respiration between the felling and the adjacent forest.

MATERIALS AND METHODS

Study site

Experimental observations of CO₂ fluxes were performed during the three summer seasons from 2016 to 2018 at the regenerating clear-cut on the territory of the (56.4435° N, 33.0478° E, Fig. 1). CFSNBR is located in the southwestern part of the Valdai Hills, within the main watershed of the Russian Plain (Baltic, Black and Caspian seas) [Karpov, 1983]. The long-term monthly mean temperatures in the area range from -8.2°C in January to 17.1°C in July, long-term mean annual precipitation total is 760 mm (Köppen climate - Dfb). The relief and the underlying bedrock leads to the formation of water-logged soils both on the territory of the entire CFSNBR [Pugachevskiy, 1992] and at the felling site of interest. The combination of hydrothermal characteristics determines the predominance of spruce forests with *Picea abies* L., which, after being cutted, are usually substituted with small-leaved forests of silver birch (*Betula pendula* Roth), aspen (*Populus tremula* L.), and grey alder (*Alnus incana* (L.) Moench). The study site is adjacent to the protective zone of the CFSNBR that is intended to reduce the anthropogenic impact on the territory of the conservation area and to study the influence of human activity on the ecosystems. It is also the transition zone to the regime of conservation of biological resources in the reserve. The harvesting was carried out in a secondary birch-spruce forest in April 2016. The surrounding forest stand is composed from typical species of the southern taiga subzone of the European Taiga: Norway spruce and silver birch. The tree density of the stand is 0.6, the height of the stand is 30 m, and the average age is 90 years. The sparse ground cover is mostly formed *Oxalis acetosella* L., *Rubus holostea* (L.) M.T.Sharple & E.A.Tripp, and *Luzula pilosa* (L.) Willd. The soil within the study area and the surrounding forest is drained, sod-pale-podzolic (Albeluvisols Umbric), clay-loamy, leached.

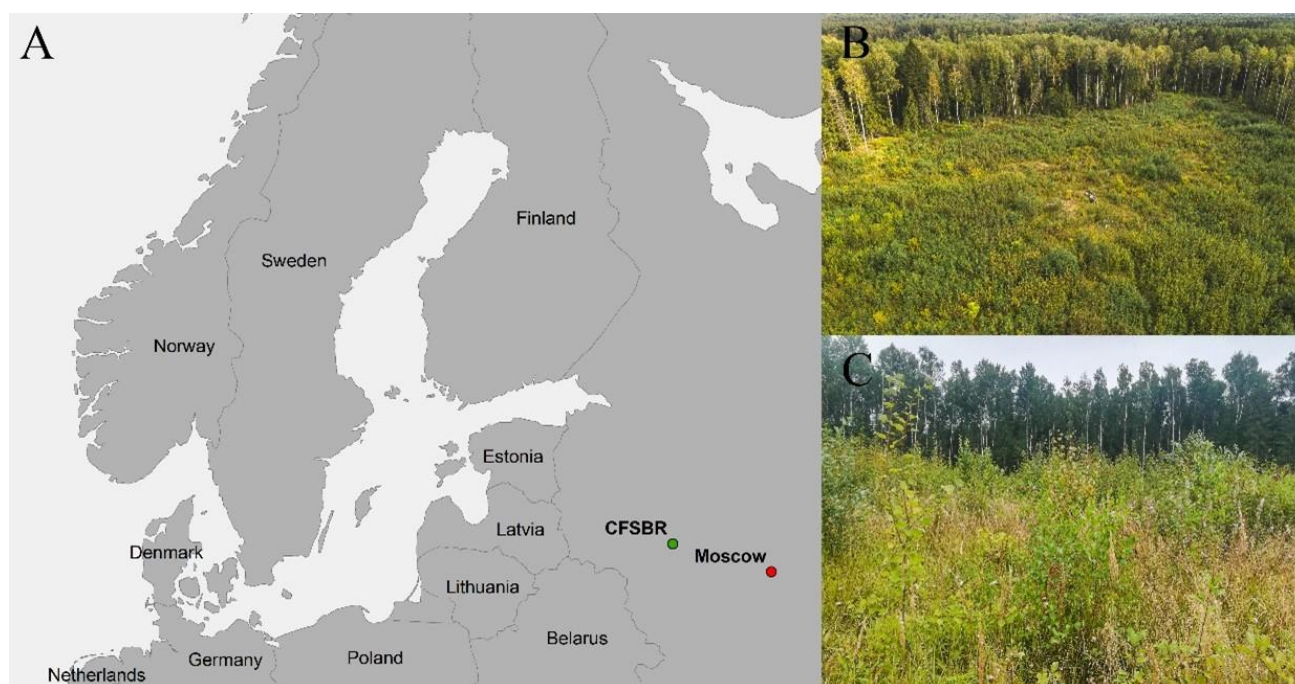


Fig. 1. Location of Central-Forest state biosphere reserve (CFSNBR) on the map (A); aerial photo of the clear-cut area (B); photo of the vegetation cover on the clear-cut (C)

The clear-cut area is about 0.05 km². The surface topography of the clear-cut is levelled, with a slight slope from west to east. Geobotanical research conducted at the site in 2018 by Ivleva, Leonova [2019] showed that the spatial structure of vegetation at the clear-cut was characterized by internal inhomogeneity. That vegetation structure is determined by microrelief, soil moisture, the composition of the previous forest ecosystem, and the distance from the forest edge. The main part of the area was occupied by forb communities with dense undergrowth of aspen, birch and other (Table 1), and in the central part meadow communities dominated by *Deschampsia cespitosa* (L.) P.Beauv., *Juncus effusus* L., *Epilobium angustifolium* L. were located in patches.

Table 1. Predominant vegetation cover of the clear-cut area

Site	Woody plants	Herbaceous plants
Meadow		<i>Deschampsia cespitosa</i> (L.) P.Beauv., <i>Juncus effusus</i> L., <i>Epilobium angustifolium</i> L., <i>Hypericum maculatum</i> Crantz, <i>Carex leporina</i> L., <i>Luzula pilosa</i> (L.) Willd.
Undergrowth	<i>Populus tremula</i> L., <i>Betula pendula</i> Roth, <i>Rubus idaeus</i> L., <i>Sorbus aucuparia</i> L., <i>Frangula alnus</i> Mill.	<i>Chamaenerion angustifolium</i> (L.) Scop., <i>Hypericum maculatum</i> Crantz, <i>Veronica chamaedrys</i> L., <i>Fragaria vesca</i> L., <i>Rubus</i> <i>holostea</i> (L.) M.T.Sharple & E.A.Tripp, <i>Calamagrostis</i> <i>arundinacea</i> (L.) Roth, <i>Solidago virgaurea</i> L., <i>Scirpus sylvaticus</i> L.

Experimental design

Since April 2016 eddy covariance (EC) and supplementary meteorological measurements are conducted at this clear-cut site according to Euroflux methodology [Aubinet et al., 1999]. In the current study these data were applied for comparison with upscaled fluxes measured by chamber method. In 2016 and 2017 five circular PVC collars with a diameter of 30 cm were installed in the meadow part of the felling covering typical vegetation of this plant community. CO₂ exchange measurements between the soil surface and vegetation cover with the atmosphere were performed by closed chamber method [Fiedler et al., 2022] using a lab-made hemispherical transparent plexiglass chamber with a diameter of 35 cm and a height of 17 cm, which was placed alternately on the collars during the measurement with the exposure time of 200 seconds. The collars were embedded into the soil 15 cm deep and were located 3-5 m apart within meadow communities. CO₂ balance (NEEch) was measured between the ground cover and the atmosphere by a transparent chamber. In order to measure the level of CO₂ emission (Rch) the chamber was covered with a light-tight dome. CO₂ uptake during photosynthesis (GPPch) was calculated as the difference between emission and net flux: $GPPch = Rch - NEEch$ (according to the tradition of FluxNET community we denote CO₂ sinks as negative and sources as positive). The CO₂ concentration in the chamber was measured at a frequency of 1 Hz by the infrared gas analyzer Li-840 (Li-Cor, Inc., USA) connected to the chamber by two tubes 1.5 m long. Air was pumped at the speed of 1 L/min from the top of the chamber, and, after passing through the gas analyzer, returned through a perforated annular tube along the lower part of the chamber, which provided air circulation inside the chamber. The air inside chamber was mixed by a fan. CO₂ flux was determined according to the rate of change in CO₂ concentration in the chamber. The measurement technique is described in details by Ivanov et al. [2017].

In 2018, a cubic transparent plexiglass chamber measuring 40x40x40 cm was used. It was installed on square aluminum collars with 46 cm long sides, embedded in the soil by 6 cm deep and 1.5-3 m apart. Three plots were located in undergrowth site, the other three – in a meadow site. System integrity was ensured by a water gate. CO₂ concentration was measured by Li-840 gas analyzer. The flux calculation and partitioning of CO₂ flux into Rch and GPPch was performed the same way as in 2016-2017. For the comparison with eddy covariance data Rch, NEEch and GPPch were upscaled to the clear-cut area using the partitioning of this area into grassland and undergrowth areas (75% and 25%, respectively): $Rch_{upscaled} = 0.75 \times Rch_{grassland} + 0.25 \times Rch_{undergrowth}$.

During all three years of observations the CO₂ flux measurements were conducted twice a month from June to August in midday time (10:30-14:30), once in each collar. Along with CO₂ fluxes, the following parameters were recorded: soil temperature at a depth of 10 cm (HI 98509 Checktemp 1, Hanna instruments, USA), soil moisture at the depth of 5 cm (Campbell CS655, USA), air temperature inside the chamber (DHT22, SparkFun Electronics, USA), as well as air temperature at a height of 30 cm (IVA-6, RPC MICROFOR, Russia). Every year after the measurements were completed, on August 31, all the vegetation inside the collars was taken to determine the total aboveground biomass.

In order to capture the spatial variability of soil respiration of different plant associations within the clear-cut area and to compare it with soil respiration in the adjacent forest, in 2017 during 6 days (July 28 – August 1) additional measurements of CO₂ emissions from the soil surface without vegetation were carried out by the open chamber method at the clear-cut within the undergrowth part and in different herbaceous associations, as well as in the forest 20 m from the clearing. The data recording system allowed to take measurements by turns with five chambers. Forest measurements were obtained at two areas located between the tree trunks and near the trunk, between the roots of a mature aspen (at a distance of ~0.5 m from the

trunk) – one chamber in each position. At the clear-cut three chambers were installed under a dense cover of *Solidago virgaurea*, under the aspen undergrowth and under *Scirpus sylvaticus* dominance. Under *S. sylvaticus* measurements were carried out in the micro-depression of relief.

When being measured, the patch of soil was covered with a transparent chamber with a diameter of 20 cm and a height of 10 cm. The chambers were installed on the soil without vegetation for the period of measurements. A constant flow of ambient atmospheric air through the chamber was provided by means of an external pump at a rate of 1-2 l/min. The air flow rate through each chamber was measured and adjusted using a float flowmeter PC-3A (Russia). Switching the air flow through the chambers to the gas analyzer was done regularly and automatically, so that a full cycle of measurements at all plots was completed in 20 minutes. The intensity of CO₂ emission in all sampling plots was determined in turns, every half hour during daylight hours (10-19 h) from the difference between CO₂ concentrations in the chamber incoming and outgoing air according to the equation:

$$R_{chs} = F \frac{C_{ch} - C_{air}}{S}$$

where R_{chs} is the respiration of soil without vegetation, F is air flow rate, C_{ch} and C_{air} are CO₂ concentrations in chamber and ambient air and S is the surface area of soil within the chamber.

The serial connection of the measuring chambers to the gas analyzer was made using an automatic channel switching system based on a three-way switch that allows air to be pumped through the chambers during the entire measurement period, preventing stagnation of air in the chambers during periods when gas exchange was not measured. The concentration of CO₂ at the entrance and exit from the chamber was measured using a portable infrared gas analyzer LI-820 (Li-Cor Inc., USA). The logger MiniCube (EMS, Czech Republic) recorded the readings of the gas analyzer every 10 seconds in parallel with air and soil temperatures. A detailed description of the measurement technique was given earlier [Rayment, Jarvis, 1997; Tatarinov et al., 2009; Molchanov et al., 2017]. Additionally, on July 29th, soil moisture was determined at a depth of 0-5 and 5-10 cm by gravimetric method.

To analyze the effect of environmental factors on CO₂ fluxes, measured data obtained at the clear-cut by the eddy covariance method were used [Mamkin et al., 2019a]. Additional environmental parameter, seasonal water balance deficit (WD), defined as the difference accumulated from the beginning of the year between precipitation and potential evapotranspiration, was calculated using meteorological data from the eddy covariance station in a spruce forest located 8 km from the clear-cut [Kurbatova et al. 2008; Mamkin et al. 2019a]. Precipitation data was taken from the weather station «Lesnoy Zapovednik» (5 km from the study site). The potential evapotranspiration was calculated using Priestley-Taylor equation [Priestley, Taylor, 1971]. To compare the level of the soil respiration measured by the chamber method with the ecosystem respiration measured by the eddy covariance at the same site, soil respiration was upscaled to the clear-cut area using the proportion of meadow (26%) and undergrowth sites (74%) in the total area.

Data analysis

The analysis of the effect of vegetation on CO₂ fluxes was performed using one-way ANOVA and repeated measures ANOVA. In particular, in 2018, when the soil fluxes were measured in parallel in grassland and undergrowth area, we conducted repeated measures ANOVA (taking each day of measurement as one repetition) to detect the effects of vegetation type and time. The dependence of fluxes on environmental variables was performed by means of linear and nonlinear regression. The data processing was performed using Statistica 10 (StatSoft Inc., USA) and Matlab R2023a (MathWorks, Inc., USA) software.

RESULTS AND DISCUSSION

Weather conditions during the observation period

Annual precipitation in 2016 and 2017 (864 and 956 mm, respectively) was higher than in 2018 (560 mm) and then its long-term average (760 mm) value. There was no climatic WD during the measurement period in 2017. In 2016, WD was observed since the end of June, reaching -91 mm by the end of the measurement period (mid-August). In 2018, WD was significant during the entire measurement period ranging from -126 mm in early June to -270 mm at the end of August. In 2016, the average monthly temperatures in June–August were 3–4°C above the long-term average. In 2017, in August the air temperature was 3°C above the average, and in June and July, as well as throughout the summer of 2018, temperatures approximately matched the long-term average.

Spatial and temporal variability of soil CO₂ fluxes

Chamber measurements revealed pronounced interannual and spatial variability in soil CO₂ exchange within the clear-cut area. In the meadow site, midday Rch progressively increased from year to year: average values rose from $7.1 \pm 3.0 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in 2016 to $10.2 \pm 3.3 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in 2017 and $12.9 \pm 3.4 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in 2018—representing an overall increase of about 80% over the three-year period. This consistent rise in Rch suggests an intensification of belowground biological activity as vegetation recovered after clear-cutting.

In the undergrowth (aspen) site, Rch in 2018 averaged $9.8 \pm 3.1 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, slightly lower than that of the meadow, but still substantial. Median values in both sites support this pattern, with the meadow site showing higher respiration overall.

GPPch in the meadow was also higher in 2018 ($-20.3 \pm 7.9 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) than in 2017 ($-14.7 \pm 5.1 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), showing a ~38% increase, consistent with greater canopy development. The aspen site in 2018 exhibited a GPPch comparable to that of the meadow in 2017, at $-15.0 \pm 7.3 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, indicating notable productivity despite younger vegetation.

NEEch also shifted accordingly. The meadow site displayed stronger carbon uptake in 2018 ($-7.4 \pm 8.5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) than in 2017 ($-4.6 \pm 5.7 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), reflecting the combined effects of increasing respiration and photosynthesis. In the aspen site in 2018, the NEEch averaged $-5.2 \pm 5.3 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, indicating similar levels of net CO₂ sink activity.

Minimum values of NEEch, i.e., the highest net CO₂ uptake, were typically observed in June, coinciding with peak vegetative growth and moderate temperatures. The spatial variability of Rch and GPPch across measuring points ranged considerably, with coefficients of variation from 9–28% for Rch and 4–63% for GPPch, indicating heterogeneity both within and between vegetation types with mean values for the whole period of observations 22% and 32%, respectively.

Table 2. Statistics of the clear-cut soil with vegetation CO₂ exchange in 2016–2018

Year	Vegetation	Variable	Mean	N	St.dev.	Minimum	Maximum	Median
2016	meadow	Rch	7.1	40	3.0	3.0	16.0	6.9
2017	meadow	Rch	10.2	50	3.3	4.0	19.2	9.8
2018	meadow	Rch	12.9	18	3.4	7.9	23.4	12.4
2018	aspens	Rch	9.8	18	3.1	6.1	15.6	8.8
2017	meadow	NEEch	-4.6	47	5.7	-18.5	5.8	-4.3
2018	meadow	NEEch	-7.4	18	8.5	-27.3	4.7	-6.9
2018	aspens	NEEch	-5.2	18	5.3	-13.8	4.9	-6.0
2017	meadow	GPPch	-14.7	47	5.1	-26.9	-2.3	-13.7
2018	meadow	GPPch	-20.3	18	7.9	-38.1	-9.2	-18.4
2018	aspens	GPPch	-15.0	18	7.3	-29.2	-2.4	-15.3

Chamber-based soil respiration values, scaled to represent the entire clear-cut area, showed moderate to strong correlation with total ecosystem respiration (TER) measured by the eddy covariance system during midday hours (10:30–14:30) on corresponding days (Fig. 2). The explained variance was considerable ($R^2 = 0.52$), suggesting that soil respiration remained a key component of overall CO_2 flux.

However, this relationship varied by year. In 2016, chamber-based estimates of daily Rch were on average 20% lower than TER, while in 2017, they were 1.7 times higher, and in 2018, 14% lower again. These shifts suggest year-specific differences in the relative contributions of autotrophic and heterotrophic respiration components.

Despite a general correspondence between Rch and TER, the regression slopes and statistical significance weakened in 2017 and 2018. This decline likely reflects changing ecosystem structure: as vegetation cover and undergrowth biomass increased, the share of soil-derived CO_2 in total respiration declined, while contributions from plant and woody debris respiration rose. This is consistent with the observed flattening of diurnal TER dynamics and relatively stable TER amplitudes across years, even as soil activity varied.

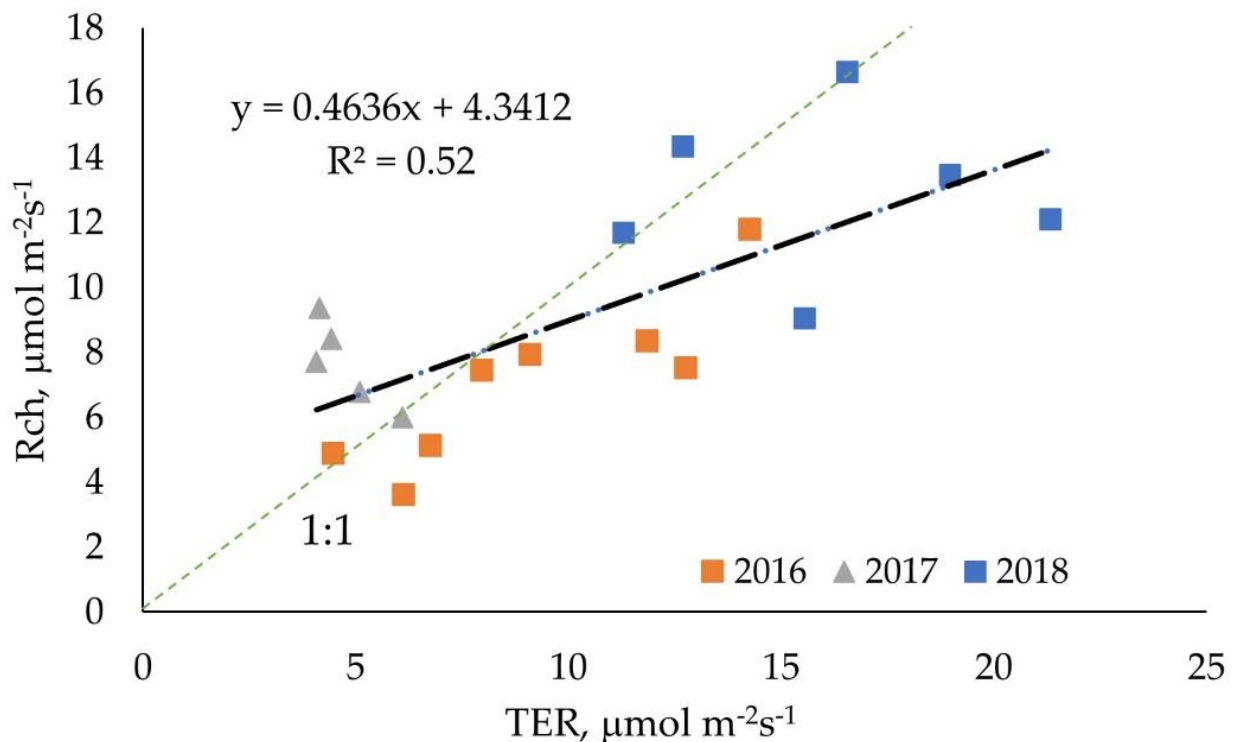


Fig. 2. Relationship between chamber-measured and upscaled respiration of soil with ground vegetation (Rch) and total ecosystem respiration (TER) across study years. The black dashed line shows the overall regression, while the green line is the 1:1 reference. Regression statistics: $F(1,17) = 14.836$, $p < 0.00128$, Std. Error = $2.33 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$.

In the summer of 2018, midday chamber measurements revealed that both soil respiration (Rch) and gross primary production (GPPch) were significantly higher in areas *without* undergrowth compared to areas *with* undergrowth. Specifically, Rch was on average about 32% higher and GPPch approximately 34% higher in open meadow areas (Student's t-test: $p = 0.008$ for Rch, $p = 0.045$ for GPPch; data met normality assumptions, Shapiro-Wilk $p > 0.05$) (Fig. 3). However, a repeated measures ANOVA, which accounts for temporal variation, found that vegetation type had no statistically significant effect on either Rch ($p = 0.29$) or GPPch ($p = 0.24$), while the effect of time on GPPch was significant ($p = 0.03$), suggesting that seasonal dynamics played a stronger role than vegetation type alone.

Despite the differences in Rch and GPPch, net ecosystem exchange (NEEch) did not differ significantly between the two vegetation types (t-test: $p = 0.352$; repeated measures ANOVA: $p = 0.1$). Both areas functioned as CO_2 sinks, with slightly stronger uptake in the meadow plots. The average NEEch in

areas without undergrowth was $-7.4 \pm 8.5 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, compared to $-5.2 \pm 5.3 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in undergrowth areas.

The different results of t-test and repeated measures ANOVA show that although generally the magnitudes of CO_2 fluxes of soil with herbaceous layer in the meadow and undergrowth areas were similar, their seasonal dynamics differed. In particular, the meadow exhibited a peak in GPPch in mid-June, whereas in the undergrowth, the peak occurred three weeks later. This phenological lag may reflect differences in light availability or species composition. By late August, herbaceous biomass was also greater in the open plots ($447 \text{ g} \cdot \text{m}^{-2}$) than in the undergrowth ($374 \text{ g} \cdot \text{m}^{-2}$), further supporting the observed differences in carbon fluxes and productivity.

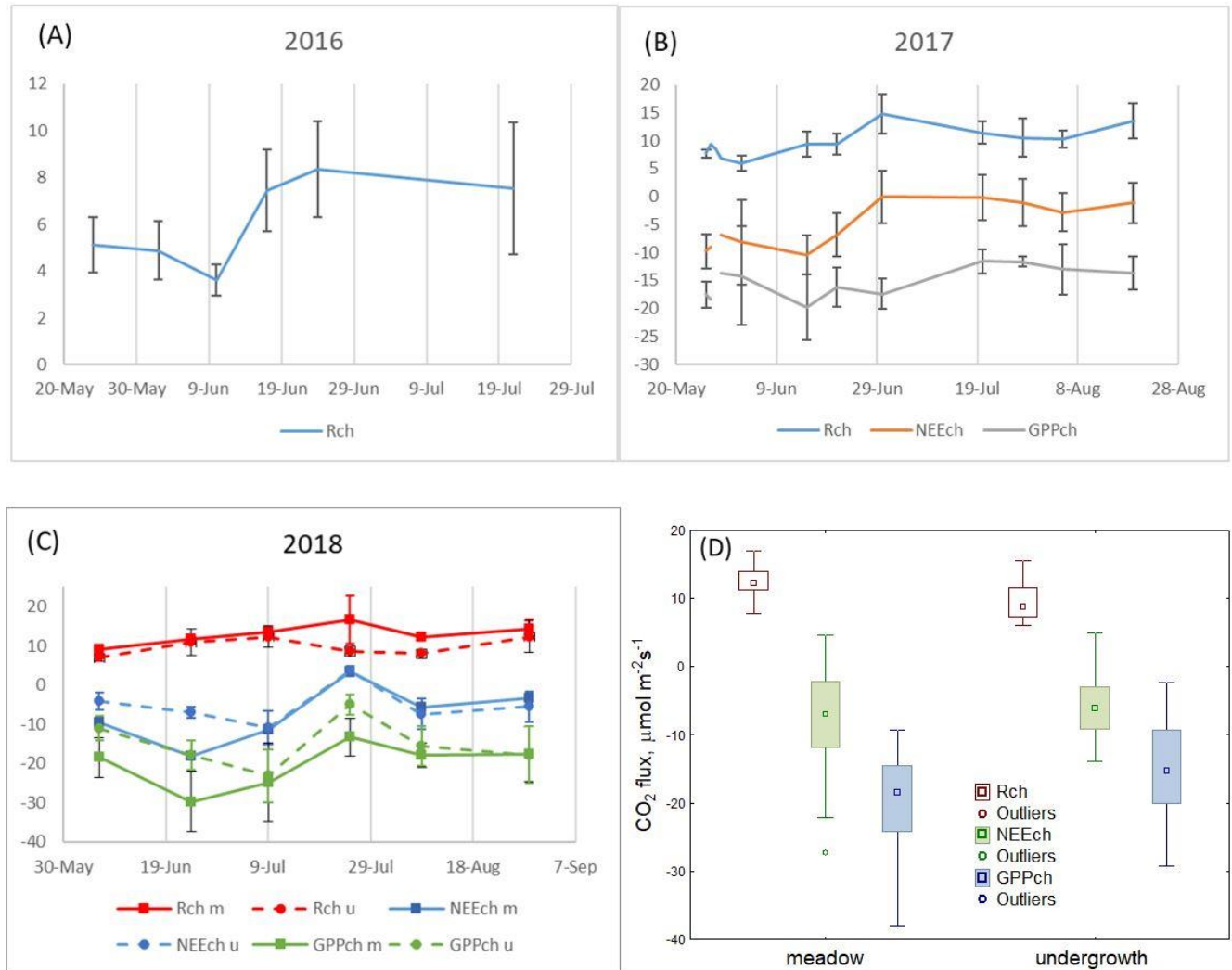


Fig. 3. (A-C) Seasonal dynamics of CO_2 fluxes (gross primary production - GPPch, respiration Rch and balance NEEch) at the clear-cut in different years averaged among measuring points in the same vegetation type ((A-B) only meadow) with standard deviations as error bars. Indices m and u at (C) correspond to meadow and undergrowth, respectively. (D) Median values of CO_2 fluxes in the meadow and undergrowth sites according to the measurements by the chamber method on the clear-cut plots at noontime in the summer months of 2018. Boxes and whiskers show quartiles and non-outlier ranges, respectively.

Comparative measurements of respiration of soil without vegetation (Rchs) at various undergrowth plots and in the surrounding forest, conducted at the end of July 2017, showed significant variability in CO_2 emissions from the soil surface depending on the dominant vegetation type. Thus, in the forest near the aspen trunk, the CO_2 emission from the soil surface was 7.4 ± 3.3 , and between the tree trunks $8.8 \pm 1.9 \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$ (Table 3). Higher Rchs between trees than near tree could be explained by higher presence of ground vegetation around the chamber between trees. In the dry pine forest in Israel with minimum ground vegetation the situation was the opposite: Rchs near tree trunk was two times higher than between trees [Qubaja et al., 2020]. At the clear-cut, the CO_2 emission was the lowest under the *S. sylvaticus* ($9.0 \pm 3.0 \mu\text{mol}$

$\times \text{m}^{-2} \times \text{s}^{-1}$ for the whole period) and the highest under the aspen undergrowth ($11.7 \pm 4.5 \text{ } \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$). Over-all means of Rchs in the clear-cut and in the forest were 10.7 and $8.3 \text{ } \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$, respectively and differed significantly ($p = 0.001$). It should be noted that the soil moisture in the forest was about 10% lower than in the clear-cut, which is associated with lower transpiration in the clear-cut and, consequently, its waterlogging.

In most days it was no clear diurnal trends of Rchs within the time of measurements (~9-19 h), only in the hot clear day of July 31 Rchs in all sample points increased during the whole day. Midday (10-15 h) variance of Rchs for different points and days ranged from 6.1% to 33.4% with median of 12.4%. T-test showed significant ($p < 0.05$) differences in Rch between all sampling points in the clear-cut, as well as between points near tree and between trees in the forest.

Table 3. Intensity of CO₂ emission from the soil surface under the birch-aspen stand and in the clear-cut in the daytime in 2017

Date	Site	Average air temperature, °C	Average CO ₂ emission, $\mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$ (st. deviation)	Soil moisture, %	
				0-5 cm	5-10 cm
28-30.07, 01.08	Forest, near the trunk	23.4	7.4 (3.2)	22.7	20.2
28.07-01.08	Forest, between the trunks	24.6	8.8 (1.9)	22.5	22.9
30.07	Clear-cut, <i>S. sylvaticus</i>	17.2	7.0 (1.5)		
31.07	Clear-cut, <i>S. sylvaticus</i>	27.8	10.0 (3.5)		
28.07-01.08	Clear-cut, <i>S. virgaurea</i>	25.0	10.8 (2.3)	39.0	30.4
28-30.07	Clear-cut, aspen undergrowth	20.9	9.3 (3.4)	34.5	30.7
31.07-01.08	Clear-cut, aspen undergrowth	29.7	14.4 (4.1)		

The obtained values of soil CO₂ emission differ from the results in other types of forests, obtained by the authors earlier. For example, in a spruce forest in the Moscow region [Molchanov et al., 2017], where observations were carried out for two years, the soil respiration in July-August reached $8 \text{ } \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$, whereas in the spruce forest it was much lower, reaching 3 and $1.5 \text{ } \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$ near the spruce trunk and between its trunks, respectively. Apparently, such a difference in the intensity of CO₂ emission is associated with higher root density and consequently higher root respiration close to the trunk relatively to the inter-crown space, as well as with the weather conditions of the measurement periods. In the spruce forest of the Tver region in July the emission of CO₂ from the soil surface under soil temperature of 17°C was slightly higher than in the previous case – $5 \text{ } \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$, which is close to the estimates obtained from the soil surface in a forest with *Pinus sylvestris* L. [Molchanov, Tatarinov, 2017]. Thus, under the canopy of a deciduous birch-aspen stand, and at the clear-cut, the intensity of CO₂ emission from the soil surface was significantly higher than in coniferous stands. The estimates obtained corresponded to the estimates of CO₂ emissions from the soil surface in *Quercus robur* L. stands of the forest-steppe zone [Molchanov, 2020]. In addition, the growth rate of birch and aspen is higher than that of spruce [Shvidenko et al., 2008], which may affect the intensity of root respiration. Generally, different authors report rather high values of the respiration of sod-podzolic soils in Central Russia. In particular, transect measurements in CSFBR in early August showed mean values of soil respiration in different ecosystem types from 7.53 to $13.79 \text{ g C} \times \text{m}^{-2} \times \text{d}^{-1}$, i.e., 7.26 to $13.30 \text{ } \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$ [Šantrůčková et al., 2010]. Measurements of soil respiration of pine forests in Karelia at the different stages of afforestation of arable land showed mean values in July from $5.3 \text{ } \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$ in 20-years-old forest to $10.1 \text{ } \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$ in 110-years-old forest [Medvedeva et al., 2022]. Phillips et al. [2013] showed mid-summer soil respiration in a temperate deciduous forest in USA around $7-8 \text{ } \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$ with individual peaks up to $25-30 \text{ } \mu\text{mol} \times \text{m}^{-2} \times \text{s}^{-1}$.

Dependence of soil respiration on environmental factors

The measurements results showed strong, and negative, dependence of soil respiration in the meadow site on the soil moisture at all levels ($R = -0.57 \div -0.82$ for various plots and depths of soil moisture measurement, all values are significant at 5% level) and on WD ($R = -0.68 \div -0.85$ for various plots) (Table 4). For the undergrowth plots, the dependence of soil respiration on its humidity was not observed for all plots and was not reliable. Obviously, this is due to waterlogging of the soil, which is stronger under herbaceous plants than under undergrowth. The correlation of soil respiration in the undergrowth site with incoming solar radiation was quite large (-0.75), but it was not significant due to the small number of measurements in this site. The correlation of the ground cover photosynthesis (GPPch) with soil moisture was practically absent. Its correlation with incoming solar radiation varied greatly from plot to plot (from 0.19 to 0.97), being significant for half of the plots (two in the meadow site and one in the undergrowth site), which is obviously related to the level of shading – at more shaded plots this dependence was lower, because solar radiation there changed less than in more open places. The correlation of photosynthesis averaged between the plots with incoming radiation was relatively high (0.47 for areas with grassy vegetation and 0.73 under aspens) but was not significant at the 5% level. A positive dependence of respiration on temperature was observed both in the meadow and in the undergrowth site but was not significant. For photosynthesis, the temperature dependence, and negative, was observed only in the undergrowth site.

Table 4. Correlation coefficients between the components of the CO_2 fluxes from the soil surface and external factors measured simultaneously at the clear-cut by eddy covariance system

	Rch		NEEch		GPPch	
	grass	undergrowth	grass	undergrowth	grass	undergrowth
P_{24h}	0.11	0.44	0.33	0.51	0.23	0.04
T_a	0.42	0.51	0.38	-0.44	0.14	-0.54
P_{day}	0.00	0.15	-0.20	0.02	-0.05	-0.07
VPD	0.14	-0.32	0.46	-0.15	0.41	0.09
SW_{in}	-0.05	-0.75	0.46	0.52	0.47	0.73
R_n	0.08	-0.62	0.56	0.55	0.48	0.67
SWC	-0.66*	-0.25	-0.11	0.16	0.14	0.21
T_{soil}	0.28	0.23	0.40	-0.32	-0.20	0.39
NEE	-0.59	0.16	0.56	0.24	0.77	0.13
Re	0.72	-0.34	0.35	-0.16	0.01	0.00
GPP	0.80	-0.43	0.11	-0.31	-0.25	-0.08
WD	-0.84*	-0.54	-0.30	0.29	0.10	0.42

Note: * - significant correlations at 5% level. P_{24h} и P_{day} – precipitation for 24 hours and for the time of measurements (10:30-14:30), respectively, T_a – the air temperature, SW_{in} and R_n – the incident solar radiation and the radiation balance, respectively, SWC – the soil moisture at a depth of 5 cm, averaged over 3 plots, NEE, Re and GPP were obtained using by eddy covariance measurements, WD (climatic water deficit) is the accumulated difference between precipitation and potential evapotranspiration.

CONCLUSION

This study aimed to assess the spatial and temporal variability of CO_2 fluxes in a recently clear-cut area and to quantify the contribution of soil respiration and photosynthesis by ground vegetation in comparison with an adjacent intact mixed forest. The results confirmed that CO_2 fluxes within the clear-cut are highly variable both across plant communities and throughout the growing season, and that logging significantly alters the carbon balance of forested ecosystems.

1. Spatial variability across plant communities within the clear-cut area was substantial. For instance, soil respiration (Rch) in midsummer 2018 was on average 32% higher in open meadow areas ($12.9 \pm 3.4 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) than in patches where tree undergrowth was present ($9.8 \pm 3.1 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). Similarly, gross primary production (GPPch) was about 34% higher in the meadow ($-20.3 \pm 7.8 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) compared to undergrowth areas ($-15.1 \pm 7.3 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). These

differences reflect the impact of vegetation structure on carbon cycling and underscore the need to consider this mosaic composition when scaling fluxes to the ecosystem level.

2. Seasonal (temporal) dynamics of CO₂ fluxes were also significant. R_{ch} increased progressively over the three study years, from $7.1 \pm 3.0 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in 2016 to $12.9 \pm 3.4 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in 2018, indicating intensified soil biological activity during post-logging succession. GPP_{ch} likewise increased by approximately 38% from 2017 to 2018, suggesting increasing photosynthetic capacity with regrowth. Peak GPP_{ch} occurred in mid-June in open meadow areas but was delayed by 2–3 weeks in undergrowth patches, revealing different phenological trajectories.
3. The partitioning between respiration and photosynthesis revealed that, on average, NEE_{ch} values were negative across all plots, indicating net CO₂ uptake during the day. However, meadow areas had stronger net sink activity ($-7.4 \pm 8.5 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) than undergrowth areas ($-5.2 \pm 5.3 \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$), driven by both higher respiration and higher photosynthesis. This emphasizes the complexity of CO₂ exchange, where high emissions can coexist with high uptake depending on the vegetation structure.
4. Comparison between the clear-cut area and the adjacent intact forest revealed that soil respiration in the clear-cut exceeded that of the control forest by 1.3 to 1.5 times on average, depending on year and vegetation type. Despite increasing uptake by ground vegetation over time, the clear-cut remained a stronger midday source of CO₂ to the atmosphere, primarily due to decomposition and absence of tree-level assimilation.

Overall, the results confirmed the expectations that logging leads to increased soil CO₂ emissions and that these emissions vary widely depending on vegetation type and season. While this variability might seem intuitive, our study quantified it explicitly, showing differences in fluxes of up to 1.5 times between areas within the same clear-cut and over 40% between years. Such findings are crucial for improving regional carbon budget models and for interpreting eddy covariance measurements in regenerating landscapes.

Importantly, the upscaled chamber-based estimates of NEE—when adjusted for spatial heterogeneity—aligned well with eddy covariance data, lending confidence to their representativeness. This further highlights the value of incorporating fine-scale spatial vegetation data into CO₂ flux assessments for disturbed or transitional forest systems.

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