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RESEARCH

# Production of greenhouse gases by logging residue in boreal clear-cut forests

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## Abstract

Forest deadwood is an important carbon reserve, estimated to contain 8% of the total forest carbon. This type of woody debris is recognized as a source of carbon dioxide ($CO_2$), as the carbon is released back into the atmosphere by microbial decomposition. Production of methane ($CH_4$) and nitrous oxide ($N_2O$) has also been reported. In managed forests, logging residues form a major source of fine deadwood, but its role in the greenhouse gas exchange of forest ecosystems is poorly understood. We studied the greenhouse gas production of spruce and birch left-over fine woody debris and estimated the residence time of these residues at 18 spruce-dominated boreal forest sites in Central Finland. The study areas consisted of clear-cut forest stands, totally covering approximately 47 hectares, with logging residue ages varying between 0 and 10 years. The research was carried out over eight months from May to December 2019. We observed that $CO_2$ dominated the greenhouse gas production of the logging residues, with the production being regulated by air temperature, tree species, residue age, and wood moisture. Emission of $CO_2$ continued throughout the research period with a clear seasonal pattern. Production of $CH_4$ and $N_2O$ was also observed, but not in climatically-relevant amounts. Deadwood half-life was estimated at 18 years for spruce and 9 years for birch. Our study demonstrates that logging residues form a mid-term carbon reserve and suggests that global warming could reduce the lifetime of the residues as a result of elevated and temperature-dependent $CO_2$ release in the studied *Myrtillus* type forest stands.

**Keywords** Carbon dioxide · Deadwood · Decomposition · Fine woody debris · Methane · *Picea abies*

## Introduction

Forest deadwood forms a globally large and potentially long-lived carbon reserve (e.g., Harmon et al. 1986, 2020), being an important part of the natural carbon cycle. Woody debris is estimated to contain 73 Pg of carbon, representing approximately 8% of the total forest carbon storage (Pan et al. 2011). Deadwood – which is especially abundant in old-growth forests (Siitonen et al. 2000) – is important for forest biodiversity, providing habitats for animals, fungi, invertebrates, and plants (Harmon et al. 1986; Dittrich et al. 2014; Seibold et al. 2015; Fukasawa 2021). However, deadwood also forms a significant carbon dioxide ($CO_2$) source when the carbon is recycled back into the atmosphere as $CO_2$ by microbial decomposition. A recent estimate for global carbon release from deadwood is high, 10.9 ± 3.2 Pg yearly, with 93% originating from tropical forests (Seibold et al. 2021). Previous studies have also reported the production of methane ($CH_4$) and nitrous oxide ($N_2O$) (Mukhin and Voronin 2009; Covey et al. 2016; Pastorelli et al. 2017, 2021;

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Warner et al. 2017; Carmichael et al. 2018; Jeffrey et al. 2019; Mukhortova et al. 2021; Kipping et al. 2022; Martinez et al. 2022) in deadwood. However, extensive measurements including all three greenhouse gases are still lacking.

In boreal unmanaged late-successional forests, deadwood volumes typically equal 41–170 $m^3$ $ha^{-1}$, being up to half of the total wood volumes, with expected half-life of spruce snags (standing dead trees) varying from 12 to 27 years and downed woody debris from 20 to 40 years (Aakala 2010). In a Swiss forest study, the carbon half-life in the log pool varied from 11 years in the warmest study plots to 65 years in the coldest plots, and in the snag pool from 22 to 118 years, with the main drivers of the decay rate (besides soil connection) being tree species, temperature, and precipitation (Hararuk et al. 2020). Accurate prediction of deadwood decomposition rate and lifetime has proven to be challenging, as decomposition is regulated by several factors – e.g., temperature, moisture, oxygen ($O_2$) availability, log size and position, tree species, and weather conditions – and the lifetime of downed deadwood can vary from just a few years to centuries (Harmon et al. 1986, 2020; Laiho and Prescott 2004; Mäkinen et al. 2006; Rock et al. 2008; Forrester et al. 2012; Jomura et al. 2012; Vanderhoof et al. 2013; Russell et al. 2015). While the deadwood in late-successional forests consists mainly of coarse woody debris (CWD), the main stock of deadwood in managed forests is fine woody debris (FWD, diameter < 10 cm) in the form of logging residues (Siitonen et al. 2000; Siitonen 2001; Harmon 2021). These residues are produced during harvesting and management operations and include woody debris – left-over treetops and larger branches – as well as litter – needles, leaves, bark, and twigs. In clear-cuts, deadwood total volumes have been estimated as 26.0–42.3 $m^3$ $ha^{-1}$, dependent on whether the fuel harvesting has been conducted or not (Eräjää et al. 2010).

In the forests of the European Union, over 200 million cubic meters of logging residues is produced annually, of which approximately one-sixth is produced in Finland (Asikainen et al. 2008). These residues – especially needles and leaves – form an important nutrient source for nutrient-deficient forest soils (Mälkönen et al. 2001). To reduce nutrient removal in Finnish boreal forests, 30% of the residual tree biomass is recommended to be left on the logging site, if residues are harvested soon after logging (Äijälä et al. 2019). This is typically fulfilled when seasoned spruce residues are harvested from the logging sites (Peltola et al. 2011). The remaining logging residues form an additional deadwood source, enhance biodiversity, and serve as a source of greenhouse gases. Piirainen et al. (2015) reported that logging residues in boreal forests do not necessarily increase soil carbon content, but over the decomposition time, a large fraction of carbon from the residues is lost into the atmosphere as $CO_2$. Similarly, when forest energy storage was studied in Finland, small-size energy wood lost 0.07–1.52% dry matter per month, probably as $CO_2$, when stored in piles (Routa et al. 2018). Previously, it has been observed, that logging residues can promote the decomposition of soil organic matter below the residues, and hence increase the release of greenhouse gases from the soil (Mäkiranta et al. 2012). The greenhouse gas exchange of the logging residue itself – however – is poorly understood.

We studied the production of greenhouse gases $CO_2$, $CH_4$, and $N_2O$ in spruce and birch FWD (treetop residue) in the field at boreal forest sites, and examined, how the gas production is affected by tree species, air temperature, logging residue age, and wood moisture content. These were chosen as relevant criteria, as deciduous trees generally have a faster decay rate than conifers (Harmon et al. 1986; Pearce 1996; Weedon et al. 2009; Kahl et al. 2015, 2017), with temperature and wood moisture as the primary drivers of the decomposition process (Rock et al. 2008). We also aimed to explore whether the air temperature and residue age could be used to predict the greenhouse gas release rate. The half-life and lifetime of the logs were also estimated. It was hypothesized that along with the production of $CO_2$, logging residues have the potential to produce stronger gases $CH_4$ and $N_2O$. We assumed that especially $CO_2$ production varies seasonally, with production being connected to tree species and regulated by air temperature, wood moisture, and logging residue age. Logs were thought to remain in the forest for several decades, forming simultaneously a carbon storage and a greenhouse gas source.

## Materials and methods

### Field sampling

To study the greenhouse gas exchange and the residence time of logging residues, we carried out an extensive, eight-month-long field campaign from May to December 2019. For the study, we selected 18 clear-cut forest areas (Table 1). Site areas were 0.5–6 hectares with total forest coverage of approximately 47 hectares. The site selection was based on even logging residue age distribution between 0 and 10 years, landowner permissions, and site access also during the snow cover. All forest stands were located around Petäjävesi, Central Finland (62.26°N, 25.20°E), with elevations ranging from 131 to 222 m above sea level. According to the Finnish forest type classification system (Cajander 1949), the selected forest type was a mesic heath forest, which was further classified as a *Myrtillus* type forest. The *Myrtillus* type forest is the most common forest type in the area, with dominating tree species being Norway spruce

**Table 1** Basic characteristics of the 18 forest sites. The age of logging residue is calculated for the beginning of the study (May)

| Site number | Area (ha) | Time of harvest (month/year) | Residue age (years) | Elevation (m) | Coordinates (WGS84) | |
|---|---|---|---|---|---|---|
| | | | | | °N | °E |
| 1 | 0.5 | 01/2019 | 0.4 | 222 | 62.3959 | 25.2708 |
| 2 | 2.4 | 12/2018 | 0.5 | 203 | 62.4103 | 25.2617 |
| 3 | 1.9 | 04/2018 | 1.1 | 131 | 62.2435 | 25.1605 |
| 4 | 1.9 | 01/2017 | 2.4 | 219 | 62.4065 | 25.2620 |
| 5 | 2.4 | 06/2016 | 3.0 | 188 | 62.2394 | 25.1169 |
| 6 | 2.5 | 05/2016 | 3.0 | 216 | 62.4086 | 25.2591 |
| 7 | 2.1 | 05/2015 | 4.0 | 200 | 62.4035 | 25.2739 |
| 8 | 2.8 | 12/2014 | 4.5 | 208 | 62.4025 | 25.2710 |
| 9 | 4.3 | 03/2014 | 5.2 | 168 | 62.2392 | 25.0784 |
| 10 | 3.0 | 05/2013 | 6.0 | 203 | 62.3852 | 25.2563 |
| 11 | 3.9 | 10/2012 | 6.6 | 177 | 62.2420 | 25.1382 |
| 12 | 4.6 | 10/2012 | 6.6 | 159 | 62.2423 | 25.1461 |
| 13 | 0.8 | 08/2011 | 7.8 | 213 | 62.3874 | 25.2658 |
| 14 | 6.0 | 06/2011 | 8.0 | 203 | 62.3834 | 25.2554 |
| 15 | 3.0 | 05/2011 | 8.0 | 213 | 62.3909 | 25.2688 |
| 16 | 2.0 | 08/2010 | 8.8 | 211 | 62.3874 | 25.2678 |
| 17 | 1.9 | 08/2010 | 8.8 | 201 | 62.3876 | 25.2727 |
| 18 | 0.9 | 08/2010 | 8.8 | 213 | 62.3905 | 25.2688 |

(*Picea abies*), Scots pine (*Pinus sylvestris*), and birch (*Betula* sp.) (Hotanen et al. 2018). Shrubs are dominated by bilberry (*Vaccinium myrtillus*) and mosses with *Pleurozium schreberi* and *Hylocomium splendens* (Hotanen et al. 2018). In 2019, the annual mean temperature was 4.4 °C, and the total rainfall was 837 mm in the area (Fig. 1a); the ground was covered with snow during January – May and October – December, with the highest snow depth (70 cm) reached in February (Finnish Meteorological Institute 2023).

All research areas were clear-cut forests with a cut age of 0.4–8.8 years at the beginning of the study in May, with the age of the oldest site being extended to 9.3 years at the end of the study in December. This was observed to be a practical maximum for logging residue age, as residues got increasingly difficult to find in the oldest cuts due to wood decomposition and undergrowth. Forest management operations also produce additional debris and litter. In older cuts, the identification of woody debris as logging residue would have been uncertain. In this study, we were able to accurately date the collected logs – here referred to as logging residue age – as the clear-cut date was well-documented.

The study focused on Norway spruce and birch (*Betula* sp.), as spruce was the dominating tree in selected research areas, and birch was the most common deciduous tree. Gas production from FWD was measured once a month in all study areas. From each site, we collected logging residues of spruce and birch by randomly walking in the area; each month, new logs were collected. Logs originated from treetops, which had not been harvested for further use. Using a handsaw, the selected larger logs were sawn into smaller logs with an average log length of 35 cm, so that they could fit inside a chamber used for the flux measurement. Possible branches were cut off. The generated sawdust was collected into clean 100 ml plastic cans for further analysis of moisture and dry matter content; cans were stored in a cold storage box right after the sawdust collection. Finally, the logs that would be used for the gas flux measurement were weighed.

On average, six kilograms of logs (eight liters in volume) were placed inside the chambers. The chambers were gas-tight portable polypropylene boxes with a volume of 32 l; removable lid was equipped with a rubber sealant and a septum for gas sampling. With logs inside, chambers were closed for two hours in shade to avoid direct sunlight from heating the chamber. Gas samples were taken 15, 30, 60, and 120 minutes after the chamber was closed, and injected immediately into 12 ml glass vials (Labco Exetainer). The ambient air temperature was recorded during the chamber measurement. After the measurement, volume of the residues was determined by submerging the logs into water. The total amount of logging residue studied was approximately 1674 kg (equals approximately 2.3 $m^3$). A total number of measurements performed during the field study was 288.

The data from the field measurements from May – December (Fig. 4c, d) was used to predict the annual $CO_2$ production rate, as the measurements showed a clear connection between $CO_2$ production and air temperature. First, the monthly $CO_2$ production rates were estimated from monthly mean air temperatures (Fig. 1a) of each month in 2019, which were obtained from the nearest weather station located in Jyväskylä Airport (62.40°N, 25.67°E). Data was provided by the Finnish Meteorological Institute. The monthly fluxes were further used to estimate the cumulative annual $CO_2$ production.

### Temperature incubations

We also studied the temperature dependency of greenhouse gas production of the logging residues. Gas flux measurements were carried out in the laboratory at three different environmentally realistic temperatures of +12, +20, and +28 °C, which are in the range of temperature optimum for most wood-decaying fungi (Harmon et al. 1986). The laboratory measurements were carried out every second month with samples collected from the field sites. Logging residues of different ages (approximately 3, 5, and 8 years) were selected for the measurements, which represented similar age distribution as in field measurements. We used the data from laboratory measurements along with field data to determine the Quotient 10 ($Q_{10}$) value for a temperature range of +15 – +25 °C. $Q_{10}$ was used to estimate how much $CO_2$ production rate in logging residues increase when temperature rises by 10 °C.

### Laboratory analysis

Greenhouse gas ($CO_2$, $CH_4$, and $N_2O$) concentrations were analysed with an Agilent Technologies 7890B GC System gas chromatograph equipped with a thermal conductivity detector (TCD) for $CO_2$, flame ionization detector (FID) for $CH_4$, and electron capture detector (ECD) for $N_2O$. The gas production rate was calculated as g $m^{-3}$ $h^{-1}$, which determines how many grams (grams for $CO_2$; mg for $CH_4$ and $N_2O$) of gas one cubic meter of logging residue produced during one hour. Greenhouse gas production rates of $CH_4$ and $N_2O$ were also calculated as $CO_2$ equivalents. The 20-year global warming potential ($GWP_{20}$) values of 79.7 and 273 (IPCC 2021) were used for estimating the significance of $CH_4$ and $N_2O$ emissions, respectively.

Dry matter and moisture contents of logging residues were determined by drying the collected sawdust at 105 °C for approximately 20 h. Logging residue density was calculated as kg DW (dry weight) $m^{-3}$. The decay rate of logging residue was estimated from the wood density data by applying a single negative exponential model – a commonly used method to estimate the rate of deadwood decomposition (Harmon et al. 1986, 2020).

### Statistical analysis

Statistical testing was performed with IBM SPSS Statistics 26 and R (version 3.6.3) (R Core Team 2020). The differences in the moisture content and in $CO_2$ production in laboratory conditions between tree species were tested with t-test, and the differences in the greenhouse gas exchange between tree species in the field measurements with Mann-Whitney U-test, as the normality assumptions were not met. The relationship between wood density and logging residue age was examined with exponential non-linear regression analysis, separately for spruce and birch. The models were used to estimate the decomposition rate-constant ($k$), and the time that was required to decompose 50 and 95% of the initial logging residue biomass, later referred to as logging residue half-life and lifetime. The relationship between $CO_2$ production and air temperature in field and laboratory conditions was examined with exponential non-linear regression analysis, and the relationship between $CO_2$ production and logging residue age or moisture content was examined with linear regression analysis, both separately for spruce and birch.

## Results

### Moisture content and density of the logging residues

Moisture contents of both spruce and birch logging residues followed a seasonal pattern (Fig. 1b). The average (± SE) moisture content during the eight-month study was 44.1 ± 1.4% in spruce and 51.3 ± 1.5% in birch, with birch having significantly higher moisture content than spruce (t-test, t(286) = -3.449, $P = 0.001$). Moisture content of logging residue varied in a wide range; 7.2–80.6% for spruce and 16.9–88.6% for birch. The lowest monthly average moisture contents were observed in July; 27.0 ± 4.6% for spruce and 37.8 ± 4.5% for birch, and the lowest measured moisture contents in single forest sites for spruce and birch were 7.2 and 16.9%, respectively. The highest monthly average moisture contents were observed at the end of the year, in October for spruce (54.7 ± 2.7%), and in November for birch (60.9 ± 3.6%).

Logging residue density (kg DW $m^{-3}$) of both spruce and birch decreased with increasing logging residue age (Fig. 2a, b). There was a high variation in densities even in logging residues of similar age, and in the monthly deadwood density values from the same sampling areas. Dry weight measurement was repeated for November samples, but the repeated analysis did not explain the variation in the density results. By fitting an exponential model to the wood density data, decomposition rate-constant ($k$) was determined as 0.039 (95% CI: 0.028–0.051) for spruce and 0.081 (0.067–0.094) for birch. The spruce and birch logging residues were estimated to be 50% decomposed in 18 (14–25) and 9 (7–10) years, respectively. Furthermore, logging residue lifetime (95% density loss) was determined as

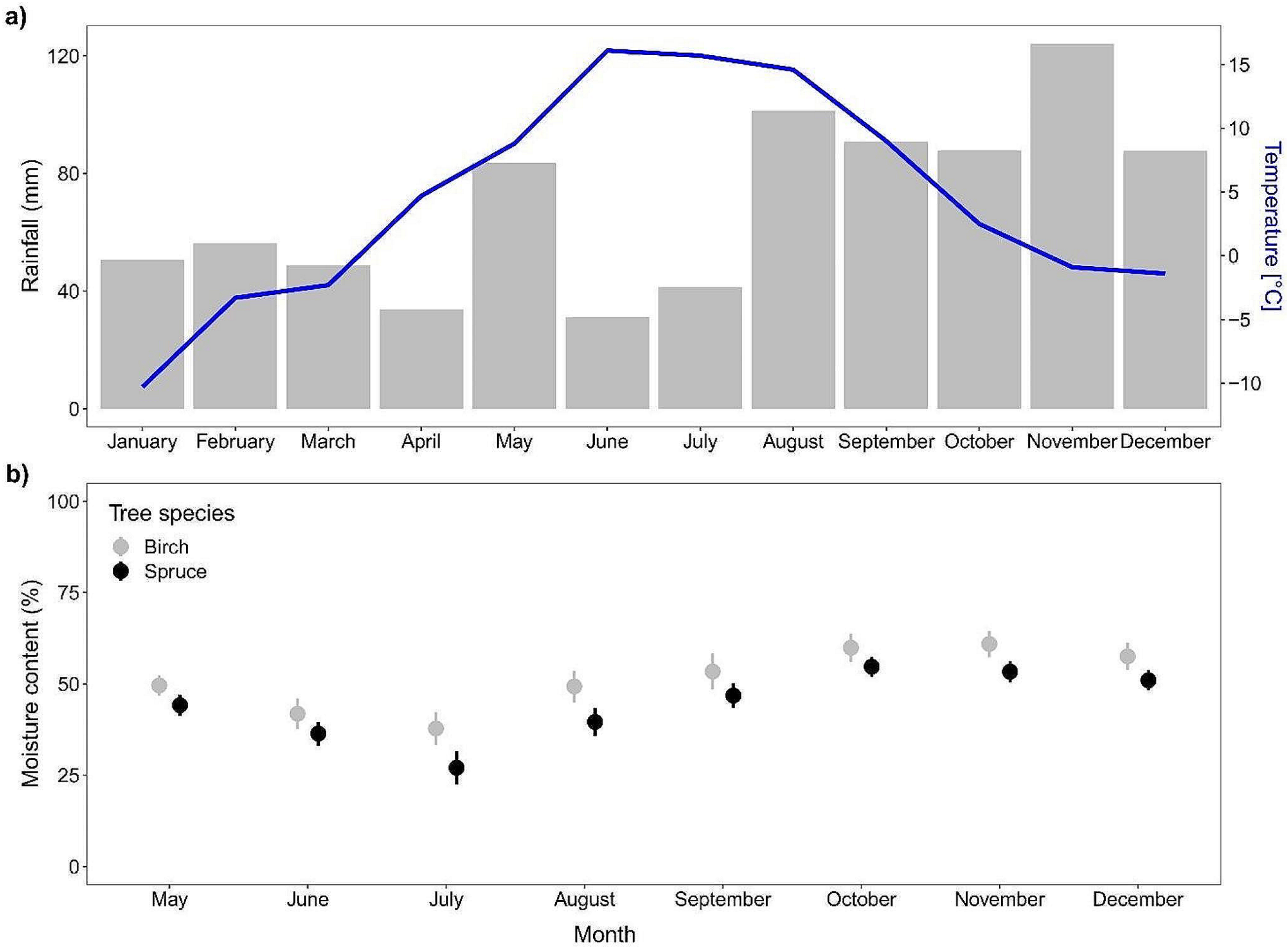

**Fig. 1** (**a**) Monthly mean temperature and rainfall in 2019 (measured at the nearest weather stations; Finnish Meteorological Institute 2023), and (**b**) moisture content of logging residues (includes all age classes, 0–10 years) at the research sites (mean ± SE, $n = 18$)

76 (59–106) years for spruce and 37 (32–45) years for birch. The results indicate that birch logging residues were decomposed approximately two times faster than spruce residues.

## Seasonal variation in greenhouse gas production in field measurements

We observed a clear seasonal variation in the $CO_2$ production in the logging residues of spruce and birch (Fig. 3a), and $CO_2$ fluxes followed monthly mean air temperature. Production of $CO_2$ occurred throughout the eight-month study period, varying in a range of 0.1–27.3 for spruce and 0.1–56.7 g $CO_2$ $m^{-3}$ $h^{-1}$ for birch. The average $CO_2$ production rates were $7.0 \pm 0.5$ for spruce and $11.7 \pm 0.9$ g $CO_2$ $m^{-3}$ $h^{-1}$ for birch, with birch producing significantly more $CO_2$ (Mann-Whitney U-test, U = 7177.5, $P < 0.001$). The highest $CO_2$ emissions were observed in the summer months, with spruce emissions peaking in August ($14.9 \pm 1.7$ g $CO_2$ $m^{-3}$ $h^{-1}$) and birch emissions in July ($23.7 \pm 3.9$ g $CO_2$ $m^{-3}$ $h^{-1}$). Logging residues produced $CO_2$ even in sub-zero temperatures in the winter months. The annual $CO_2$ emissions were estimated as 42 and 65 kg $CO_2$ $m^{-3}$ $year^{-1}$ (equals 80 and 134 g $CO_2$ $kg^{-1}$ $year^{-1}$) for spruce and birch.

We also detected low $CH_4$ and $N_2O$ production in logging residues (Fig. 3b, c). Even though $CH_4$ emissions were – in general – low, several forest sites showed elevated $CH_4$ production rates in both spruce and birch. Unlike for $CO_2$, there was no clear seasonal variation in $CH_4$ emissions. The average $CH_4$ flux during the eight-month study for both spruce and birch did not differ, with production rate being $0.02 \pm 0.01$ mg $CH_4$ $m^{-3}$ $h^{-1}$ (U = 9937.0, $P = 0.996$), which in $CO_2$ equivalents ($GWP_{20}$) were $1.7 \pm 0.5$ and $1.9 \pm 0.5$ mg $CO_2$ $m^{-3}$ $h^{-1}$, respectively. The highest measured $CH_4$ production rate was 0.58 mg $CH_4$ $m^{-3}$ $h^{-1}$ in birch. Both species also occasionally consumed $CH_4$. When the eight-month average $CH_4$ exchange rate was scaled up, the annual estimate for spruce and birch ranged from 180 to 200 (equals 15 and 16 g $CO_2$ $m^{-3}$ $year^{-1}$ in $CO_2$ equivalents ($GWP_{20}$)) mg $CH_4$ $m^{-3}$ $year^{-1}$.

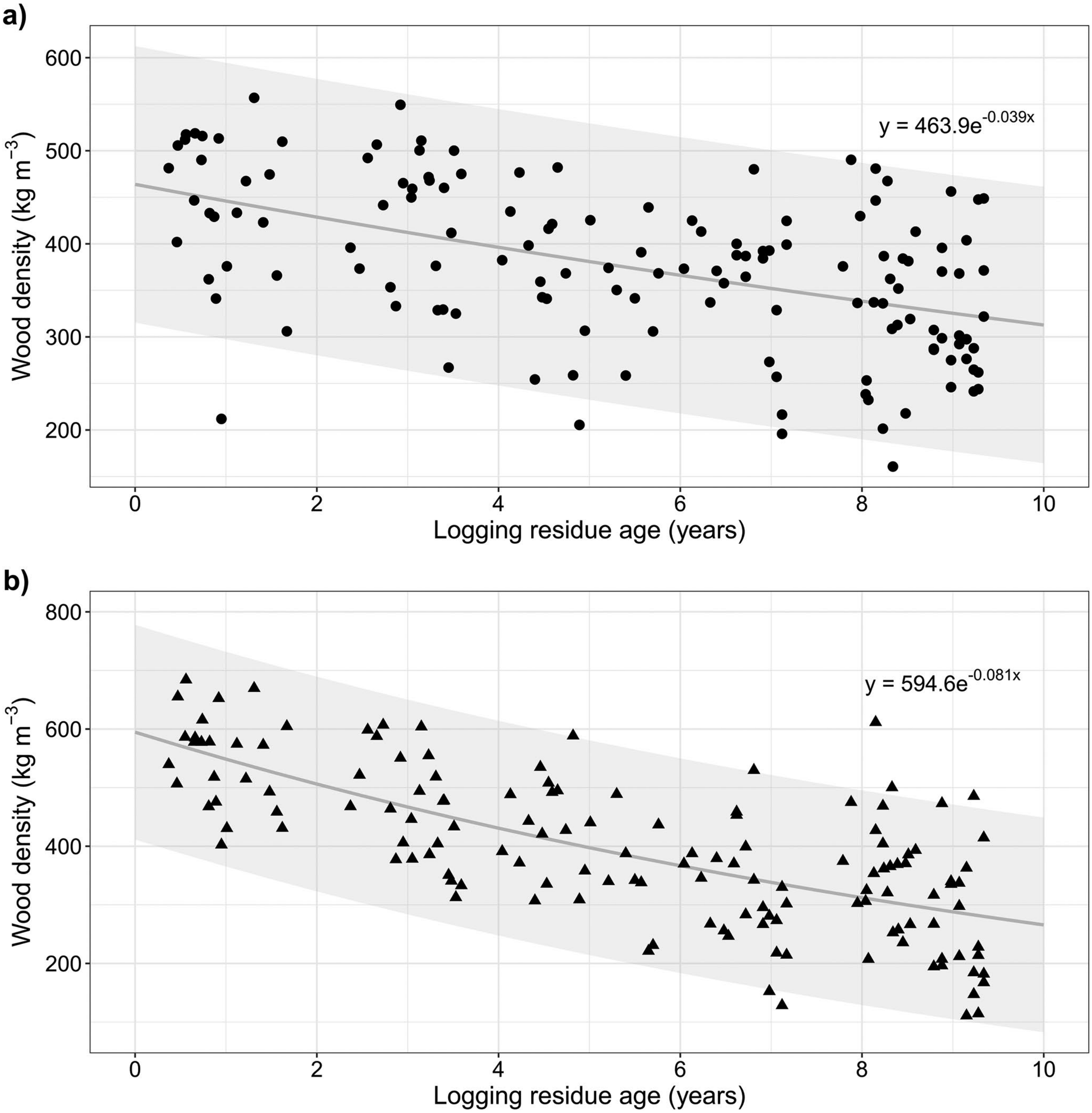

**Fig. 2** Effect of logging residue age on wood density (kg DW m$^{-3}$) in (**a**) spruce, and (**b**) birch ($n = 141$). The grey area represents a 95% confidence interval. The graph includes measurements from eight months for logging residue ages of 0–10 years

Similar to $CH_4$, there was no clear seasonal variation in $N_2O$ emissions (Fig. 3c). Production rates were generally low, even though some areas had occasionally high production rates. The average $N_2O$ flux during the eight-month study for spruce and birch was 0.02 ± 0.02 and 0.08 ± 0.03 mg $N_2O$ m$^{-3}$ h$^{-1}$, which in $CO_2$ equivalents ($GWP_{20}$) was 5.8 ± 6.0 and 21.4 ± 9.1 mg $CO_2$ m$^{-3}$ h$^{-1}$, respectively. Statistical analysis revealed no significant differences between the eight-month average production rates of spruce and birch ($U = 8199.0$, $P = 0.155$). The high mean value and variation in birch $N_2O$ production rate in August were affected by elevated $N_2O$ production in one of the research areas (3.0 mg $N_2O$ m$^{-3}$ h$^{-1}$), which was also the highest $N_2O$ production rate measured during the study.

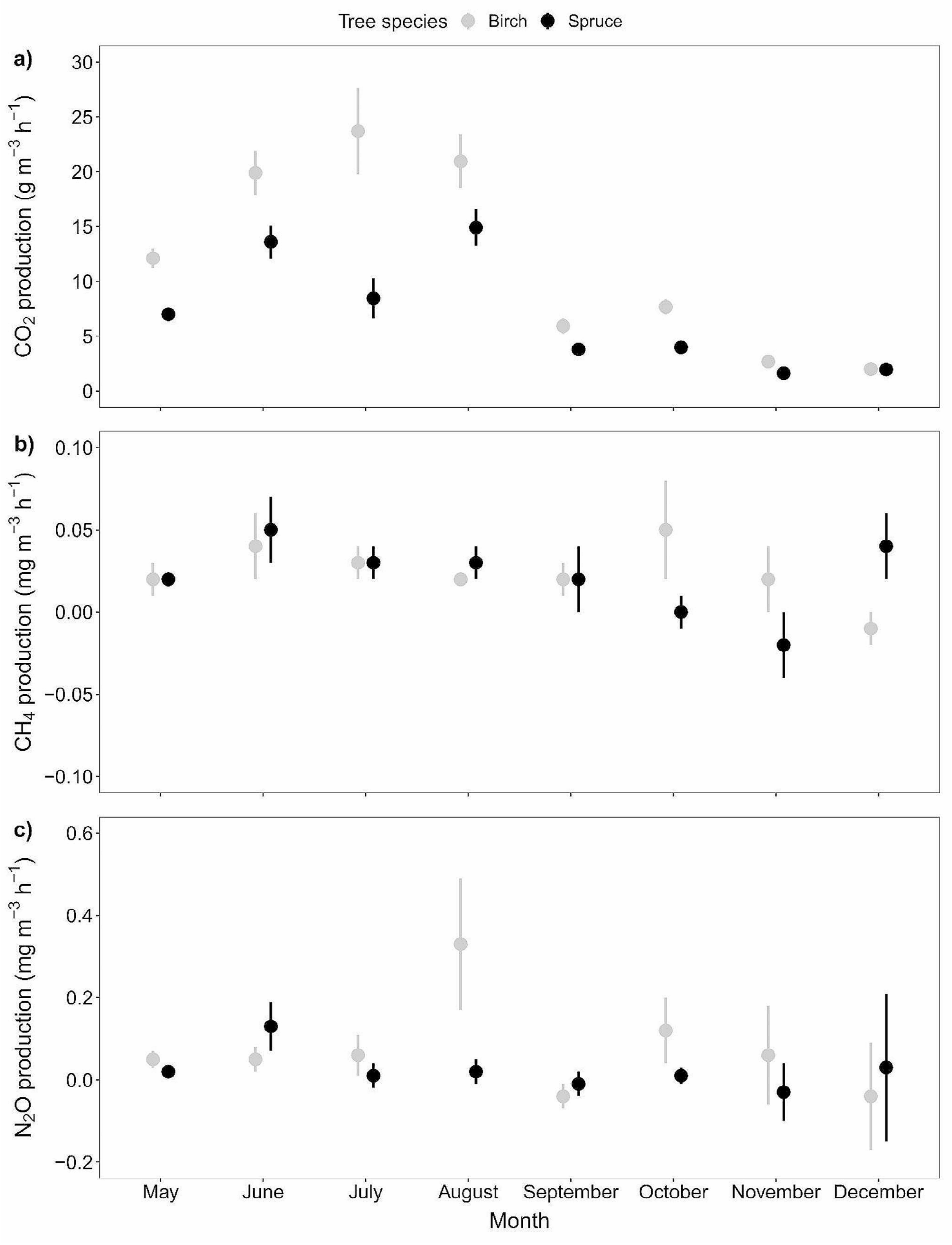

**Fig. 3** Monthly mean (**a**) $CO_2$, (**b**) $CH_4$, and (**c**) $N_2O$ production rates in spruce and birch logging residues from May to December (mean ± SE, $n = 18$, but with few monthly exceptions where $n = 16–18$ for $CO_2$ and $CH_4$, and $n = 13–18$ for $N_2O$) including all age classes

## Carbon dioxide production and temperature

Both laboratory and field measurements indicated an exponential dependency between $CO_2$ production and air temperature in logging residues (Fig. 4), with $CO_2$ production increasing along with rising temperature. The mean $CO_2$ production rate in laboratory measurements at 12, 20, and 28 °C was $4.2 \pm 0.6$, $7.4 \pm 1.2$, and $10.9 \pm 2.1$ for spruce, and $9.6 \pm 0.7$, $19.6 \pm 1.9$, and $32.1 \pm 3.1$ g $CO_2$ $m^{-3}$ $h^{-1}$ for birch, indicating that birch produced $CO_2$ at a significantly higher rate than spruce (t-test, t(22) = -6.169 (12 °C), t(22) = -5.458 (20 °C), t(22) = -5.674 (28 °C), $P < 0.001$). The $Q_{10}$ values determined from the laboratory data were 1.8 for spruce and 2.0 for birch for a temperature range of 15–25 °C. When $Q_{10}$ values were determined from field measurements for the same temperature range (15–25 °C), we obtained similar values of 1.7 for spruce and 1.9 for birch.

## Temperature-independent $CO_2$ production

The connection between $CO_2$ production and air temperature in laboratory measurements (Fig. 4a, b) was used to normalize the $CO_2$ production in field measurements to 20 °C, which allowed us to estimate if $CO_2$ production was dependent on logging residue age and moisture content in the field (Fig. 5). $CO_2$ production was connected to logging residue age and moisture content in both spruce and birch (Fig. 5). Logging residue age explained 9 and 12% of the variation in $CO_2$ production in spruce and birch, respectively. The moisture content of the spruce and especially birch residues limited $CO_2$ production in dry conditions at moisture levels below 30%, whereas above 30% moisture content, the $CO_2$ production was independent of moisture. The effect of logging residue age or moisture on $CO_2$ production was not constant throughout the study. In monthly

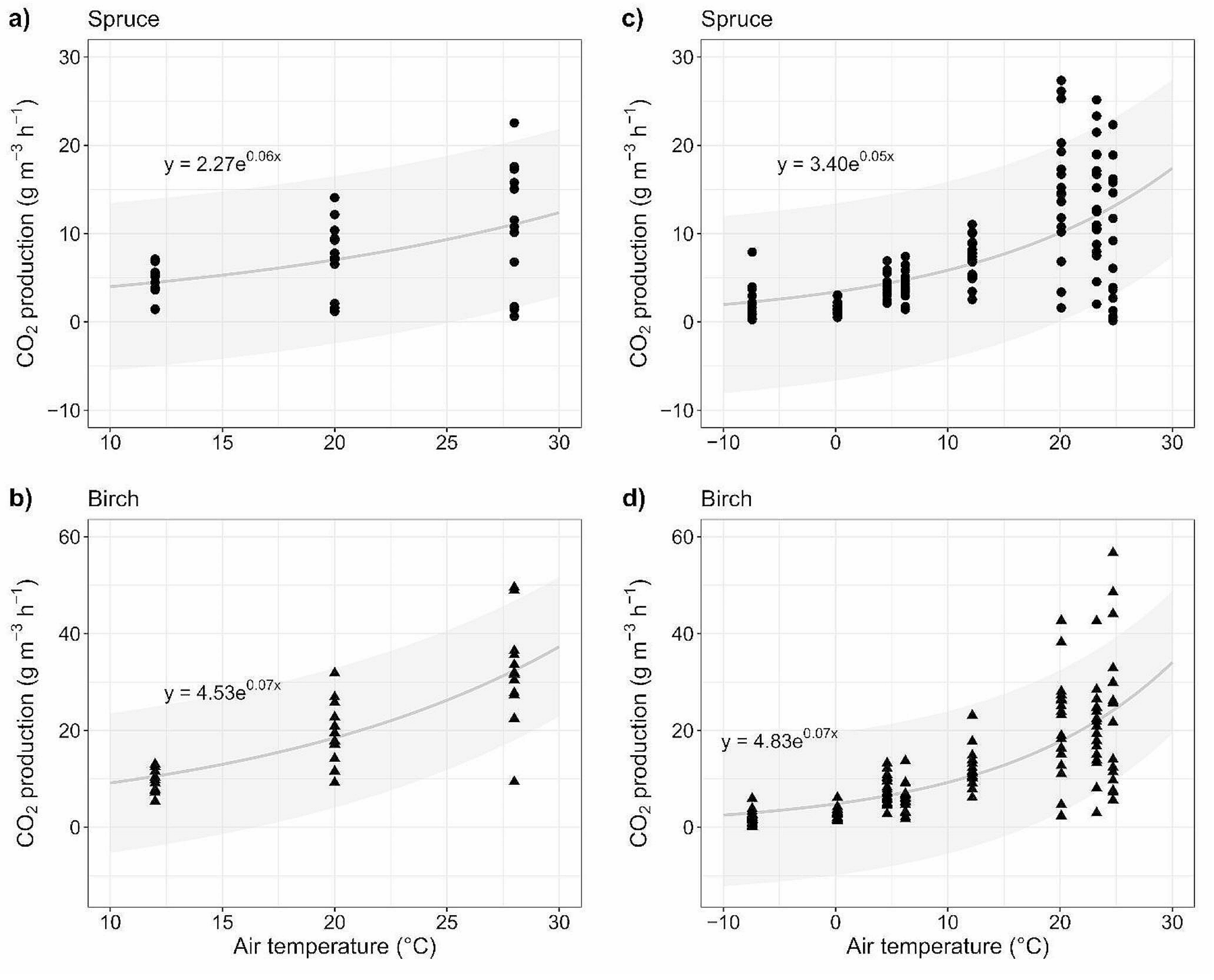

**Fig. 4** Effect of air temperature on logging residue $CO_2$ production in laboratory measurements in (**a**) spruce and (**b**) birch, and field measurements in (**c**) spruce and (**d**) birch ($n = 12$ in laboratory measurements; $n = 18$ in field measurements, but with few monthly exceptions where $n = 16$–$18$). The grey area represents a 95% confidence interval. Field measurements include all age classes

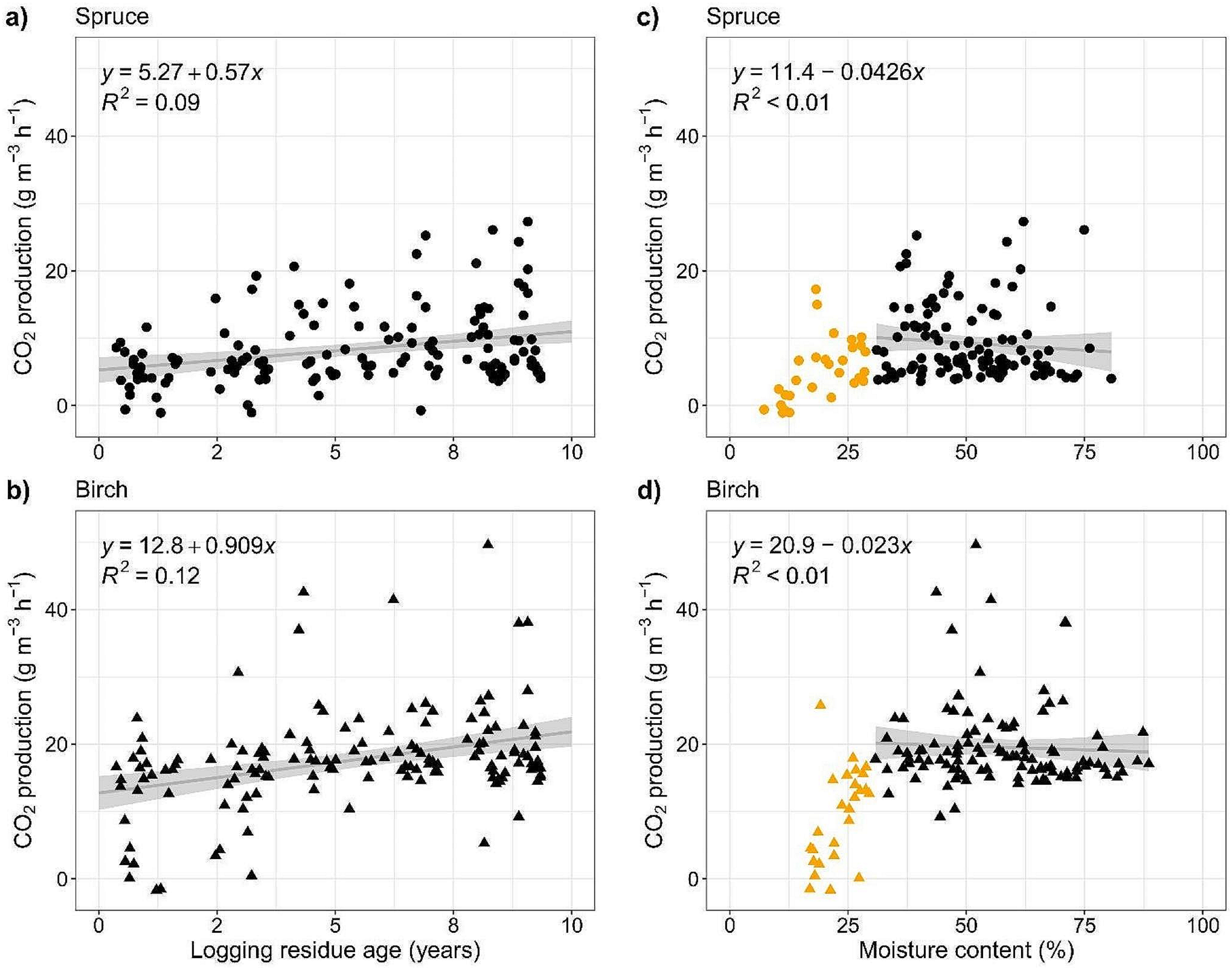

**Fig. 5** Effect of logging residue age and moisture content on $CO_2$ production in (**a**, **c**) spruce, and (**b**, **d**) birch. $CO_2$ production was normalized to 20 °C. Moisture content includes all age classes. The graph includes measurements from eight months ($n=141$). The grey area represents a 95% confidence interval. In Fig. 5c, d, measurements with moisture content below 30% are shown in yellow

data, logging residue age explained 32–51% and moisture content explained 41–66% of the variation in $CO_2$ production during the summer months (June – August). In December, during the coldest month of the study, production of $CO_2$ decreased with increasing logging residue age and moisture content.

## Discussion

### Production of $CO_2$ by logging residues

Our results provide a profound understanding of the greenhouse gas dynamics of fine deadwood in the studied forest type over 8 months covering the snow-free period in Finland, and also including measurements from the snow-covered season. Throughout the study, $CO_2$ dominated the gas emissions with a clear seasonal pattern in both spruce and birch logging residues, supporting earlier findings on the seasonality of deadwood $CO_2$ production (Warner et al. 2017). Our observations indicate that carbon from the logging residues is mainly emitted into the atmosphere in the form of $CO_2$, as previously suggested (Piirainen et al. 2015). While the release of $CO_2$ averaged at 7.0 and 11.7 g $CO_2$ $m^{-3}$ $h^{-1}$ for spruce and birch, respectively, the average emission rate of $CH_4$ and $N_2O$ in $CO_2$ equivalents ranged from 1.7 to 21.4 mg $CO_2$ $m^{-3}$ $h^{-1}$. Thus, the results suggest that the release of $CH_4$ and $N_2O$ from the residues is climatically insignificant in the studied forest type.

The logging residues of birch produced $CO_2$ at a significantly higher rate than those of spruce in both field and laboratory measurements, showing that $CO_2$ production was species-dependent. This is in line with the general observation that deciduous trees tend to decay at a faster rate than conifers, resulting from the different structures and chemical composition that affect decomposer activity (Harmon et al. 1986; Pearce 1996; Weedon et al. 2009; Kahl et al. 2015, 2017). Birch also expressed significantly higher mean moisture content, which possibly supported enhanced microbial activity. Birch $CO_2$ production peaked in July, which was the warmest month measured. Production of $CO_2$ in spruce, however, decreased in July, likely resulting from low moisture content (Harmon et al. 1986), which fell below 30%, most probably limiting microbial respiration. Our study showed that logging residues also produced $CO_2$ in sub-zero temperatures – although at a low rate – which indicates that deadwood in boreal forests could be a $CO_2$ source throughout the year, which was not evident in the study by Rinne-Garmston et al. (2019).

Previously Vanderhoof et al. (2013) measured $CO_2$ emission rates of CWD in the Harvard Forest Long Term Ecological Research site. They determined a $CO_2$ production rate of 40.0 mg $CO_2$ kg$^{-1}$ h$^{-1}$ in Norway spruce logs at a clear-cut site during summer (May – July), which is similar to the average spruce $CO_2$ production rate we measured in May – July (9.7 ± 0.9 g $CO_2$ m$^{-3}$ h$^{-1}$, which equals 26.7 ± 2.8 mg $CO_2$ kg$^{-1}$ h$^{-1}$). Vanderhoof et al. (2013) recognized that spruce respiration rate increased if the wood was in contact with the ground, which was explained by the moisture content and/or microbial establishment. Their observation that the respiration rate was better connected to moisture than temperature is in line with our observation of the decline in the spruce deadwood respiration during July when the temperature reached its highest point, with moisture content being at the lowest level. Jomura et al. (2008) measured a mean deadwood $CO_2$ production rate of 34.4 mg $CO_2$ kg$^{-1}$ h$^{-1}$ in a temperate broad-leaved secondary forest, which is similar to the eight-month average $CO_2$ production rates in our study in spruce (7.0 ± 0.5 g $CO_2$ m$^{-3}$ h$^{-1}$, which equals 19.8 ± 1.7 mg $CO_2$ kg$^{-1}$ h$^{-1}$) and especially in birch (11.7 ± 0.9 g $CO_2$ m$^{-3}$ h$^{-1}$, which equals 33.5 ± 3.0 mg $CO_2$ kg$^{-1}$ h$^{-1}$); this indicates that deadwood in boreal forests can produce $CO_2$ at a similar rate as in temperate forests.

Our annual $CO_2$ production rate estimates of 42 and 65 kg $CO_2$ m$^{-3}$ year$^{-1}$ (which equals 80 and 134 g $CO_2$ kg$^{-1}$ year$^{-1}$) for spruce and birch are lower, but similar in magnitude to the previous measurements from spruce deadwood in an unmanaged forest site (117 g kg$^{-1}$ year$^{-1}$ of carbon, which equals 429 g $CO_2$ kg$^{-1}$ year$^{-1}$; Rinne-Garmston et al. 2019). The difference could be explained by varying deadwood sizes and decay stages, research methods (e.g., upscaling from laboratory or field measurements; Jomura et al. 2022), and environmental conditions. Microclimate conditions between a clear-cut and unmanaged site are most likely variable, leading to expected differences in $CO_2$ emission rates. It has been estimated that the volume of FWD in boreal spruce-dominated clear-cuts varies from 5.9 to 9.7 m$^3$ ha$^{-1}$, depending on whether the residues are harvested for energy use or not (Eräjää et al. 2010). Assuming an emission rate of 42 kg $CO_2$ m$^{-3}$ year$^{-1}$, $CO_2$ release from the residues in a clear-cut could potentially be in the range of 248–407 kg $CO_2$ ha$^{-1}$ year$^{-1}$. However, knowing that wood decomposition is driven by many factors, yearly values are likely to vary, reflecting the weather and overall environmental conditions.

## Release of $CH_4$ and $N_2O$ from the deadwood

We observed production and occasional consumption of $CH_4$ in logging residues – supporting earlier reports on deadwood $CH_4$ exchange (Mukhin and Voronin 2009; Covey et al. 2016; Pastorelli et al. 2017, 2021; Warner et al. 2017; Mukhortova et al. 2021; Kipping et al. 2022). Our results suggest that logging residues can be anaerobically degraded, but in general, $CH_4$ had a minor role in the total greenhouse gas exchange of the residues when compared to $CO_2$ – a similar finding as previously reported for coarse deadwood (Warner et al. 2017). Despite the low overall $CH_4$ emissions, our study also indicated that FWD has temporal potential for elevated $CH_4$ emissions, as observed occasionally in some of the study areas. The diameter of the logging residue logs is usually relatively small and can be classified as FWD (< 10 cm), but in CWD, elevated $CH_4$ release rates could be observed (Covey et al. 2016). The $CH_4$ exchange in deadwood is most likely driven by $CH_4$-cycling microbial communities, as decaying wood probably supports methanogenesis by forming favorable anaerobic habitats for methanogenic archaea (Pastorelli et al. 2021), similar to living trees (Barba et al. 2019; Covey and Megonigal 2019; Putkinen et al. 2021). Fungal $CH_4$ production could also occur, as fungi are primarily responsible for decomposing wood (Harmon et al. 1986; Johnston et al. 2016; Bani et al. 2018; Fukasawa 2021; Tláskal et al. 2021) and fungi have already been observed to produce $CH_4$ (Lenhart et al. 2012). The role of lichens and mosses growing on the deadwood surface in $CH_4$ – and also $N_2O$ – exchange of deadwood (Lenhart et al. 2015) cannot be fully ruled out. Identification of methanotrophic bacteria in spruce deadwood (Mäkipää et al. 2018) and the bark of living trees (Jeffrey et al. 2021) suggests that the observed $CH_4$ consumption was a microbial process. Further characterization of these microbial communities combined with isotope techniques would provide a deeper understanding of $CH_4$ dynamics in deadwood.

Even though the studied material showed overall low $CH_4$ emissions, anaerobic decay and $CH_4$ production might be pronounced inside large logging residue piles – similar to wood chip storage (Wihersaari 2005) – where anaerobic pockets could be found. Different environmental conditions e.g., the burial of the deadwood in a wet environment could promote anaerobic degradation. Previously high $CH_4$ concentrations have been measured inside deadwood (Covey et al. 2016), but it is possible that methanotrophic activities in the well-aerated zones of deadwood could suppress the net emissions (Harmon 2021). In addition to downed deadwood, discoveries on $CH_4$ production and consumption in standing dead trees (Carmichael et al. 2018; Jeffrey et al. 2019; Martinez et al. 2022) suggest that deadwood $CH_4$ exchange could widely occur in ecosystems, highlighting the need for further research. Scaling up the measured monthly $CH_4$ exchange rates to an annual level is challenging, as $CH_4$ flux was not connected to any environmental factor, and both production and consumption of $CH_4$ were observed.

Similar to $CH_4$, exchange rates of $N_2O$ were low, but give further support to previous reports on production (Pastorelli et al. 2017) and consumption (Covey et al. 2016; Pastorelli et al. 2021) of $N_2O$ in deadwood. Despite the numerous measurements, we observed high $N_2O$ emissions only in one study site. Earlier measurements by Törmänen et al. (2020) indicated that logging residue piles could have a role in the exchange of $N_2O$. However, the effect of soil below the pile on $N_2O$ exchange could not be excluded in their study, while we measured gas exchange directly from the residues. Even though $CH_4$ and $N_2O$ did not seem to play a large role in the total greenhouse gas exchange of logging residues in the studied forest type, they still add an interesting component to logging residue greenhouse gas dynamics.

## Residence time of the residues

The measured densities were used to estimate the logging residue decomposition rate, as we were able to accurately date the studied logs. Our results show that birch decomposed approximately two times faster than spruce. The relatively long lifetime (95% decay) estimated for the logging residues – 76 years for spruce and 37 years for birch – suggests that logging residues form a mid-term carbon reserve, and a source of greenhouse gases for this period. Previously, Rinne-Garmston et al. (2019) estimated that the complete degradation of spruce deadwood in Finnish forests can take over 100 years. The different lifetime estimates could result from different deadwood sizes and environmental conditions. The estimation of decay is likely to include more uncertainties after half of the biomass is respired, which in our research was reached after 18 and 9 years for spruce and birch, using the estimated decomposition rate-constants ($k$) 0.039 and 0.081, respectively. The estimated $k$ for spruce is similar to previously reported values (Laiho and Prescott 2004; Rock et al. 2008; Herrmann and Bauhus 2013; Herrmann et al. 2015). Even though the decomposition rate of deadwood is not necessarily constant, and other models have been developed (e.g., Mäkinen et al. 2006), the single negative exponential model along with decomposition rate-constant $k$ is widely used due to its simplicity (Harmon et al. 2020). Our results provide half-life and lifetime estimates on treetop debris, but for example finer and coarser material is likely to decompose at a different rate. Boreal forests can also preserve large amounts of buried deadwood, which can decrease the decomposition rate (Hagemann et al. 2010; Moroni et al. 2010, 2015; Stokland et al. 2016) – at least in anaerobic conditions – which creates a challenge for the accurate estimation of deadwood lifetime. As the decomposition rate is affected by several different factors (e.g., Rock et al. 2008), and logging residues can be found in highly variable environmental conditions – even in the same clear-cut area – therefore, the estimation of the half-life of deadwood is likely to be more reliable than the estimation of the complete degradation.

The measured wood densities showed unexpectedly high variation, especially in less decayed residues. Even though log volume could be affected by changes in deadwood moisture content, this would not explain density variation this high. We conclude that the variation was likely a result of the used method. Each month, new logs were collected from the same area, and logs had likely experienced different environmental conditions and decay rates in the same clear-cut area. The studied logs were cut from larger logs, and the generated sawdust was used for dry matter content analysis; the density of the larger log might not be constant throughout the whole log (Herrmann et al. 2024) – e.g., if deadwood has been partly buried – and the collected sawdust might not represent the dry matter content of the whole log. The bark was also included in the measurements, and especially in residues with smaller diameters, the relative amount of bark could be high, affecting the results. However, the determined decay rates are likely realistic, as the decomposition rates were estimated from 141 observations for each species, and densities showed a decreasing trend, with decay rate estimates comparing well with previous studies.

## The effect of air temperature, wood moisture and residue age on the carbon release

In our field and laboratory measurements, $CO_2$ production in logging residues responded exponentially to increasing air temperature, as was also reported by Jomura et al. (2007). Our data indicated that in the temperature range of 15–25 °C, $CO_2$ production in birch was more sensitive to temperature increase than spruce, as it had a higher $Q_{10}$ value. Field and laboratory data resulted in $Q_{10}$ values of

1.9 and 2.0 for birch and 1.7 and 1.8 for spruce, respectively, thus showing that field and laboratory measurements produced similar values. As the $Q_{10}$ of spruce was lower, microbial respiration and $CO_2$ production in spruce in elevated temperatures was likely limited by low moisture content. The observed $Q_{10}$ values are comparable to those reported earlier (Harmon et al. 1986; Herrmann and Bauhus 2013). Our results indicate that decomposition rate of logging residue and microbial respiration could increase as a result of global warming, leading to elevated $CO_2$ emissions, but the activity of decomposer organisms could be limited by drought events.

In our study, wood moisture content below 30% limited $CO_2$ production, showing that drought inhibits microbial activity (Harmon et al. 1986) and thus respiration. On the other hand, $CO_2$ production can also be limited by excess water (Harmon et al. 1986; Progar et al. 2000; Jomura et al. 2012), but this was not observed in the studied logs. On a monthly level – especially during summer months – $CO_2$ production seemed to be more strongly connected with increasing moisture content, supporting earlier findings (e.g., Herrmann and Bauhus 2013; Liu et al. 2013). However, in December, $CO_2$ emissions decreased in elevated moisture levels, possibly caused by the freezing of the material. The results indicate that an optimal decomposition requires sufficient moisture levels, assuming that the process is not limited by temperature. We found that logging residue age also explained part of the variation in $CO_2$ production. In the temperature-normalized data, residue age explained 9–12% of the variation in $CO_2$ production, hence showing that the residue age alone does not necessarily strongly reflect the release of $CO_2$. Despite the age, logging residues of similar age might have experienced highly variable environmental conditions – as an example, contact to soil possibly significantly promotes the colonization of wood-decaying fungi (Bani et al. 2018).

## The role of deadwood in mitigating the $CO_2$ emissions

It has been speculated that $CO_2$ emissions could be potentially mitigated by implementing strategies that retain carbon in the dead forest biomass. Woody debris contains large amounts of carbon, which eventually returns into the atmosphere in the form of $CO_2$. It has been suggested that these emissions could be reduced by collecting deadwood and burying it in trenches under a soil layer, which would slow down decomposition and the subsequent release of $CO_2$ (Zeng 2008). Large-scale harvesting and burial of woody debris would, however, be energy-demanding and likely have negative impacts on the environment, such as habitat loss and decreased biodiversity (Riffell et al. 2011; Bouget et al. 2012; Repo et al. 2020). On the other hand, logging residues are recognized as an important biomass source (Asikainen et al. 2008). From a bioenergy perspective, the utilization of logging residues could help to replace fossil fuels with renewable energy, thus reducing global net $CO_2$ emissions (e.g., Guest et al. 2013; Hammar et al. 2015; Liu et al. 2020). While biomass combustion generates direct $CO_2$ emissions, forest fine woody debris will also be decomposed to $CO_2$, but with a half-life of one or two decades in the studied environment.

## Conclusions

Greenhouse gas production of spruce and birch logging residues in the selected *Myrtillus* type boreal forest stands was dominated by $CO_2$, with emissions peaking during the summer months. Release rates of $CH_4$ and $N_2O$ remained low throughout the study, being climatically irrelevant. The results indicate that logging residues can act as a mid-term carbon reserve in the studied forest type, however, global warming may speed up the release of this carbon back into the atmosphere – assuming that drought is not limiting the decay process – decreasing the deadwood lifetime. Our study focused on woody debris from treetops, but in other types of residues, especially in the litter, greenhouse gas dynamics could be different. Combining flux measurements with isotope techniques and molecular biology methods, and studying different forest types and environments, would provide a deeper understanding of logging residue greenhouse gas exchange and the decomposer organisms involved. This understanding is essential when evaluating the utilization of the residues as sustainable bioenergy, reflecting on the multiple political targets.

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**Author contributions** AL and MT designed the study. AL performed the collection and analysis of the samples and data. AL wrote the first draft of the manuscript and SA designed the figures. All authors read and approved the manuscript.

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## Declarations

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**Conflict of interest** The authors have no conflicts of interest to declare.

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