Towards climate optimised riparian buffer zones in boreal forests

Investigation of clearcutting effects on soil temperature, soil moisture and greenhouse gas fluxes in riparian buffer zones with different widths

Alice Falk

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Abstract

Boreal forests have the potential to mitigate the increased concentrations of greenhouse gases (GHGs) in the atmosphere. However, forestry alters the soil biogeochemical processes which can cause an increase in GHG emissions from nearby water bodies, soil and vegetation. Soil biogeochemical processes related to GHG emissions are in general higher in the wet zones of soil and vegetation near freshwater bodies – riparian zones (RZs). Leaving the RZs during clearcutting as riparian buffer zones (RBZs) can prevent soil disturbances and hence prevent GHG emissions from nearby water bodies. However, whether the design of the RBZs matter in terms of minimising GHG emissions from the soil and vegetation is not sufficiently investigated. This study aimed to investigate how clearcutting in a boreal forest located in Vindeln municipality in Västerbotten, Sweden, affected the soil temperature, soil moisture and soil-atmosphere carbon dioxide (CO_2) and methane (CH_4) fluxes and whether the factors differed between a wide (15 meters) and a narrow (5 meters) RBZ. The study followed a Before/After-Control/Impact (BACI) approach and the measurements were performed in two RBZs in an impact site before and after clearcutting and in a control site without clearcutting between the measurement occasions. Tree-atmosphere CO_2 and CH_4 fluxes of the two tree species silver birch (*Betula pendula* Roth) and Norway spruce (*Picea abies* (L.) H. Karst.) were also compared between the two RBZs in the impact site after the clearcutting. The results showed significant higher soil temperature (1.3 ± 0.5 ºC) after clearcutting relative to before clearcutting, in the narrow buffer relative to the control site. The results showed also significant lower soil CH_4 uptake (0.0008 ± 0.00074 µmol m^{-2} s^{-1}) after clearcutting relative to before clearcutting, in the narrow buffer relative to the control site. No significant clearcutting effects on soil moisture or soil-atmosphere CO_2 fluxes were however shown. Both the silver birches and Norway spruces showed, in general, both CO_2 and CH_4 emissions. No significant differences in any of the factors soil temperature, soil moisture, soil-atmosphere CO_2 and CH_4 fluxes or tree-atmosphere CO_2 and CH_4 fluxes between the two RBZs were shown. Hence, according to the results of this study, the design of the RBZs, or more specifically the width, had no effect on CO_2 or CH_4 emissions from soil and vegetation in the RBZs. However, leaving stable RBZs that prevent an increase in soil temperature would, according to other similar studies, possibly reduce changes in soil biogeochemical processes related to GHG emissions from nearby water bodies, soil and vegetation and would therefore be recommended in boreal forests.

Keywords: forestry, biogeochemical hotspots, carbon dioxide, methane

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1. Introduction

Boreal forests play an important role in the global biogeochemical cycles (Pan et al. 2011). Boreal forests store large amounts of carbon (C) in both soil and vegetation and play thus an important role in the C turnover (Hazlett et al. 2005). The C turnover is central when investigating greenhouse gas (GHG) fluxes in forest ecosystems (Dalal et al. 2013). Increased concentrations of carbon dioxide (CO_2) and methane (CH_4) in the atmosphere is a major concern worldwide since it enhances the greenhouse effect which leads to climate changes. Climate changes leads to changed weather patterns with, for example, more frequent and intense drought, wildfires, storms and floods as a result. Different types of human activities are the main reasons to the increased concentrations of CO_2 and CH_4 in the atmosphere and land use, such as forestry, is an important contributing factor (Faranda et al. 2020). Forestry alters the biogeochemical cycles (e.g., Bowden & Bormann 1986; Burrows et al. 2012; Boggs et al. 2015) but the effect of forestry on soil and vegetation in terms of GHG fluxes is poorly understood. Therefore, it is important to understand the biogeochemical processes related to GHG fluxes in forest ecosystems.

In forest ecosystems, CO_2 is mainly produced via aerobic respiration under aerobic conditions and CH_4 is mainly produced in the process of anaerobic methanogenesis under anaerobic conditions. CH_4 could also be consumed by methanotrophic microorganisms under aerobic conditions (Hedin et al. 1998). Aerobic respiration and anaerobic methanogenesis are influenced by electron donor availability and the dynamics of electron acceptors. In addition, the reactions are influenced by other factors, such as soil temperature and soil moisture (Hedin et al. 1998; Luo & Zhou 2006; Vidon et al. 2010). Soil temperature and soil moisture are well-established drivers of soil respiration, often defined as soil CO_2 emission (e.g., Rayment & Jarvis 2000; Lou & Zhou 2006; Dunn et al. 2007). Soil temperature controls soil CO_2 emission by controlling, for example, cellular enzyme activity, microbial activity and root growth. Soil CO_2 emission typically increases exponentially with increasing soil temperature, reaches a maximum and thereafter declines. Soil moisture controls soil CO_2 emission by controlling cellular enzyme activity and microbial activity (Lou & Zhou 2006). Soil CO_2 emission is typically low under dry conditions, reaches a maximum at intermediate moisture conditions and thereafter decreases under wet conditions where anaerobic microbial activity depress aerobic microbial activity (Lou & Zhou 2006). Furthermore, soil temperature and soil moisture are contributing drivers of microbial activities related to soil CH_4 emission (e.g., Ullah et al. 2009; Silverthorn & Richardson 2021). For example, higher soil temperatures and higher soil moisture conditions generally promote methanogenesis and thereby soil CH_4 emission (Kähkönen et al. 2002; Ullah et al. 2009).

Soil temperature and soil moisture and other factors such as soil pH, organic C and nitrogen (N) availability that influence production and consumption of GHGs in forest ecosystems are affected by forestry (e.g., Huttunen et al. 2003; Hotta et al. 2010; Mojeremane et al. 2012; Kulmala et al. 2014). For example, clearcutting leads to an increased amount of litter (foliage etc.) on the site immediately after clearcutting but to a decreased amount of litter on the site over time when the new forest is young (Korkiakoski et al. 2019). Clearcutting also leads to an initial reduction of mycorrhiza, bacteria and root exudates in the soil (Högberg et al. 2001; Pumpanen et al. 2008). Hence, clearcutting affects the availability of organic as well as inorganic materials in the soil and soil pH (Kalbitz et al. 2004; Ussiri & Johnson 2007). Furthermore, removal of forest canopy leads to higher insolation to the soil which increases the soil temperature during the snow-free period (Hashimoto & Suzuki 2004). Removal of forest canopy also leads to lower interception and evapotranspiration which thus leads to an increased groundwater level and hence higher soil moisture deeper into the soil (Chen et al. 1993; Hotta et al. 2010). Moreover, in Sweden, clearcutting is in general performed with forestry machines, most commonly harvesters and forwarders (Krekula et al. 2018), which can increase the transport of organic and inorganic materials to nearby water bodies (Nieminen 2003) and hence promote GHG fluxes in the water bodies (Schade et al. 2016).

Once produced, the GHGs in forest ecosystems can move as dissolved gases in water bodies and in the soil water and soil atmosphere. In addition, the GHGs can be emitted to the atmosphere via transport through soil and vegetation (e.g., Bowden & Bormann 1986; Högberg & Read 2006; Burgin & Groffman 2012; Machacova et al. 2016; Maier et al. 2018; Schindler et al. 2020; Barba et al. 2021; Silverthorn & Richardson 2021). For example, several herbaceous species and tree species have been shown to emit both CO_2 and CH_4 (Machacova et al. 2016; Maier et al. 2018; Schindler et al. 2020; Barba et al. 2021). For example, Scots pine trees (*Pinus sylvestris* L.) studied in a mature forest in Finland emitted CH_4 from the shoots and stems (Machacova et al. 2016). In addition, European beech trees (*Fagus sylvatica* L.) studied in upland mature forests in Germany and the Czech Republic emitted CO_2 and CH_4 from the stems (Maier et al. 2018), bitternut hickory trees (*Carya cordiformis* (Wangenh.) C. Koch) studied in an upland forest in eastern United States emitted CO_2 and CH_4 from the stems (Barba et al. 2021) and grey alder trees (*Alnus incana* L.) studied in a wetland forest in eastern Estonia emitted

CH_4 from the stems (Schindler et al. 2020). The studies indicate that GHGs can be emitted from both deciduous and coniferous tree species in both upland areas and wetland areas and from both shoots and stems. However, the GHG emissions from stems are poorly understood (Pangala et al. 2013; Barba et al. 2021). The GHG emissions from stems may result from plant physiological, photochemical or microbial gas production within the stem (Pangala et al. 2013; Barba et al. 2021; Salomón et al. 2021). For example, studies have shown high concentrations of CO_2 and CH_4 in the heartwood in trees. However, the high concentrations of CO_2 and CH_4 in the heartwood does not necessarily correlate with stem CO_2 and CH_4 fluxes (Barba et al. 2021). Hence, the emissions may also result from microbial gas production in the soil followed by gas transport via roots into above-ground plant tissues (Mukhin & Voronin 2011; Covey et al. 2012; Barba et al. 2021).

Microbial gas production in the soil is, relative to upland areas, generally higher in wetland areas, i.e., riparian zones (RZs) (e.g., McClain et al. 2003; Gundersen et al. 2010; Vidon et al. 2010; Tiwari et al. 2016; Silverthorn & Richardson 2021). RZs are zones of soil and vegetation adjacent to freshwater bodies such as lakes, ponds, ephemeral ponds, rivers, streams and ephemeral streams. RZs are characterized by distinctive soil, hydrological and biotic conditions with unique properties. The unique properties, such as high organic matter content in the soil, high N concentration in the soil and soil water, shallow water table and strong spatial and temporal variability in hydrological and biogeochemical conditions, makes the RZs as zones with disproportionally high reaction rates relative to the surroundings. Hence, RZs could be defined as biogeochemical hotspots (McClain et al. 2003) which is relevant when investigating GHG fluxes in forest ecosystems. Except providing a wide range of riparian functions, RZs also provide many important ecosystems services. For example, RZs receive water and nutrients from upslope areas and are important habitats for many species (Gundersen et al. 2010; Kuglerová et al. 2014). However, the riparian functions and ecosystem services provided by RZs in terms of GHG fluxes are rarely discussed.

The riparian functions and ecosystem services provided by RZs could be affected by clearcutting (e.g., Palviainen et al. 2013; Silverthorn & Richardson 2021) which in turn could affect the GHG concentrations and fluxes in the RZs and in nearby water bodies (e.g., Klaus et al. 2018; Silverthorn & Richardson 2021). For example, a study in three-paired catchments in eastern Finland showed that clearcutting and soil scarification caused an increase in annual runoff and export of several organic and inorganic compounds, especially when the clearcutting area exceeded 30% of the catchment area (Palviainen et al. 2013). Furthermore, a study in four catchments in northern Sweden showed significant increased concentrations of CO_2 and CH_4 in hillslope groundwater within three years after clearcutting and soil scarification (Klaus et al. 2018). However, the study did not show any significant changes in GHG emissions from the inland waters that were measured.

The two impact areas in the study covered 18% and 34% of the total catchment area, respectively. The non-significant changes in GHG emissions from the inland waters may indicate that the GHGs leached from the clearcutting areas were buffered in the RZs. Hence, the results in the study indicate that leaving the RZs as riparian buffer zones (RBZs) during clearcutting may prevent GHG emissions from nearby water bodies (Klaus et al. 2018). It has been proposed that the spatial arrangement and the extent of RBZs along streams and rivers impose a control over, at least, stream water quantity and quality (Kuglerová et al. 2014) and that RBZs can be effective in protecting several ecosystem functions (e.g., Silverthorn & Richardson 2021). However, the pathways of GHGs in the RBZs in response to upslope clearcutting are relatively unknown. In addition, the role of the RBZs and the design of them, i.e., the width, in terms of GHG fluxes, is not sufficiently investigated (e.g., Silverthorn & Richardson 2021).

To date, there are no strict regulations in Swedish forestry regarding RBZs, only some general advice from the Swedish Forest Agency regarding general environmental considerations during forestry operations. Most production forests in Sweden are, however, affiliated to forest certifications, e.g., Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC). FSC and PEFC requires protecting RBZs along water bodies but the required buffer width is not specified (Chellaiah & Kuglerová 2021). The most common practice is to define a distance from the water body (often a stream) and, during clearcutting, leave fixed widths of RBZs along the stream, most commonly less than 5 meters wide with one or two rows of trees on each side of the stream (Kuglerová et al. 2020). However, the design of the RBZs is in general based on the forest practitioner's visual evaluation of local conditions before or during the clearcutting (Kuglerová et al. 2014). Hence, many streams are left without any RBZs at all (Chellaiah & Kuglerová 2021). Knowledge regarding the role of RBZs and whether the design of them matter in terms of GHG fluxes could therefore contribute to an improved forest policy in Sweden and contribute to developing climate optimised RBZs in boreal forests in future.

1.1 Aim

The aim with this study was to investigate the effects of upslope clearcutting on soil temperature, soil moisture and GHG fluxes in RBZs in a boreal forest and investigate whether the design of RBZs affected the different factors. The key questions explored in this study were:

- How soil temperature in RBZs is affected by clearcutting and whether the soil temperature differs between a wide and a narrow RBZ.

- How soil moisture in RBZs is affected by clearcutting and whether the soil moisture differs between a wide and a narrow RBZ.

- How soil-atmosphere CO_2 and CH_4 fluxes in RBZs are affected by clearcutting and whether the fluxes differ between a wide and a narrow RBZ.

- Whether tree-atmosphere CO_2 and CH_4 fluxes in RBZs differ between a wide and a narrow RBZs and between the tree species silver birch (*Betula pendula* Roth) and Norway spruce (*Picea abies* (L.) H. Karst.).

2. Materials and Methods

2.1 Experimental setup and site description

This study followed a Before/After-Control/Impact (BACI) approach, which is a common approach to evaluate impacts of natural and anthropogenic perturbations on ecosystems. The principle of the BACI approach is to compare the changes of a factor of interest between a control site without perturbation and an impact site with perturbation, before and after. The advantage of the BACI approach is the control site without perturbation between the before period and after period, which makes the BACI approach less prone to severe design bias, in comparison to, for example, a Before/After (BA) approach or an After (A) approach (Conner et al. 2016; Christie et al. 2020).

This study included two forested watersheds located in Vindeln municipality in Västerbotten, Sweden (Figure 1). The control site was located near Svartberget and the impact site was located near Trollberget. In the control site, the forest stayed intact throughout the experiment period. In the impact site, the forest was clearcut by the land owner (Holmen Skog) in February 2021. During the clearcutting, two stretches of RBZs with a length of 100 meters each were left on both sides along the stream, one wide RBZ and one narrow RBZ with a width of 15 meters and 5 meters, respectively. The wide RBZ was downstream the narrow RBZ.

The forest in the control site was dominated by Scots pine, Norway spruce and silver birch and had an average age of 80 years (Laudon et al. 2013) and an average height of 22 meters. The forest in the impact site was dominated by Norway spruce and silver birch and had an average age of 100 years and an average height of 23 meters. The ground vegetation of both sites was dominated by mosses (e.g., *Polytrichum* spp. Hedw. and *Sphagnum* spp. L.) and dwarf shrubs (e.g., *Vaccinium myrtillus* L. and *Vaccinium vitis-idaea* L.). The soil type of both sites was podsol developed on glacial till. In the impact site, there was a mire of about one hectare upstream the narrow buffer.

The annual average air temperature in Vindeln municipality was 4.7 ºC in 2020 (SMHI 2022a) and 2.7 ºC in 2021 (SMHI 2022b). The annual average precipitation was 771 mm in 2020 (SMHI 2022c) and 781 mm in 2021 (SMHI 2022d). The global radiation in Umeå municipality (the nearest solar radiation station) was 971.9 kWh m^{-2} in 2020 (SMHI 2022c) and 945.1 kWh m^{-2} in 2021 (SMHI 2022d).

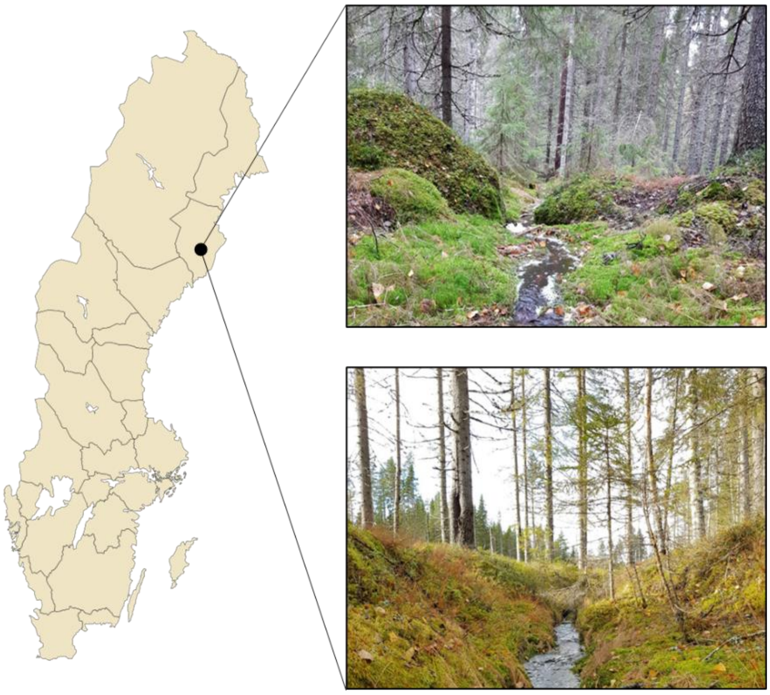

Figure 1. Map of Sweden. The black dot shows the location of Vindeln municipality where the control site and impact site were located. The upper picture shows the stream in the control site and the lower picture shows the stream in the impact site in 2021 (CC BY-SA 2.5; Alice Falk).

2.2 Sampling and measurements

Soil temperature, soil moisture and soil-atmosphere CO_2 and CH_4 fluxes were measured within 2-3 days in the control site and impact site in May, June, August, September and October 2020 and 2021. The measurements varied between morning and afternoon (09.00-17.00). In spring 2020, 3 and 12 square soil chamber collars of 45*45 cm in stainless steel were placed along the stream in the control site and the impact site, respectively. In the impact site, 6 soil chamber collars were placed in the wide buffer and 6 soil chamber collars were placed in the narrow buffer along the stream. The soil chamber collars were inserted 10 cm into the soil to prevent gas leakage during the gas measurements. The soil temperature and soil moisture were measured at 5 cm soil depth, 10 cm from every side of the soil chamber collar. The soil temperature was manually measured with a Tsuruga Electric Corporation Digital Thermometer Model 3527A (Tsuruga Electric Corporation, Osaka, Japan) and the soil moisture was manually measured with a ML3 ThetaProbe Soil Moisture Sensor with a HH2 Soil Moisture Meter (Delta-T Devices Ltd, Cambridge, United

Kingdom). The measurements of the soil-atmosphere CO_2 and CH_4 fluxes were performed by placing a gastight soil chamber of 40.5 L on the soil chamber collar which was connected with a gas tube to a Los Gatos Research's Ultra-Portable Greenhouse Gas Analyzer (LGR's GGA) (Los Gatos Research, San Jose CA, United States). The soil-atmosphere CO_2 and CH_4 fluxes were measured at a rate of 2 readings per second (0.5 Hz) for about 5 minutes per chamber. To prevent radiation absorption and photosynthesis during the measurement, the chamber was covered with an opaque quilt (Figure 2). A similar measurement method of soil-atmosphere GHG fluxes is described in e.g., Korkiakoski et al. (2019).

Tree-atmosphere CO_2 and CH_4 fluxes were measured during one day in the impact site in June, August, September and October 2021. 28 trees (14 silver birches and 14 Norway spruces) in total were measured, 14 trees in the wide RBZ and 14 trees in the narrow RBZ. The measurements varied between morning and afternoon (09.00-17.00). In spring 2021, 2 stem chamber collars made from rectangular plastic boxes of 0.73 L with removed bottoms were glued with silicone at every tree stem at about 30 cm above ground. To prevent gas leakage during the gas measurements, the bark under the stem chamber collar was first flattened superficially (without damaging living tissue) and a 2 cm thick neoprene sealing was then placed between the bark and the stem chamber collar. The measurements started two weeks after the stem chamber collar installation when the silicone had dried. The measurements were performed by placing lids on the two stem chamber collars on every tree connected with a gas tube to each other and to a LGR's GGA (Figure 2). The tree-atmosphere CO_2 and CH_4 fluxes were measured at a rate of 2 readings per second (0.5 Hz) for about 10 minutes per tree. A similar measurement method of tree-atmosphere GHG fluxes is described in e.g., Machacova et al. (2017).

Figure 2. Measurements of soil-atmosphere CO_2 and CH_4 fluxes (left picture) and tree-atmosphere CO_2 and CH_4 fluxes (right picture) in the impact site (Alice Falk).

2.3 Calculations and statistics

A LGR's GGA measures the partial pressure of CO_2 and CH_4 simultaneously. Hence, to obtain the gas flux, the gas flux rates (*F*) were calculated from the recorded gas partial pressure with the linear equation;

$$F = vol/(R \cdot Ta \cdot area) \cdot dG/d \cdot p$$

where *vol* is the volume of the chamber (L), *R* is the universal gas constant (l atm K^{-1} mol^{-1}), *Ta* is the ambient temperature (*K*), *area* is the area of chamber base (m^2), *dG/dt* is the rate of the measured gas partial pressure change over time *t* (ppm s^{-1}) and *p* is the specific air pressure (atm) (Zhao 2019). In addition, the gas flux rates were corrected with a factor for the gas tube volume (i.e., the volume (L) of the gas tube connected to the LGR's GGA) and a factor for the specific chamber volume for the soil-atmosphere fluxes (i.e., the additional volume (L) between the base of the chamber and the soil surface within the soil chamber collar).

Both the soil-atmosphere CO_2 and CH_4 fluxes and the tree-atmosphere CO_2 and CH_4 fluxes were obtained using the R-package FluxCalR (v0.2.2; Zhao 2019). The gas partial pressures recorded from the raw datasets provided by the LGR's GGA were re-calculated to gas fluxes based on time series. The time series that corresponded to the start and stop of all the gas partial pressure measurements in field were defined manually. FluxCalR fitted all possible linear regressions to the time series within a pre-defined window and a tolerance of ± 1 minute, and selected the regression that yielded the greatest determination coefficient (R^2), in general between 0.7 and 1 (Figure 3). The window size for the individually tested regressions was set to 3 minutes for the soil-atmosphere fluxes and 7 minutes for the tree-atmosphere fluxes. The gas fluxes were generated in µmol m^{-2} s^{-1}.

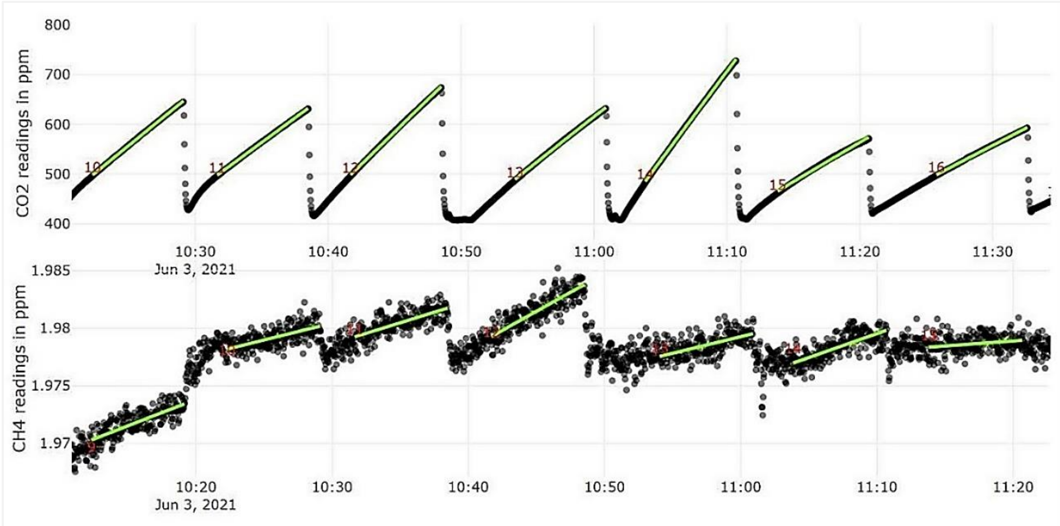

Figure 3. Example of a window of tree-atmosphere CO_2 and CH_4 partial pressure measurements seen in the R-package FluxCalR. The green lines show the best fitting linear regressions for each measurement.

Clearcutting effects of soil temperature, soil moisture and soil-atmosphere CO_2 and CH_4 fluxes were assessed by following an adjusted paired BACI approach of Stewart-Oaten et al. (1986) described in Klaus et al. (2018). The “before period” was set to 2020 and the “after period” was set to 2021. The clearcutting effects of soil temperature, soil moisture and soil-atmosphere CO_2 and CH_4 fluxes were analysed in terms of effect size (ES). ES was defined as the arithmetic mean change of the differences in soil temperature, soil moisture, soil-atmosphere CO_2 fluxes and soil-atmosphere CH_4 fluxes between 2020 and 2021, between the control site and impact site and between the wide buffer and narrow buffer in the impact site. The significance of ES was tested using a linear mixed-effects model (LME) which was analysed by means of the lme-function in the R-package nlme (v3.1-149; Pinheiro et al. 2020). The LME had “paired difference” (soil temperature, soil moisture, soil-atmosphere CO_2 fluxes, soil-atmosphere CH_4 fluxes) as dependent variable and “time” (before, after), “buffer width” (wide, narrow) and their interaction (“time*buffer width”) as fixed effects and “sampling site” as random effect on both the intercept and slope of the model. To account for variation among replicates, 1000 randomly sampled combinations of matching replicates of control and impact were compared. To validate the BACI analysis, the assumptions; “constancy of differences”, “no additivity” and “no autocorrelation” were checked as in Klaus et al. (2018). “Constancy of differences” was checked by testing on linear relationships between the differences between control and impact and sampling date in before period, “no additivity” was checked by testing on linear relationships between the sum and the differences between control and impact in before period (Tukey’s test of additivity) and “no autocorrelation” was checked by ensuring no systematic variation over time in the distribution of model residuals

(Durbin-Watson statistic). If autocorrelation was detected, it was accounted for in the LME by including an autocorrelation structure of order 1 as a function of time. To ensure normality and homoscedasticity of model residuals, the dependent variables were transformed when necessary (log or signsqrt). To assess the statistical and biogeochemical significance, P value of the LME and Cohen's *D* (defined as D = ES/2s, where s is the standard deviation of paired differences in the before period (Osenberg & Schmitt 1996)) were used. For the P value, alpha level 0.05 was used. For the Cohen's *D*, $D < 0.2$ = "SMALL", $0.2 \leq D < 0.8$ = "MEDIUM", $0.8 \leq D < 1.3$ = "LARGE", $D \geq 1.3$ = "VERY LARGE" were used, which is a verbal interpretation of the ES relative to background variability.

Tree-atmosphere CO_2 and CH_4 fluxes were assessed by two-way ANOVAs. The dependent variables "tree-atmosphere CO_2 fluxes" and "tree-atmosphere CH_4 fluxes" were analysed with the independent variables "tree species" (silver birch, Norway spruce) and "buffer width" (wide, narrow). The analysis accounted for replicates, i.e., repeated measurements of same trees. To validate the ANOVAs, normality and homoscedasticity of model residuals were ensured. None of the dependent variables needed any transformation. The analysis was made using the R-packages lme4 (v1.1-28; Bates et al. 1015) and lmerTest (v3.1-3; Kuznetsova et al. 2020). For the P value, alpha level 0.05 was used.

3. Results

3.1 Soil temperature

The mean soil temperature in before period (2020) ranged between approximately 3.8 – 11.6, 4.6 – 11.4 and 3.9 – 11.3 ºC in control, wide buffer and narrow buffer, respectively (Figure 4). The mean soil temperature in after period (2021) ranged between approximately 5.3 – 11.2, 5.1 – 14.8 and 6.9 – 15.2 ºC in control, wide buffer and narrow buffer, respectively. The mean soil temperature increased from May to August, where it reached a maximum, and thereafter decreased to October in both control, wide buffer and narrow buffer in 2020. In 2021, the highest mean soil temperature was observed in June in both control, wide buffer and narrow buffer.

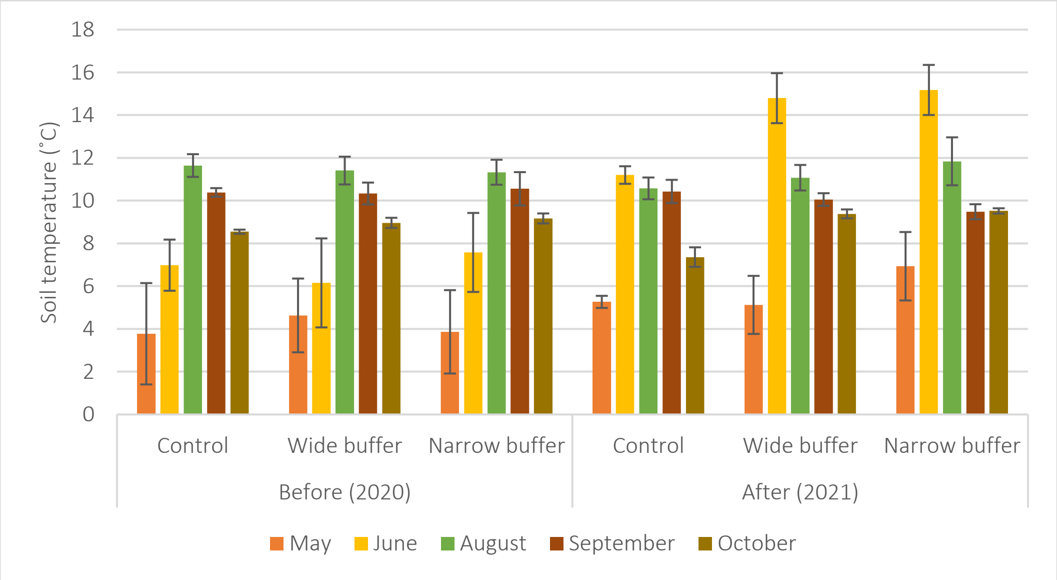

Figure 4. Mean soil temperature expressed in ºC in control, wide buffer and narrow buffer in May, June, August, September and October in before period (before clearcutting, 2020) and in after period (after clearcutting, 2021). The error bars show the standard deviations of the mean values, which represents the variation among the replicates.

The BACI analysis showed significant clearcutting effects on soil temperature (non-transformed data) (Table 1). The median P value was < 0.05 for the "Time"-parameter and the median Cohen's *D* was "MEDIUM" for the "TimeN"-parameter and "TimeW" parameter. In addition, approximately 87% of the 1000 randomly sampled combinations were significant for the "Time"-parameter (Appendix 1: Table A1a; Figure A1), which further confirm the significant result. The median mean value was 1.3411 and the median standard deviation was 0.4844 ºC for the "Time"-parameter. Hence, the soil temperature was on average 1.3 ± 0.5 ºC higher in the narrow buffer, relative to the control site, in 2021 relative to 2020.

The BACI analysis showed no significant differences in clearcutting effects between the wide buffer and narrow buffer (Table 1). The median P value was > 0.05 and the median Cohen's *D* was "Small" for the "Width"-parameter and "Time:Width"-parameter. In addition, approximately 0% and 0.7% of the 1000 randomly sampled combinations were significant for the "Width"-parameter and "Time:Width"-parameter, respectively (Appendix 1: Table A1a, Figure A1), which further confirm the non-significant result.

None of the BACI model assumptions "constancy of differences", "no additivity" and "no autocorrelation" were violated. The assumption "normality and homoscedasticity of model residuals" was not fully met (median P value < 0.05 and probability 56% for the normality test) (Appendix 1: Table A1a, Table A1b).

Table 1. BACI analysis statistics of soil-temperature. The table shows the median, standard deviation and the 2.5% and 97.5% quantiles for 95% confidence intervals of the mean value, standard deviation, T value and P value of the parameters Intercept, Time, Width and Time:Width and the Cohen's D of TimeN, TimeW, Width and Time:Width. Mean of Intercept is the mean model intercept, mean of Time is the mean model coefficient of "Time" effect, mean of Width is the mean model coefficient of "Width" effect and mean of Time:Width is the mean model coefficient of "Time:Width" effect. Cohen's D of TimeN and TimeW is the Cohen's D of before-after-change in control-impact-site-difference in narrow buffer sites/wide buffer sites, Cohen's D of Width is the Cohen's D of difference between narrow and wide buffer sites in before period and Cohen's D of Time:Width is the Cohen's D of difference between narrow and wide buffer sites in the before-after change in control-impact-site-differences. Bold values represent significant results. The values are based on non-transformed data

				CONFIDENCE INTERVAL	
Parameter	*Measure*	*Median*	*St dev.*	*2.5%*	*97.5%*
Intercept	*Mean*	0.2306	0.1781	-0.1073	0.6076
	St dev.	0.3509	0.0351	0.2980	0.4460
	T value	0.6460	0.5096	-0.3409	1.7183
	P value	0.5190	0.2567	0.0887	0.9604
Time	*Mean*	1.3411	0.2637	0.8222	1.8343
	St dev.	0.4844	0.0392	0.4201	0.5785
	T value	2.7548	0.6434	1.6202	4.0519
	P value	**0.0069**	0.0301	0.0001	0.1082
Width	*Mean*	-0.1825	0.2634	-0.7067	0.3136
	St dev.	0.4963	0.0415	0.4210	0.5789
	T value	-0.3533	0.5435	-1.3885	0.6783
	P value	0.6797	0.2384	0.1910	0.9868
Time:Width	*Mean*	-0.3248	0.3880	-1.0527	0.4502
	St dev.	0.6844	0.0549	0.5941	0.8136
	T value	-0.4784	0.5763	-1.6117	0.6349
	P value	0.6149	0.2532	0.1100	0.9431
TimeN	*Cohen's D*	**0.3900**	0.1294	0.2000	0.7000
TimeW	*Cohen's D*	**0.2900**	0.1131	0.1213	0.5200
Width	*Cohen's D*	-0.0500	0.0794	-0.2100	0.0988
Time:Width	*Cohen's D*	-0.0900	0.1152	-0.3188	0.1300

3.2 Soil moisture

The mean soil moisture in before period (2020) ranged between approximately 39.3 – 44.6, 15.6 – 25.1 and 11.3 – 24.3 % in control, wide buffer and narrow buffer, respectively (Figure 5). The mean soil moisture in after period (2021) ranged between approximately 45.9 – 62.3, 12.8 – 25.4 and 11.6 – 26.3 % in control, wide buffer and narrow buffer, respectively. The highest mean soil moisture was in general observed in May and October in both control, wide buffer and narrow buffer in 2021. The lowest mean soil moisture was in general observed in August and September in both 2020 and 2021. The mean soil moisture was higher in control compared to the wide buffer and narrow buffer in both 2020 and 2021.

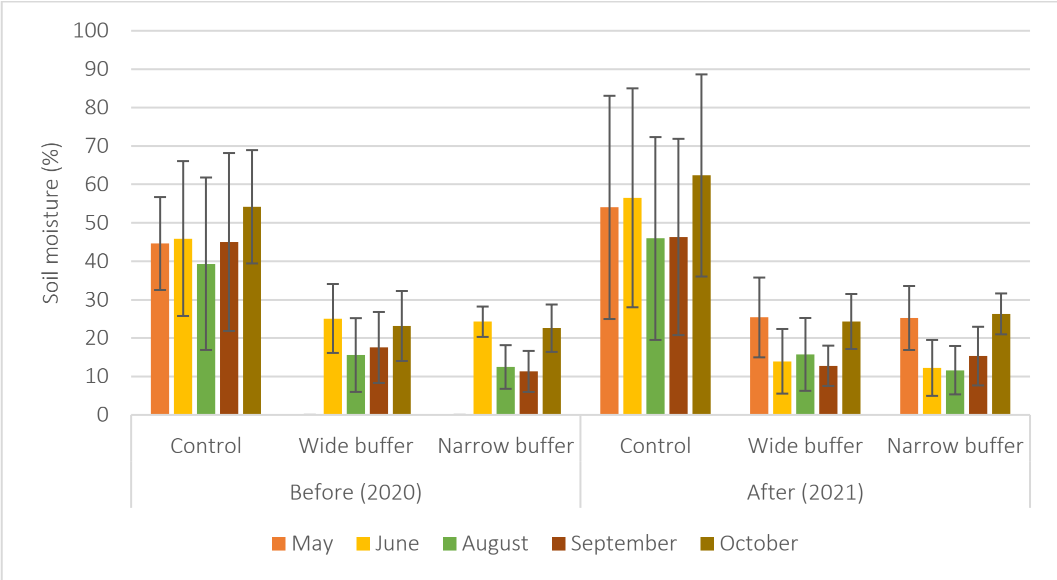

Figure 5. Mean soil moisture expressed in % in control, wide buffer and narrow buffer in May, June, August, September and October in before period (before clearcutting, 2020) and in after period (after clearcutting, 2021). The error bars show the standard deviations of the mean values, which represents the variation among the replicates. Data in the wide buffer and narrow buffer in May 2020 are missing.

The BACI analysis showed no significant clearcutting effects or differences in clearcutting effects between the wide buffer and narrow buffer of soil moisture (log-transformed data) (Table 2). The median P value was > 0.05 and the median Cohen's *D* was "Small" for all parameters. In addition, approximately 3%, 1% and 0% of the 1000 randomly sampled combinations were significant for the "Time"-parameter, "Width"-parameter and "Time:Width"-parameter, respectively (Appendix 2: Table A2a, Figure A2), which further confirm the non-significant results.

None of the BACI model assumptions were violated (Appendix 2: Table A2a, Table A2b).

Table 2. BACI analysis statistics of soil-moisture. The table shows the median, standard deviation and the 2.5% and 97.5% quantiles for 95% confidence intervals of the mean value, standard deviation, T value and P value of the parameters Intercept, Time, Width and Time:Width and the Cohen's D of TimeN, TimeW, Width and Time:Width. Mean of Intercept is the mean model intercept, mean of Time is the mean model coefficient of "Time" effect, mean of Width is the mean model coefficient of "Width" effect and mean of Time:Width is the mean model coefficient of "Time:Width" effect. Cohen's D of TimeN and TimeW is the Cohen's D of before-after-change in control-impact-site-difference in narrow buffer sites/wide buffer sites, Cohen's D of Width is the Cohen's D of difference between narrow and wide buffer sites in before period and Cohen's D of Time:Width is the Cohen's D of difference between narrow and wide buffer sites in the before-after change in control-impact-site-differences. The values are based on log-transformed data

				CONFIDENCE INTERVAL	
Parameter	*Measure*	*Median*	*St dev.*	*2.5%*	*97.5%*
Intercept	*Mean*	-0.3730	0.0720	-0.4999	-0.2460
	St dev.	0.0951	0.0232	0.0553	0.1392
	T value	-3.7192	1.2830	-7.1671	-2.6522
	P value	0.0004	0.0026	0	0.0096
Time	*Mean*	-0.0665	0.0198	-0.1025	-0.0305
	St dev.	0.0537	0.0049	0.0458	0.0640
	T value	-1.1874	0.3431	-2.0284	-0.6529
	P value	0.2385	0.1219	0.0458	0.5157
Width	*Mean*	0.0585	0.1022	-0.1319	0.2489
	St dev.	0.1517	0.0255	0.0990	0.1951
	T value	0.3896	0.7437	-0.9862	1.9383
	P value	0.6315	0.2740	0.0765	0.9969
Time:Width	*Mean*	-0.0572	0.0278	-0.1112	-0.0032
	St dev.	0.0762	0.0056	0.0655	0.0874
	T value	-0.7490	0.3822	-1.5339	-0.0433
	P value	0.4560	0.2104	0.1289	0.9318
TimeN	*Cohen's D*	-0.1200	0.0405	-0.2300	-0.0800
TimeW	*Cohen's D*	-0.2200	0.0707	-0.4600	-0.1600
Width	*Cohen's D*	0.1100	0.2018	-0.2700	0.5200
Time:Width	*Cohen's D*	-0.1100	0.0588	-0.2300	-0.0100

3.3 Soil-atmosphere GHG fluxes

3.3.1 CO_2 fluxes

The results showed a mean CO_2 emission from the soil to the atmosphere in both control, wide buffer and narrow buffer in both the before period (2020) and after period (2021) (Figure 6). The mean soil CO_2 emissions in 2020 ranged between approximately 1.57 – 4.36, 1.64 – 4.33 and 1.48 – 4.30 µmol m^{-2} s^{-1} in control, wide buffer and narrow buffer, respectively. The mean soil CO_2 emissions in 2021 ranged between approximately 1.36 – 3.75, 0.80 – 2.89 and 1.03 – 3.54 µmol m^{-2} s^{-1} in control, wide buffer and narrow buffer, respectively. The mean soil CO_2 emissions increased, in general, from May to August, where the soil CO_2 emissions researched a maximum, and thereafter decreased to October, in both 2020 and 2021. However, the wide buffer showed lower mean soil CO_2 emissions in August compared to June and September in 2021.

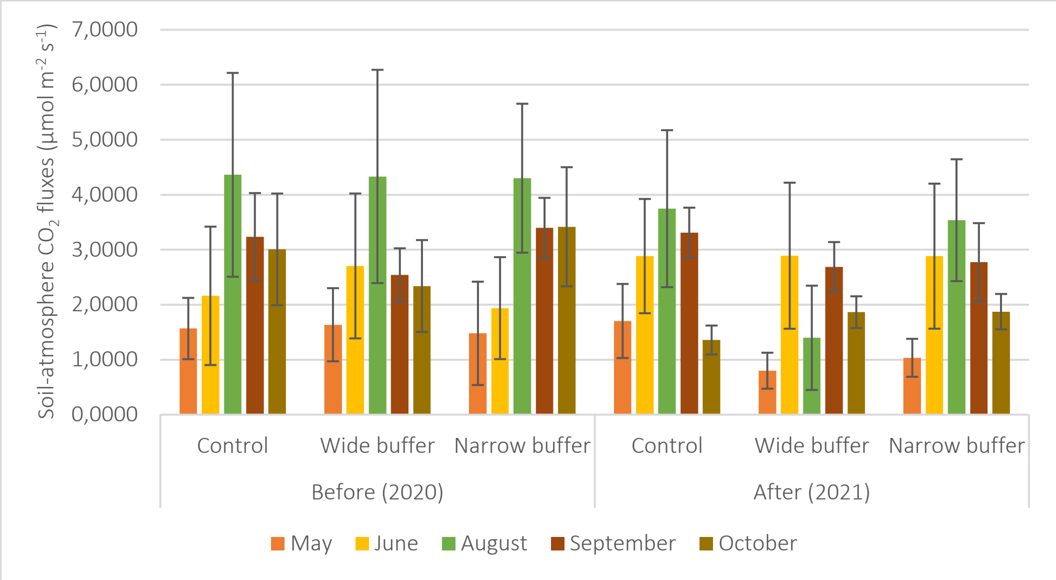

Figure 6. Mean soil-atmosphere CO_2 fluxes expressed in µmol m^{-2} s^{-1} in control, wide buffer and narrow buffer in May, June, August, September and October in before period (before clearcutting, 2020) and in after period (after clearcutting, 2021). The error bars show the standard deviations of the mean values, which represents the variation among the replicates.

The BACI analysis showed no significant clearcutting effects or differences in clearcutting effects between the wide buffer and narrow buffer of soil-atmosphere CO_2 fluxes (non-transformed data) (Table 3). The median P value was > 0.05 and the median Cohen's *D* was "Small" for all parameters. In addition, approximately 0%, 1% and 0% of the 1000 randomly sampled combinations were significant for the "Time"-parameter, "Width"-parameter and "Time:Width"-parameter, respectively (Appendix 3: Table A3a, Figure A3), which further confirm the non-significant results.

None of the BACI model assumptions were violated (Appendix 3: Table A3a, Table A3b).

Table 3. BACI analysis statistics of soil-atmosphere CO_2 fluxes. The table shows the median, standard deviation and the 2.5% and 97.5% quantiles for 95% confidence intervals of the mean value, standard deviation, T value and P value of the parameters Intercept, Time, Width and Time:Width and the Cohen's D of TimeN, TimeW, Width and Time:Width. Mean of Intercept is the mean model intercept, mean of Time is the mean model coefficient of "Time" effect, mean of Width is the mean model coefficient of "Width" effect and mean of Time:Width is the mean model coefficient of "Time:Width" effect. Cohen's D of TimeN and TimeW is the Cohen's D of before-after-change in control-impact-site-difference in narrow buffer sites/wide buffer sites, Cohen's D of Width is the Cohen's D of difference between narrow and wide buffer sites in before period and Cohen's D of Time:Width is the Cohen's D of difference between narrow and wide buffer sites in the before-after change in control-impact-site-differences. The values are based on non-transformed data

				CONFIDENCE INTERVAL	
Parameter	*Measure*	*Median*	*St dev.*	*2.5%*	*97.5%*
Intercept	*Mean*	0.0401	0.2239	-0.3819	0.4622
	St dev.	0.3437	0.0734	0.2159	0.4870
	T value	0.1687	0.7248	-1.3139	1.6505
	P value	0.6286	0.2694	0.0795	0.9882
Time	*Mean*	-0.2197	0.0822	-0.3617	-0.0777
	St dev.	0.3196	0.0151	0.2918	0.3504
	T value	-0.6971	0.2611	-1.1607	-0.2377
	P value	0.4873	0.1622	0.2484	0.8126
Width	*Mean*	-0.1952	0.3220	-0.8283	0.4379
	St dev.	0.4788	0.0715	0.3299	0.6114
	T value	-0.3998	0.7195	-1.9520	0.9932
	P value	0.6045	0.2611	0.0778	0.9750
Time:Width	*Mean*	-0.2971	0.1122	-0.5027	-0.0841
	St dev.	0.4785	0.0222	0.4404	0.5261
	T value	-0.6222	0.2389	-1.0822	-0.1723
	P value	0.5352	0.1534	0.2816	0.8635
TimeN	*Cohen's D*	-0.0800	0.0332	-0.1500	-0.0300
TimeW	*Cohen's D*	-0.1700	0.0352	-0.2500	-0.1100
Width	*Cohen's D*	-0.0700	0.1166	-0.3100	0.1550
Time:Width	*Cohen's D*	-0.1000	0.0411	-0.1800	-0.0300

3.3.2 CH_4 fluxes

The results showed, in general, a mean CH_4 uptake by the soil from the atmosphere in both the wide buffer and narrow buffer in both the before period (2020) and after period (2021) (Figure 7). The results showed both a soil CH_4 uptake and a soil CH_4 emission in control in both 2020 and 2021, which means that some sample plots showed an uptake and some sample plots showed an emission of CH_4 in the control site. The mean soil-atmosphere CH_4 fluxes in 2020 ranged between approximately 0.0000 – -0.0004, -0.0006 – -0.0013 and -0.0007 – -0.0017 µmol m^{-2} s^{-1} in control, wide buffer and narrow buffer, respectively. The mean soil-atmosphere CH_4 fluxes in 2021 ranged between approximately -0.0002 – 0.0008, -0.0004 – -0.0008 and -0.0006 – -0.0012 µmol m^{-2} s^{-1} in control, wide buffer and narrow buffer, respectively. The results showed no general seasonal trend of the soil-atmosphere CH_4 fluxes in control, wide buffer or narrow buffer neither in 2020 nor in 2021.

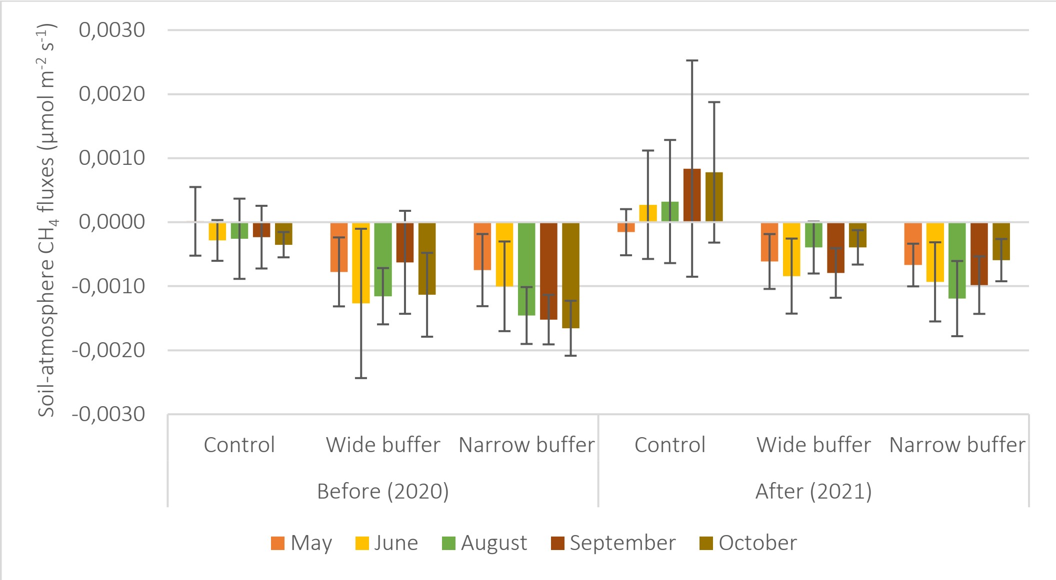

Figure 7. Mean soil-atmosphere CH_4 fluxes expressed in µmol m^{-2} s^{-1} in control, wide buffer and narrow buffer in May, June, August, September and October in before period (before clearcutting, 2020) and in after period (after clearcutting, 2021). The error bars show the standard deviations of the mean values, which represents the variation among the replicates. Positive values indicate a mean CH_4 emission from the soil to the atmosphere and negative values indicate a mean CH_4 uptake by the soil from the atmosphere.

The BACI analysis showed significant clearcutting effects on soil-atmosphere CH_4 fluxes (signsqrt-transformed data) (Table 4). The median P value was < 0.05 for the "Time"-parameter and the median Cohen's *D* was "MEDIUM" for the "TimeN"-parameter and "TimeW"-parameter. In addition, approximately 57% of the 1000 randomly sampled combinations were significant for the "Time"-parameter (Appendix 4: Table A4a, Figure A4) which further confirm the significant result. The results showed that the soil CH_4 uptake decreased in the narrow buffer, relative to control, in 2021 relative to 2020. However, the soil CH_4 uptake in control in 2020 switched to soil CH_4 emissions in 2021 and that change was larger than the change in soil-atmosphere CH_4 fluxes in the impact site between 2020 and 2021. The non-transformed median mean value of the "Time"-parameter was -0.0008 and the median standard deviation was 0.00074 µmol m^{-2} s^{-1}. As follows, in 2021, the soil CH_4 uptake was on average 0.0008 ± 0.00074 µmol m^{-2} s^{-1} lower compared to 2020 in the narrow buffer, relative to the control site.

The BACI analysis showed no significant differences in clearcutting effects between the wide buffer and narrow buffer (Table 4). The median P value was > 0.05 and the median Cohen's *D* was "Small" for the "Width"-parameter and "Time:Width"-parameter. In addition, approximately 4% and 5% of the 1000 randomly sampled combinations were significant for the "Width"-parameter and "Time:Width"-parameter, respectively (Appendix 4: Table A4a, Figure A4), which further confirm the non-significant result.

None of the BACI model assumptions "constancy of differences", "no additivity" and "no autocorrelation" were violated. The assumption "normality and homoscedasticity of model residuals" was not fully met (median P value < 0.05 and probability 85% for the normality test) (Appendix 4: Table A4a, Table A4b).

Table 4. BACI analysis statistics of soil-atmosphere CH_4 fluxes. The table shows the median, standard deviation and the 2.5% and 97.5% quantiles for 95% confidence intervals of the mean value, standard deviation, T value and P value of the parameters Intercept, Time, Width and Time:Width and the Cohen's D of TimeN, TimeW, Width and Time:Width. Mean of Intercept is the mean model intercept, mean of Time is the mean model coefficient of "Time" effect, mean of Width is the mean model coefficient of "Width" effect and mean of Time:Width is the mean model coefficient of "Time:Width" effect. Cohen's D of TimeN and TimeW is the Cohen's D of before-after-change in control-impact-site-difference in narrow buffer sites/wide buffer sites, Cohen's D of Width is the Cohen's D of difference between narrow and wide buffer sites in before period and Cohen's D of Time:Width is the Cohen's D of difference between narrow and wide buffer sites in the before-after change in control-impact-site-differences. Bold values represent significant results. The values are based on signsqrt-transformed data

				CONFIDENCE INTERVAL	
Parameter	*Measure*	*Median*	*St dev.*	*2.5%*	*97.5%*
Intercept	Mean	-0.0236	0.0055	-0.0341	-0.0141
	St dev.	0.0062	0.0015	0.0029	0.0088
	T value	-3.7615	1.1658	-6.9732	-2.4887
	P value	0.0003	0.0039	0	0.0144
Time	Mean	-0.0139	0.0059	-0.0246	-0.0031
	St dev.	0.0062	0.0011	0.0038	0.0079
	T value	-2.1209	1.5277	-6.3046	-0.4779
	P value	**0.0363**	0.1837	0	0.6337
Width	Mean	0.0057	0.0078	-0.0090	0.0206
	St dev.	0.0092	0.0016	0.0058	0.0118
	T value	0.5756	0.9743	-1.1203	2.6111
	P value	0.5065	0.2967	0.0260	0.9634
Time:Width	Mean	-0.0003	0.0081	-0.0156	0.0159
	St dev.	0.0088	0.0011	0.0065	0.0108
	T value	-0.0387	0.9686	-1.9007	1.8826
	P value	0.5539	0.2904	0.0330	0.9757
TimeN	Cohen's D	**-0.3900**	0.2069	-0.8700	-0.0800
TimeW	Cohen's D	**-0.3400**	0.1470	-0.6498	-0.0702
Width	Cohen's D	0.1350	0.2093	-0.2500	0.5500
Time:Width	Cohen's D	-0.0100	0.2162	-0.4200	0.4300

3.4 Tree-atmosphere GHG fluxes

3.4.1 CO_2 fluxes

The results showed a mean tree CO_2 emission from both the birch stems and spruce stems in both the wide buffer and narrow buffer in 2021 (Figure 8). The mean tree CO_2 emissions in the wide buffer ranged between approximately 0.47 – 1.62 and 0.43 – 1.58 µmol m^{-2} s^{-1} for birch stems and spruce stems, respectively. The mean tree CO_2 emissions in the narrow buffer ranged between approximately 0.77 – 2.00 and 0.42 – 1.53 µmol m^{-2} s^{-1} for birch stems and spruce stems, respectively. The results showed, in general, a decreasing trend in tree CO_2 emissions from both birch stems and spruce stems in both the wide buffer and narrow buffer from June to October.

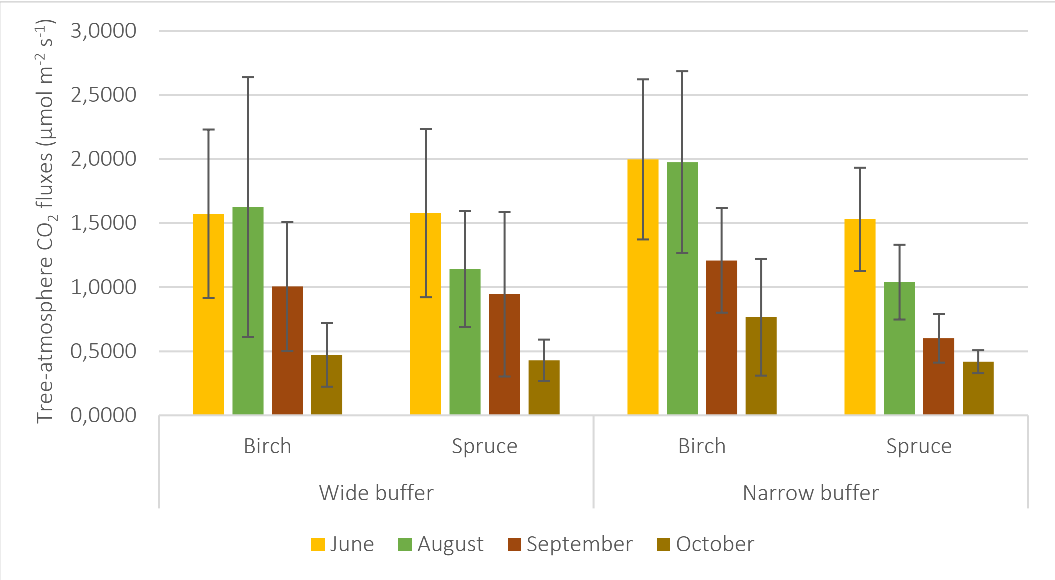

Figure 8. Mean tree-atmosphere CO_2 fluxes expressed in µmol m^{-2} s^{-1} for birch stems and spruce stems in the wide buffer and the narrow buffer in June, August, September and October in 2021. The error bars show the standard deviations of the mean values, which represents the variation among the replicates.

The ANOVA showed no significant differences in tree-atmosphere CO_2 fluxes between neither birch stems and spruce stems nor wide buffer and narrow buffer (P values > 0.05) (Table 5).

Table 5. Type III Analysis of Variance table with Satterthwaite's method of tree-atmosphere CO_2 fluxes. Fixed effects show the mean square, degrees of freedom, F value and P value of the difference in CO_2 fluxes between birch stems and spruce stems and wide buffer and narrow buffer. Random effects show the standard deviation between the total number of trees (28) and the replicates, i.e., the total number of trees times four measurement occasions (112)

Fixed effects:	*Mean square*	*Degrees of freedom*	*F value*	*P value*
Birch/Spruce	1.2222	1,24	2.8791	0.1027
Wide/Narrow	0.2829	1,24	0.6665	0.4223
Random effects:		*Standard deviation*		
ID	28 groups	0.3278		
Residuals	112 replicates	0.6515		

3.4.2 CH_4 fluxes

The results showed, in general, a mean tree CH_4 emission from both the birch stems and spruce stems in both the wide buffer and narrow buffer in 2021 (Figure 9). Some birch stems showed, however, an uptake of CH_4 in both the wide buffer and narrow buffer. The mean tree-atmosphere CH_4 fluxes in the wide buffer ranged between approximately 0.000004 – 0.000034 and 0.000005 – 0.000029 µmol m^{-2} s^{-1} for birch stems and spruce stems, respectively. The mean tree-atmosphere CH_4 fluxes in the narrow buffer ranged between approximately 0.000036 – 0.000086 and 0.000004 – 0.000057 µmol m^{-2} s^{-1} for birch stems and spruce stems, respectively. The results showed, in general, a decreasing trend in tree CH_4 emissions from both birch stems and spruce stems in both the wide buffer and narrow buffer from June/August to October when some of the birch stems, instead, showed an uptake of CH_4.

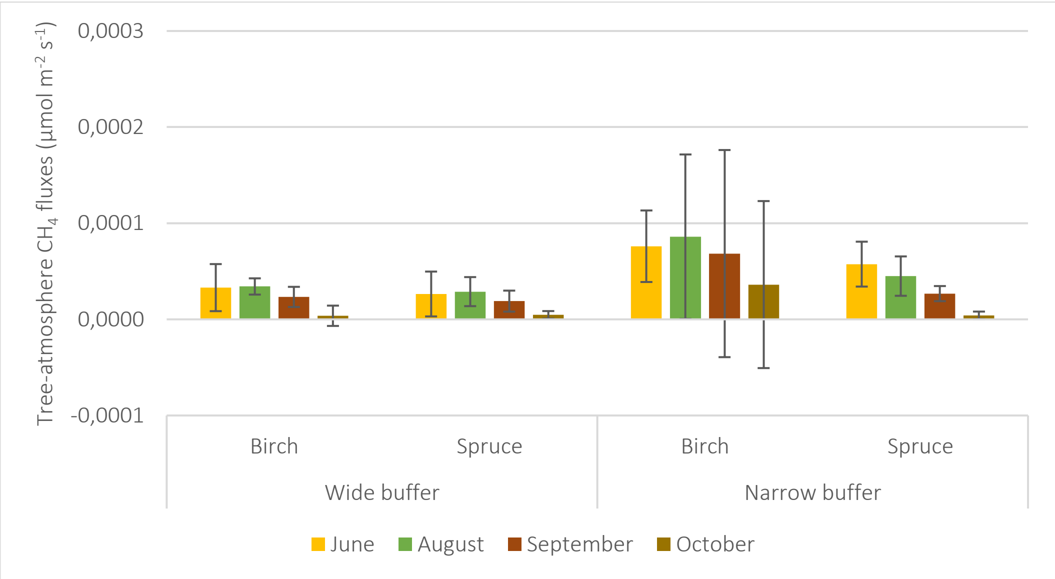

Figure 9. Mean tree-atmosphere CH_4 fluxes expressed in µmol m^{-2} s^{-1} for birch stems and spruce stems in the wide buffer and the narrow buffer in June, August, September and October in 2021. The error bars show the standard deviations of the mean values, which represents the variation among the replicates. Positive values indicate a mean emission of CH_4 and negative values indicate a mean uptake of CH_4.

The ANOVA showed no significant differences in tree-atmosphere CH_4 fluxes between neither birch stems and spruce stems nor wide buffer and narrow buffer (P values > 0.05) (Table 6).

Table 6. Type III Analysis of Variance table with Satterthwaite's method of tree-atmosphere CH_4 fluxes. Fixed effects show the mean square, degrees of freedom, F value and P value of the difference in CH_4 fluxes between birch stems and spruce stems and wide buffer and narrow buffer. Random effects show the standard deviation between the total number of trees (28) and the replicates, i.e., the total number of trees times four measurement occasions (112)

Fixed effects:	*Mean square*	*Degrees of freedom*	*F value*	*P value*
Birch/Spruce	1.3903e-09	1,24	1.6262	0.2144
Wide/Narrow	3.0239e-09	1,24	3.5370	0.0722
Random effects:		*Standard deviation*		
ID	28 groups	4.218e-05		
Residuals	112 replicates	2.924e-05		

4. Discussion

4.1 Soil temperature

The seasonal trend of the soil temperature shown in this study, with higher soil temperature during summer, was expected. In addition, the significantly higher soil temperature in 2021 is supported by, for example, a study in a Norway spruce forest in southern Finland, which showed an increase in mean soil temperature (5-8 ºC) at 0-30 cm depth during the summer months one and two years after clearcutting (Kulmala et al. 2014). Other studies have also shown an increase in maximum and mean soil temperatures after clearcutting (e.g., Kähkönen et al. 2002; Huttunen et al. 2003; Hashimoto & Suzuki 2004) and an increase in seasonal fluctuations of soil temperatures after clearcutting (Kähkönen et al. 2002). A possible explanation to increased soil-temperatures after clearcutting is the reduced canopy with higher insolation to the soil as a result (Hashimoto & Suzuki 2004; Kulmala et al. 2014). A reduced canopy in 2021 relative to 2020 is a possible explanation to the increased soil-temperature in the narrow buffer in the impact site relative to the control site, also in this study. However, the canopy in the wide buffer should have been denser compared to the narrow buffer. Therefore, the non-significant result of the soil temperature in the wide buffer compared to the narrow buffer is unexpected. However, the soil temperature likely differs between different soil depths (Kulmala et al. 2014). The soil temperature at 5 cm soil depth might be more affected by current air temperature and insolation during the measurement, compared to, for example, 10-30 cm soil depth. Hence, the non-significant differences in soil temperature between the wide buffer and narrow buffer might rather depended on the measured soil depth.

4.2 Soil moisture

The seasonal trend of the soil moisture shown in this study, with lower soil moisture during summer, was expected since higher air temperatures and higher insolation generally decreases soil moisture (Chen et al. 1993; Hotta et al. 2010). However, the non-significant result of the soil moisture in 2021 compared to 2020 is contradicting to, for example, a study in two old drained peatland forests in southern Finland and a study in a Norway spruce forest in southern Finland, which showed an increase in soil moisture after clearcutting (Huttunen et al. 2003; Kulmala et al. 2014). Other studies have also shown an increase in soil moisture after clearcutting (e.g., Hotta et al. 2010; Boggs et al. 2015). Possible explanations to an increase in soil moisture after clearcutting are the reduced interception and transpiration which leads to a higher groundwater level and higher soil moisture deeper into the soil. However, as previously discussed, a reduced canopy leads to higher insolation to the soil which decreases the soil moisture in the upper layer of the soil (Chen et al. 1993; Hotta et al. 2010). Hence, since the soil moisture in this study was measured at 5 cm soil depth, the insolation during the measurement might affected the result and contributed to the non-significant differences in soil moisture between 2020 and 2021. In addition, as for the soil temperature, the insolation during the measurement and the measured soil depth might also contributed to the non-significant differences in soil moisture between the wide buffer and narrow buffer.

4.3 Soil-atmosphere CO_2 fluxes

The seasonal trend of the soil CO_2 emissions shown in this study, with higher emissions during summer, was expected since higher soil temperature in general promote soil CO_2 emissions (Rayment & Jarvis 2000; Lou & Shou 2006; Dunn et al. 2007). The result is supported by a study in a black spruce (*Picea mariana* Mill.) forest in central Canada which showed both higher soil temperature at 10 cm soil depth and higher soil CO_2 emissions during summer and late summer, in relation to before the springtime thaw and after the wintertime freeze (Rayment & Jarvis 2000). In addition, the result could be related to studies in Sweden which have shown a high correlation of tree photosynthesis and soil CO_2 emissions. The studies showed, with girdling experiments, that a decreased tree photosynthesis decreased the soil CO_2 emissions with more than 50% two (Högberg & Read 2006) and four (Högberg et al. 2001) weeks after the girdling. One possible explanation for the reduction of the soil CO_2 emissions after the tree girdling experiment was a reduction of respiration in fine roots and root-associated microfloras (Högberg et al. 2001; Högberg & Read 2006). Another study in Finland confirms that a major part of the resources of soil CO_2 emissions are derived from root litter and photosynthetic exudates of ground vegetation and trees (Kähkönen et al. 2002). Hence, higher soil CO_2 emissions during summer, when the tree photosynthesis is higher, is reasonable.

The non-significant differences in soil-atmosphere CO_2 fluxes between 2020 and 2021 are however unexpected since the soil temperature was significantly higher in

2021 compared to 2020. Hence, it would be reasonable to assume higher soil CO_2 emissions in 2021 compared to 2020. However, as previously discussed, the non-significant results might depended on a decreased photosynthesis and subsequent root respiration in the impact site in general in 2021, and hence a decreased soil CO_2 emissions, which could possibly compensate other factors that generally increases soil CO_2 emissions after clearcutting, such as an increased soil temperature (Rayment & Jarvis 2000; Lou & Shou 2006; Dunn et al. 2007) and an increased concentration of CO_2 in hillslope groundwater (Klaus et al. 2018). The non-significant differences in soil-atmosphere CO_2 fluxes between the wide buffer and narrow buffer might also be related to several compensating factors. The tree photosynthesis should reasonably be higher in the wide buffer because of more trees, and hence the soil CO_2 emissions, but other factors, such as an increased soil temperature that generally increases the soil CO_2 emissions, might be reduced in the wide buffer because of a denser canopy, compared to the narrow buffer.

4.4 Soil-atmosphere CH_4 fluxes

The lack of a general seasonal trend in soil-atmosphere CH_4 fluxes shown in this study, is supported by other studies which have shown that same sites could show both soil CH_4 emissions and soil CH_4 uptake (Huttunen et al. 2003; Ullah et al. 2009; Pitz et al. 2018; Korkiakoski et al. 2019). However, other studies have shown seasonal trends in soil-atmosphere CH_4 fluxes with higher fluxes during late autumn and winter, i.e., during wet periods (e.g., Mander et al. 2022). Hence, the lack of significant results in seasonal trends of soil-atmosphere CH_4 fluxes might rather depended on the measurement method in this study (Barba et al. 2021; Mander et al. 2022). The high spatial and temporal variability and hot moments in CH_4 fluxes in general might be missed in this study, and other studies which measure the CH_4 fluxes manually with sparse intervals, compared to automated measurement methods, which account for temporal variability (Barba et al. 2021).

Clearcutting effects on soil-atmosphere CH_4 fluxes, as shown in this study, are however supported by other studies which have shown changed patterns of soil-atmosphere CH_4 fluxes after clearcutting. For example, a study in different types of forests in southern Canada showed increased soil CH_4 emissions after clearcutting (Ullah et al. 2009) and a study in a drained peatland forest in southern Finland showed a switch from a net soil CH_4 uptake before clearcutting to a net soil CH_4 emission after clearcutting (Korkiakoski et al. 2019). However, another study in two old drained peatland forests in southern Finland showed not any significant differences in soil-atmosphere CH_4 fluxes after clearcutting (Huttunen et al. 2003). The biogeochemical mechanisms behind the soil-atmosphere CH_4 fluxes seem to be episodic and depend on several different factors, in particular soil moisture

(Huttunen et al. 2003; Ullah et al. 2009; Korkiakoski et al. 2019; Mander et al. 2022). Several studies have shown that soil CH_4 emissions generally increase with increased soil moisture (Hedin et al. 1998; Ullah et al. 2009; Korkiakoski et al. 2019; Schindler et al. 2020; Mander et al. 2022). However, no differences in soil moisture were shown between 2020 and 2021 in this study which indicate that the soil moisture, at least at 5 cm soil depth, was probably not a driving factor for the soil-atmosphere CH_4 fluxes. The increased soil temperature in 2021 compared to 2020 could, however, be a contributing factor to the decreased soil CH_4 uptake in the narrow buffer in 2021, since other studies have shown that soil temperature can affect soil-atmosphere CH_4 fluxes (e.g., Feng et al. 2021; Mander et al. 2022). Nevertheless, a study in eastern Estonia has shown increasing soil CH_4 uptake with increasing soil temperature (Mander et al. 2022), which is contradicting to this study. However, if the soil temperature affected the soil-atmosphere CH_4 fluxes in this study, the non-significant results of differences in soil-atmosphere CH_4 fluxes between the wide buffer and narrow buffer could possibly be explained by the non-significant differences in soil temperature between the buffer widths.

4.5 Tree-atmosphere CO_2 fluxes

The tree CO_2 emissions shown in this study were expected since tree stems, with bare bark, generally show CO_2 emissions (e.g., Maier et al. 2018; Pitz et al. 2018; Barba et al. 2021). The tree CO_2 emissions are supported by studies which have shown tree-stem CO_2 emissions from European beech trees in upland mature forests in Germany and the Czech Republic (Maier et al. 2018), from bitternut hickory trees in an upland forest in eastern United States (Barba et al. 2021) and from green ash trees (*Fraxinus pennsylvanica* Marsh.), sweetgum trees (*Liquidambar styraciflua* L.), American beech trees (*Fagus grandifolia* Ehrh.), American hornbeam trees (*Carpinus caroliniana* Walter) and red maple trees (*Acer rubrum* L.) in wetland forests in eastern United States (Pitz et al. 2018). In addition, the seasonal trends in tree CO_2 emissions are supported by other studies which have shown higher emissions in the growing season due to a higher tree physiological activity, and decreasing emissions in the fall (Pitz et al. 2018; Barba et al. 2021). Furthermore, tree-atmosphere CO_2 fluxes have been shown to have a strong positive correlation to soil temperature (Pitz et al. 2018) which support higher tree CO_2 emissions during the summer months.

The non-significant differences in tree-atmosphere CO_2 fluxes between different tree species, as shown in this study, are supported by other studies (e.g., Pitz et al. 2018). However, since the tree-atmosphere CO_2 fluxes seem to vary with tree physiological activity and growth rate (Pitz et al. 2018; Barba et al. 2021), a difference between the pioneer tree species silver birch and the non-pioneer tree species Norway spruce would perhaps be reasonable to assume, since their growth rate probably differ (Shanin et al. 2014). In addition, since CO_2 movements through stems seem to vary with wood structural features, e.g., wood density (Salomón et al. 2021), a difference in tree CO_2 emissions between different tree species is reasonable. However, the growth rate, and hence the wood structural features (Zhang 1995), depend on site productivity, i.e., nutrient availability (e.g., Shanin et al. 2014). The birches and spruces were scattered in the wide buffer and narrow buffer and the nutrient availability differed probably not for the two tree species. However, the nutrient availability might differed between the wide buffer and narrow buffer due to the mire upstream the narrow buffer. The mire may leached nutrients (Sponseller et al. 2018) and thereby contributed to a higher nutrient availability for the vegetation (and possibly the trees) in the narrow buffer. Hence, higher tree CO_2 emissions in the narrow buffer would perhaps be reasonable to assume in this study since nutrients could increase microbial gas production in the soil which could lead to a transport of CO_2 into above-ground plant tissues and hence promote tree CO_2 emissions (Mukhin & Voronin 2011; Covey et al. 2012; Barba et al. 2021). However, the soil temperature, which have been shown to have a strong positive correlation to tree CO_2 emissions (Pitz et al. 2018), did not differ between the buffer widths, at least not at 5 cm soil depth.

4.6 Tree-atmosphere CH_4 fluxes

The tree CH_4 emissions shown in this study are supported by other studies which have shown tree CH_4 emissions from the stems of several deciduous tree species and coniferous tree species in upland forests as well as wetland forests in boreal, sub-boreal and temperate zones (e.g., Terazawa et al. 2015; Machacova et al. 2016; Maier et al. 2018; Pitz et al. 2018; Schindler et al. 2020; Barba et al. 2021; Schindler et al. 2021; Terazawa et al. 2021). The seasonal trend in the tree CH_4 emissions, with higher emissions during summer and decreasing emissions toward the end of fall, is supported by a study of bitternut hickory trees in an upland forest in eastern United States (Barba et al. 2021). Another study of Japanese alder (*Alnus japonica* (Thunb.) Steud.) and Manchurian ash (*Fraxinus mandshurica* Rupr.) in a mature wetland forest in northern Japan showed a similar seasonal trend in tree CH_4 emissions, but with increasing emissions from May to August and thereafter decreasing emissions toward the end of the fall (Terazawa et al. 2021). A study of grey alder in a mature wetland forest in eastern Estonia showed a similar seasonal trend in tree-atmosphere CH_4 fluxes (Schindler et al. 2021). However, a study of green ash trees, sweetgum trees, American beech trees, American hornbeam trees and red maple trees in wetland forests in eastern United States did not show any seasonal trends in tree CH_4 emissions, rather high episodic fluxes during the days

(Pitz et al. 2018). In addition, a study of Manchurian ash in a mature wetland forest in northern Japan did not show any clear seasonal trends in tree CH_4 emissions (Terazawa et al. 2015). The varying results of seasonal trends in tree CH_4 emissions might indicate that tree-atmosphere CH_4 fluxes depend on multiple factors and an interaction among them (Barba et al. 2021). For example, studies have shown that tree-atmosphere CH_4 fluxes could vary with changing weather conditions, such as air temperature and precipitation (Schindler et al. 2021; Mander et al. 2022), which affect stem temperature, soil temperature and soil moisture. Tree-stem CH_4 emissions have been shown to have a positive correlation to stem temperature (Barba et al. 2021), soil temperature (Terazawa et al. 2015; Pitz et al. 2018; Barba et al. 2021; Terazawa et al. 2021) and soil moisture (Terazawa et al. 2015; Machacova et al. 2016; Pitz et al. 2018; Schindler et al. 2020; Barba et al. 2021; Terazawa et al. 2021).

The non-significant differences in tree-atmosphere CH_4 fluxes between the different tree species, as shown in this study, are supported by a study of Japanese alder and Manchurian ash in northern Japan (Terazawa et al. 2021). Another study has shown that tree-atmosphere CH_4 fluxes marginally differ between tree species (Pitz et al. 2018). However, studies have shown that tree-atmosphere CH_4 fluxes could vary with wood structural features, for example, stem density (Wang et al. 2016). Hence, a difference between silver birch and Norway spruce would be reasonable to assume, for the same reasons as for tree-atmosphere CO_2 fluxes. However, as previously discussed, since wood structural features depend on nutrient availability (Zhang 1995; Shanin et al. 2014), a difference between the wide buffer and narrow buffer would be reasonable to assume in this study. However, since the narrow buffer was upstream the wide buffer, the soil moisture deeper into the soil (deeper than 5 cm soil depth) was perhaps lower in the narrow buffer compared to wide buffer. Since soil moisture generally promote tree CH_4 emissions (Terazawa et al. 2015; Machacova et al. 2016; Pitz et al. 2018; Schindler et al. 2020; Barba et al. 2021; Terazawa et al. 2021), a higher soil moisture deeper into the soil in the wide buffer might compensated a higher nutrient availability in the narrow buffer. Nevertheless, neither the soil temperature nor the soil moisture differed between the buffer widths at 5 cm soil depth.

4.7 Evaluation of this study and the results

The BACI approach assumes that the control site and impact site are ecologically comparable (albeit not completely identical) in terms of all factors of importance expect the perturbation (Christie et al. 2020), for example, weather patterns and site characteristics, such as global radiation, annual average air temperature, annual average precipitation, soil type, soil temperature, soil moisture, stand age, dominant tree species and ground vegetation. In this study, the weather patterns in 2020 and

2021 in the control site near Svartberget and in the impact site near Trollberget in Vindeln municipality were similar (SMHI 2022a; SMHI 2022b; SMHI 2022c; SMHI 2022d). However, some of the site characteristics, in particular soil moisture, differed remarkably between the control site and impact site in 2020. In the control site, the soil moisture was higher relative to the impact site. In addition, in the impact site, the narrow buffer was topographically higher compared to the wide buffer and there was a mire upstream the narrow buffer. The differences in soil moisture between the control site and impact site, the differences in topography between the wide buffer and narrow buffer and the mire upstream the narrow buffer in the impact site could potentially have affected soil biogeochemical processes of importance for soil-atmosphere CO_2 and CH_4 fluxes. However, since the BACI approach accounts for the changes in the differences between the control site and impact site in the before period and after period, the results of the BACI analysis of soil temperature, soil moisture and soil-atmosphere CO_2 and CH_4 fluxes should be reliable.

The tree-atmosphere CO_2 and CH_4 fluxes were only measured in the impact site in 2021 due to insufficient time for measurements in the control site and due travel restrictions within the COVID-19 pandemic in 2020. Hence, clearcutting effects on tree-atmosphere CO_2 and CH_4 fluxes could not be tested, only differences between buffer widths and tree species after the clearcutting. However, comparing tree-atmosphere CO_2 and CH_4 fluxes between two buffer widths only after clearcutting might be insufficient for any general conclusions regarding whether the design of the RBZs matter in terms of GHG emissions. In addition, the spread of the tree roots was most likely not limited to the RBZs alone. Hence, biogeochemical processes in the soil outside the RBZs might affected the root uptake and the transport and accumulation of CO_2 and CH_4 in the living tissue and hence the tree-atmosphere CO_2 and CH_4 fluxes, which further complicates any general conclusions. In addition, 15 meters and 5 meters width might be an insufficient difference in order to draw any general conclusions regarding the measured factors in this study. Hence, the non-significant differences in soil temperature, soil moisture, soil-atmosphere CO_2 and CH_4 fluxes and tree-atmosphere CO_2 and CH_4 fluxes between the wide buffer and the narrow buffer might depended on the experimental setup in the impact site rather than the buffer widths *per se*.

Furthermore, in this study, no upscaling of the soil-atmosphere CO_2 and CH_4 fluxes or tree-atmosphere CO_2 and CH_4 fluxes was done. An upscaling could have been done by recalculating the fluxes in µmol m^{-2} s^{-1} to, for example, mg ha^{-1} h^{-1}. However, when upscaling tree-atmosphere fluxes, the total stem surface area of every tree (or an average of the different tree species in the site) needs to be calculated together with the tree density and stand basal area in the site (see e.g., Machacova et al. 2016) which was not possible within the time frame of this study. As follows, comparisons of magnitudes between soil-atmosphere fluxes and tree-atmosphere fluxes and magnitudes of tree-atmosphere fluxes between different tree species were not possible in this study. Hence, further research is needed.

4.8 Further research

To evaluate clearcutting effects on soil temperature, soil moisture and soil-atmosphere and tree-atmosphere CO_2 and CH_4 fluxes in RBZs and whether the design of them matter in that context, several equivalent sites with larger differences between the widths of RBZs could be included, e.g., RBZs of 2-30 meters width and sites with no RBZs at all. In addition, other designs of RBZs, expect fixed widths, could perhaps be evaluated, such as hydrologically adapted buffer zones, i.e., zones with variable widths, more adapted to site-specific conditions in terms of topography, physical dimensions and soil properties. Hydrologically adapted buffer zones could perhaps be a more appropriate design in terms of minimising GHG emissions (Tiwari et al. 2016). In addition, to evaluate the mechanisms behind the GHG fluxes in RBZs, a more holistic view of the soil-plant-atmosphere system is probably needed (Maier et al. 2018). Measurements of soil gas profiles and automated continuous measurements of the soil-atmosphere and tree-atmosphere GHG fluxes which detect hot moments would perhaps facilitate the understanding of the pattern of GHG fluxes in RBZs. In addition, other measurement depths for soil temperature and soil moisture could be included to investigate mechanisms in a larger part of the soil profile. Furthermore, an upscaling of the soil-atmosphere and tree-atmosphere GHG fluxes would perhaps facilitate the understanding of the results at a stand level which in turn would enable an implementation of the results in the practical forestry in boreal forests.

4.9 Implications for forestry in boreal forests

In this study, soil temperature correlated with soil-atmosphere CH_4 fluxes, albeit not only emissions. In other studies, soil temperature has been shown to be an affecting factor of both soil-atmosphere CH_4 and CO_2 fluxes (e.g., Silverthorn and Richardson 2021). Hence, RBZs with stable canopies that prevent an increase in soil temperature in the RBZs would be recommended, i.e., probably more than just one or two rows of trees, which is a common practice in Sweden to date (Kuglerová et al. 2020). Leaving wider RBZs, e.g., 20-30 meters, would, according to other studies, perhaps also decrease the soil disturbance in the RBZs due to lower impacts on the soil from forestry machines and due to more stable groups of trees less sensitive to wind which could promote windthrows. Decreased soil disturbances in the RBZs could, in turn, reduce a change in chemical reactions responsible for GHG emissions from nearby water bodies, soil and vegetation (Gundersen et al. 2010; Silverthorn & Richardson 2021). However, whether wider RBZs decrease the soil disturbance and hence reduce GHG emissions from nearby water bodies, soil and vegetation is beyond the results of this study.

5. Conclusions

This study showed significant clearcutting effects on soil temperature with higher soil temperature in the narrow buffer, relative to the control site, in 2021 relative to 2020. No significant clearcutting effects on soil moisture were however shown. In addition, this study showed significant clearcutting effects on soil-atmosphere CH_4 fluxes with lower uptake in the narrow buffer relative to the control site, in 2021 relative to 2020. No significant clearcutting effects on soil-atmosphere CO_2 fluxes were however shown. Furthermore, no significant differences in soil temperature, soil moisture, soil-atmosphere CO_2 and CH_4 fluxes or tree-atmosphere CO_2 and CH_4 fluxes between the wide buffer and narrow buffer and no significant differences in tree-atmosphere CO_2 and CH_4 fluxes between silver birch and Norway spruce were shown. Hence, according to this study, the design of the RBZs, or more specifically the width, had no effect on CO_2 and CH_4 emissions from soil and vegetation in the RBZs. Since soil-atmosphere CO_2 and CH_4 fluxes and tree-atmosphere CO_2 and CH_4 fluxes seem to depend on multiple factors and an interaction among them, a more holistic view of the soil-plant-atmosphere system is probably needed in further research. However, since other studies indicate that RBZs most likely maintains a biogeochemical balance in the soil in the RBZs and in the water in nearby water bodies, compared to no RBZs at all, leaving stable RBZs during clearcutting would be recommended. Moreover, the results of this study should not diminish the importance of leaving wider RBZs for other benefits, such as minimising the soil disturbance in biogeochemical hotspots and hence prevent runoff and export of organic and inorganic materials, which otherwise could affect the water quality and water biodiversity. In conclusion, although more research is needed, this study was however a path towards climate optimised riparian buffer zones in boreal forests in future.

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Populärvetenskaplig sammanfattning

Ökade utsläpp och därmed ökade koncentrationer växthusgaser i atmosfären är en världsomfattande utmaning. Ökade koncentrationer av framförallt koldioxid (CO_2) och metan (CH_4) i atmosfären bidrar till en förstärkt växthuseffekt med klimatförändringar som följd. Klimatförändringarna leder till ändrade vädermönster vilket bland annat innebär mer frekventa och intensiva torrperioder, skogsbränder, stormar och översvämningar. Mänskliga störningar i ekosystemen, exempelvis skogsbruk, är en bidragande orsak till ökade utsläpp av CO_2 och CH_4 till atmosfären. Ändrade markförhållanden efter en kalavverkning leder till bildning av CO_2 och CH_4 i marken vilket i sin tur kan tas upp och släppas ut av mark och vegetation, särskilt i fuktiga områden nära vattendrag, s.k. strandnära zoner, där markförhållandena för de bakomliggande kemiska processerna är extra gynnsamma. Tidigare studier har visat att de strandnära zonerna är viktiga ur många ekosystemperspektiv och att de, om de lämnas orörda vid kalavverkning som s.k. strandnära kantzoner (vanligen kallade kantzoner), kan bidra till minskad transport av organiska och oorganiska material till vattendrag som annars skulle kunna bidra till ökade utsläpp av CO_2 och CH_4 från vattendragen efter kalavverkningen. I Sverige finns idag (2022) inga lagar huruvida de strandnära zonerna ska lämnas vid kalavverkning och om de lämnas är det upp till den som planerar eller utför kalavverkningen att bestämma utformningen, ofta snarare ur ett biodiversitetsperspektiv än ur ett växthusgasperspektiv. Kunskap huruvida utformningen påverkar markförhållandena och utsläppen av CO_2 och CH_4 från vegetationen i de strandnära kantzonerna skulle kunna bidra till en förbättrad svensk skogbrukspolicy och mer klimatoptimerade strandnära kantzoner i boreala skogar i framtiden.

Denna studie syftade till att jämföra marktemperatur, markfuktighet samt markflöden av CO_2 och CH_4 i en bred (15 meter) och en smal (5 meter) kantzon före och efter kalavverkning i en boreal skog i Vindelns kommun i Västerbotten. Mätningarna jämfördes med mätningar i en annan likvärdig boreal skog i närheten, som inte kalavverkades under mätningsperioden. Mätningar av trädflöden av CO_2 och CH_4 gjordes även i kantzonerna efter kalavverkningen och en jämförelse mellan de dominerande trädslagen vårtbjörk (*Betula pendula* Roth) och rödgran (*Picea abies* (L.) H. Karst) gjordes.

Resultaten visade en signifikant ökning i marktemperatur i den smala kantzonen efter kalavverkningen jämfört med skogen som inte kalavverkades. Ingen signifikant skillnad i markfuktighet kunde däremot påvisas. Resultaten visade heller ingen signifikant skillnad i markflöden av CO_2 före och efter kalavverkning, däremot visade resultaten en minskning i markupptag av CH_4 efter kalavverkning i den smala kantzonen jämfört med skogen som inte kalavverkades. Ingen signifikant skillnad i marktemperatur, markfuktighet eller markflöden av CO_2 och CH_4 mellan den breda och den smala kantzonen kunde däremot påvisas. Ingen signifikant skillnad i trädflöden av CO_2 och CH_4 mellan den breda och den smala kantzonen kunde heller påvisas och heller ingen signifikant skillnad i trädflöden av CO_2 och CH_4 mellan de två trädslagen. Resultaten i denna studie visade således att utformningen på de strandnära kantzonerna inte tycks påverka utsläppen av CO_2 och CH_4 från mark och vegetation. Eftersom studien däremot visade att marktemperaturen ökade efter kalavverkningen, bör stabila strandnära kantzoner med tillräcklig krontäckning lämnas för att minska risken för ytterligare höjningar av marktemperaturen som, enligt flertalet tidigare studier, annars skulle kunna bidra till ökade markflöden av CO_2 och CH_4.

Mer forskning behövs, exempelvis på flera olika bredder på kantzoner med större skillnad än 15 och 5 meter samt mätning av marktemperatur och markfuktighet på andra jorddjup än 5 centimeter som i denna studie, för att få en helhetsbild av omsättningen av växthusgaser i strandnära kantzoner i samband med kalavverkning. Slutligen ska denna studie dock inte minska vikten av att lämna breda strandnära kantzoner av andra anledningar än ur växthusgasperspektiv, exempelvis för att minska störning på marken ur ett vattenkvalitetsperspektiv och vattenbiodiversitetsperspektiv. Även om mer forskning behövs, kan denna studie ändå bidra till mer klimatoptimerade strandnära kantzoner i framtiden.

Acknowledgements

Firstly, I want to thank my supervisor Marcus Klaus who has been with me throughout the study period and has helped me with the field work, statistics and report writing. He has always answered all my questions very quickly and pedagogically. Secondly, I want to thank Hilda Edlund for her help with some statistical interpretations and my assistant supervisors Mats Öquist and Katerina Machacova for their inputs to the report. I also want to thank my family and my friends for their mental support throughout this study period. This study was definitely a great end to my five years of university studies at SLU in Umeå!

Appendix 1

Supplementary BACI analysis statistics of soil temperature

Table A1a. BACI analysis probability values of significant effects on a 5% alpha level. Time is the probability of significant clearcutting effect in narrow buffer, Width is the probability of significant difference between narrow and wide buffer in before period and Time:Width is the probability of significant difference in clearcutting effect between narrow and wide buffer. Const. is the probability that a constancy of control-impact differences in before period is violated, Add. is the probability that "no additivity" is violated, Autocorr. is the probability that "no autocorrelation" is violated and Norm. is the probability that BACI model residuals are not normal. Failed is the proportion of failed analyses of the 1000 randomly sampled combinations (in these cases, the model did not converge to provide a sensible solution)

Time	*Width*	*Time:Width*	*Const.*	*Add.*	*Autocorr.*	*Norm.*	*Failed*
0.8747	0	0.0071	0.0118	0.0248	0.5296	0.5579	0.1532

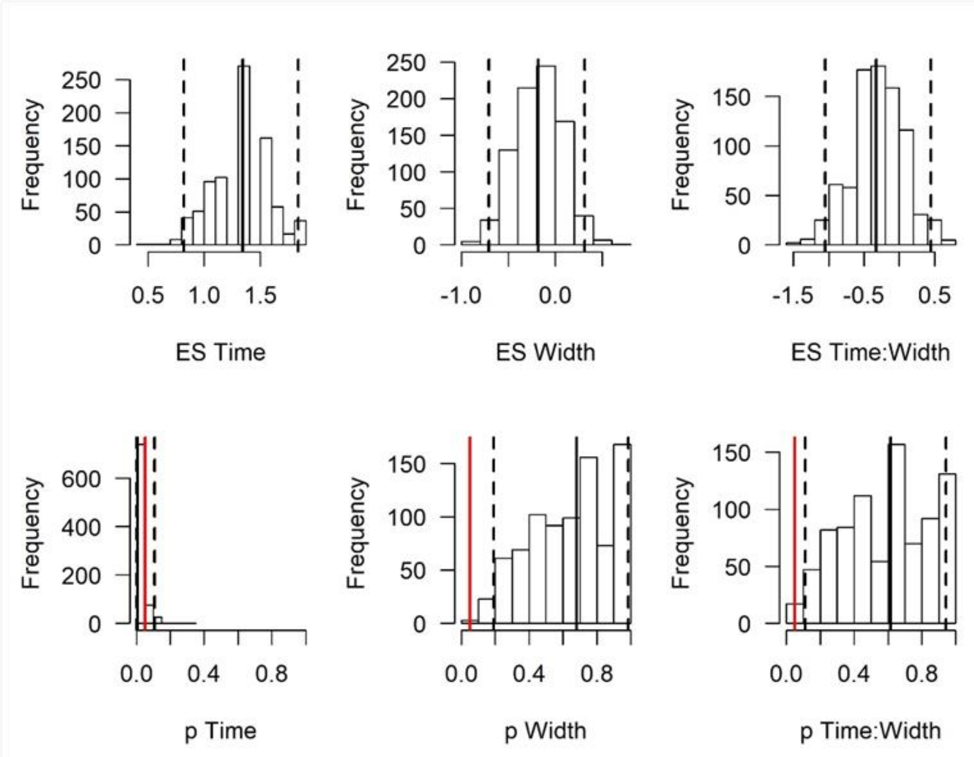

Figure A1. Histograms with frequency distribution of treatment effect (Time), buffer effect (Width) and their interaction (Time:Width) based on bootstrapping of the BACI model among the 1000 random samples of combinations of matching control and impact sites. The black vertical line shows the median and the dashed vertical lines show the 95% confidence interval. ES is the effect size and p is the probability value. The red vertical line shows the alpha level 0.05.

Table A1b. BACI analysis probability values of the BACI model assumptions “constancy of differences”, “no additivity”, “no autocorrelation” and “normality of BACI model residuals” and their median, standard deviation and 2.5% and 97.5% quantiles for 95% confidence intervals. Const. is the probability that a constancy of control-impact differences in before period is violated, Add. is the probability that “no additivity” is violated, Autocorr. is the probability that “no autocorrelation” is violated and Norm. is the probability that BACI model residuals are not normal

				CONFIDENCE INTERVAL	
Parameter	*Measure*	*Median*	*St. dev*	*2.5%*	*97.5%*
Const.	P value	0.6400	0.2525	0.0800	0.9700
Add.	P value	0.6400	0.2729	0.0500	0.9700
Autocorr.	P value	0.0600	0.1950	0	0.7005
Norm.	P value	0.0414	0.0948	0.0033	0.3453

Appendix 2

Supplementary BACI analysis statistics of soil moisture

Table A2a. BACI analysis probability values of significant effects on a 5% alpha level. Time is the probability of significant clearcutting effect in narrow buffer, Width is the probability of significant difference between narrow and wide buffer in before period and Time:Width is the probability of significant difference in clearcutting effect between narrow and wide buffer. Const. is the probability that a constancy of control-impact differences in before period is violated, Add. is the probability that "no additivity" is violated, Autocorr. is the probability that "no autocorrelation" is violated and Norm. is the probability that BACI model residuals are not normal. Failed is the proportion of failed analyses of the 1000 randomly sampled combinations (in these cases, the model did not converge to provide a sensible solution)

Time	*Width*	*Time:Width*	*Const.*	*Add.*	*Autocorr.*	*Norm.*	*Failed*
0.0315	0.0132	0	0.3838	0.1269	0.3868	0.0467	0.0140

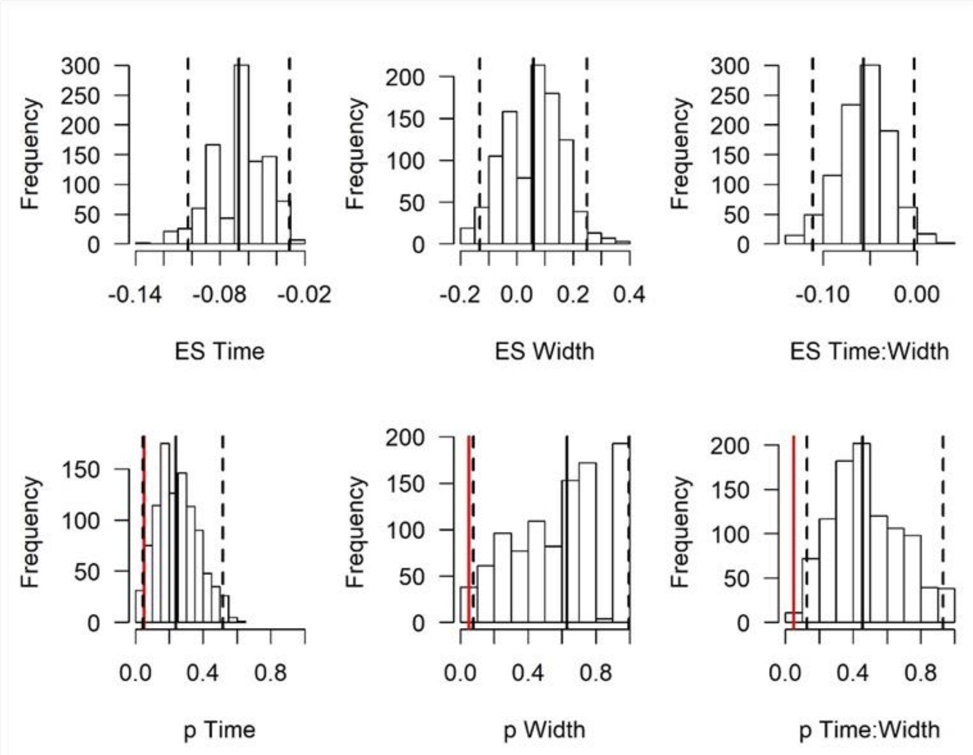

Figure A2. Histograms with frequency distribution of treatment effect (Time), buffer effect (Width) and their interaction (Time:Width) based on bootstrapping of the BACI model among the 1000 random samples of combinations of matching control and impact sites. The black vertical line shows the median and the dashed vertical lines show the 95% confidence interval. ES is the effect size and p is the probability value. The red vertical line shows the alpha level 0.05.

Table A2b. BACI analysis probability values of the BACI model assumptions "constancy of differences", "no additivity", "no autocorrelation" and "normality of BACI model residuals" and their median, standard deviation and 2.5% and 97.5% quantiles for 95% confidence intervals. Const. is the probability that a constancy of control-impact differences in before period is violated, Add. is the probability that "no additivity" is violated, Autocorr. is the probability that "no autocorrelation" is violated and Norm. is the probability that BACI model residuals are not normal

				CONFIDENCE INTERVAL	
Parameter	*Measure*	*Median*	*St. dev*	*2.5%*	*97.5%*
Const.	P value	0.0700	0.0944	0	0.3500
Add.	P value	0.2200	0.2346	0	0.8078
Autocorr.	P value	0.0800	0.2131	0	0.7205
Norm.	P value	0.2205	0.2336	0.0316	0.8975

Appendix 3

Supplementary BACI analysis statistics of soil-atmosphere CO_2 fluxes

Table A3a. BACI analysis probability values of significant effects on a 5% alpha level. Time is the probability of significant clearcutting effect in narrow buffer, Width is the probability of significant difference between narrow and wide buffer in before period and Time:Width is the probability of significant difference in clearcutting effect between narrow and wide buffer. Const. is the probability that a constancy of control-impact differences in before period is violated, Add. is the probability that “no additivity” is violated, Autocorr. is the probability that “no autocorrelation” is violated and Norm. is the probability that BACI model residuals are not normal. Failed is the proportion of failed analyses of the 1000 randomly sampled combinations (in these cases, the model did not converge to provide a sensible solution)

Time	*Width*	*Time:Width*	*Const.*	*Add.*	*Autocorr.*	*Norm.*	*Failed*
0	0.0128	0	0	0.0023	0.0128	0.3449	0.1390

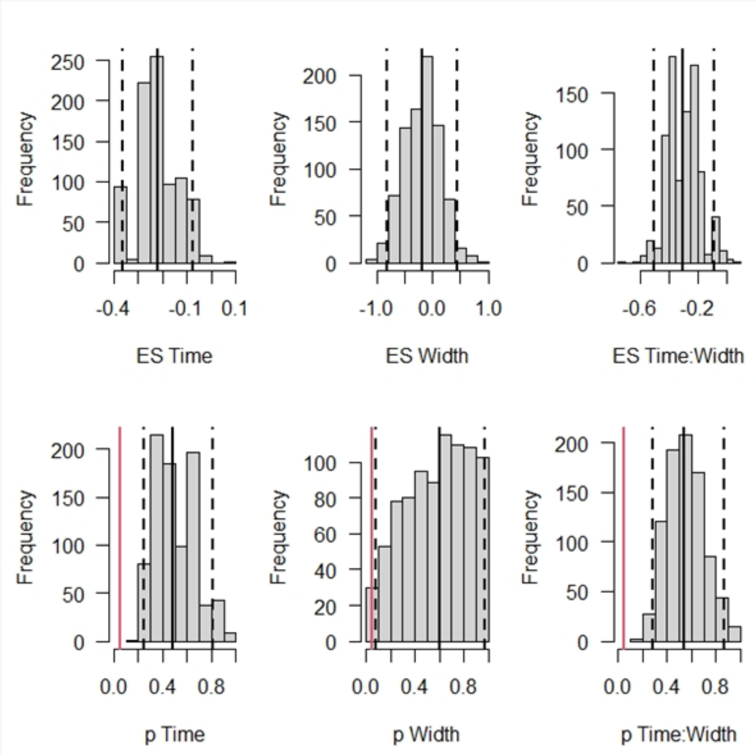

Figure A3. Histograms with frequency distribution of treatment effect (Time), buffer effect (Width) and their interaction (Time:Width) based on bootstrapping of the BACI model among the 1000 random samples of combinations of matching control and impact sites. The black vertical line shows the median and the dashed vertical lines show the 95% confidence interval. ES is the effect size and p is the probability value. The red vertical line shows the alpha level 0.05.

Table A3b. BACI analysis probability values of the BACI model assumptions "constancy of differences", "no additivity", "no autocorrelation" and "normality of BACI model residuals" and their median, standard deviation and 2.5% and 97.5% quantiles for 95% confidence intervals. Const. is the probability that a constancy of control-impact differences in before period is violated, Add. is the probability that "no additivity" is violated, Autocorr. is the probability that "no autocorrelation" is violated and Norm. is the probability that BACI model residuals are not normal

				CONFIDENCE INTERVAL	
Parameter	*Measure*	*Median*	*St. dev*	*2.5%*	*97.5%*
Const.	P value	0.7400	0.1531	0.4000	0.9800
Add.	P value	0.6700	0.2273	0.1500	0.9800
Autocorr.	P value	0.7650	0.2768	0.0800	1
Norm.	P value	0.1498	0.2961	0.0006	0.9219

Appendix 4

Supplementary BACI analysis statistics of soil-atmosphere CH_4 fluxes

Table A4a. BACI analysis probability values of significant effects on a 5% alpha level. Time is the probability of significant clearcutting effect in narrow buffer, Width is the probability of significant difference between narrow and wide buffer in before period and Time:Width is the probability of significant difference in clearcutting effect between narrow and wide buffer. Const. is the probability that a constancy of control-impact differences in before period is violated, Add. is the probability that "no additivity" is violated, Autocorr. is the probability that "no autocorrelation" is violated and Norm. is the probability that BACI model residuals are not normal. Failed is the proportion of failed analyses of the 1000 randomly sampled combinations (in these cases, the model did not converge to provide a sensible solution)

Time	*Width*	*Time:Width*	*Const.*	*Add.*	*Autocorr.*	*Norm.*	*Failed*
0.5655	0.0551	0.0374	0	0.0208	0.2328	0.8503	0.0380

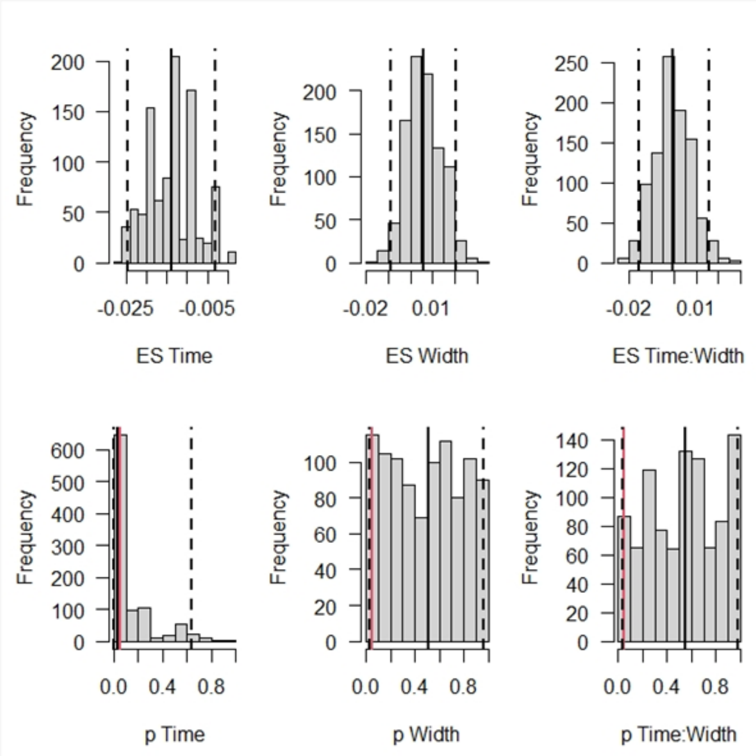

Figure A4. Histograms with frequency distribution of treatment effect (Time), buffer effect (Width) and their interaction (Time:Width) based on bootstrapping of the BACI model among the 1000 random samples of combinations of matching control and impact sites. The black vertical line shows the median and the dashed vertical lines show the 95% confidence interval. ES is the effect size and p is the probability value. The red vertical line shows the alpha level 0.05.

Table A4b. BACI analysis probability values of the BACI model assumptions "constancy of differences", "no additivity", "no autocorrelation" and "normality of BACI model residuals" and their median, standard deviation and 2.5% and 97.5% quantiles for 95% confidence intervals. Const. is the probability that a constancy of control-impact differences in before period is violated, Add. is the probability that "no additivity" is violated, Autocorr. is the probability that "no autocorrelation" is violated and Norm. is the probability that BACI model residuals are not normal

				CONFIDENCE INTERVAL	
Parameter	*Measure*	*Median*	*St. dev*	*2.5%*	*97.5%*
Const.	P value	0.8600	0.1243	0.5400	0.9900
Add.	P value	0.6500	0.2553	0.0600	0.9800
Autocorr.	P value	0.2000	0.2440	0	0.8100
Norm.	P value	0.0013	0.0800	0	0.2791

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Wildfire dynamics, local people's fire use and underlying factors for wildfires at Liwale

2021:13 Författare: Martina Lundkvist
Samband mellan ståndortsfaktorer, genetik och historiska skördedata från tall- och granfröplantager – krävs ökad precision vid val av lokaler för nyafröplantager?

2021:14 Författare: Maria Grånemo
"I stand here. I will not move" – Women in forestry in northern Sweden during the 20th century

2021:15 Författare: Tim Schacherl
Evaluating Drought Impacts on Ecosystem Water Use Efficiency of Three Different Boreal Forest Sites

2022:01 Författare: Alice Cosatti
The end of the timber frontier in northern Sweden – Early logging, natural forests and the frontier concept

2022:02 Författare: Pontus Nyqvist
Utvärdering av metod för att morfologiskt särskilja björkarterna Betula pendula och Betula pubescens

2022:03 Författare: Julia Nygårdh
Mosippans (Pulsatilla vernalis L.) reaktion på brandstörning – En populationsstudie på en av Sveriges rikaste mosippslokaler

2022:04 Författare: Oskar Karlsson
Effects on natural seed regenerated Silver birch (Betula pendula Roth) and Downey birch (Betula pubescens Ehrh) by mechanical soil scarification and environmental factors

2022:05 Författare: Eric Lundqvist
Riparian forests – a comparison of tree diversity, deadwood and canopy cover between primary and production riparian forests along headwaters

2022:06 Författare: Louise Nordström
Growth and development of Eucalyptus grandis seedlings in response to arginine phosphate application

2022:07 Författare: Alice Falk
Towards climate optimised riparian buffer zones in boreal forests. Investigation of clearcutting effects on soil temperature, soil moisture and greenhouse gas fluxes in riparian buffer zones with different widths