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Carbon emissions from stumps vary by species but not sprouting in a temperate hardwood forest

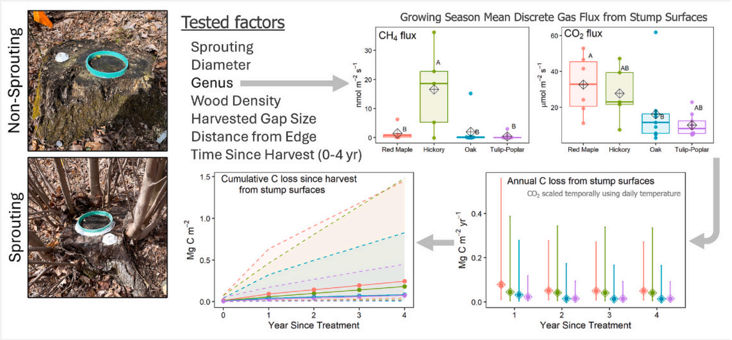
Morgan L. Arteman [a,*], Jodi A. Forrester [a], Tara L. Keyser [b]

[a] Department of Forestry and Environmental Resources, North Carolina State University, 2800 Faucette Dr, Raleigh, NC 27695, United States of America
[b] USDA Forest Service, Southern Research Station, Asheville, NC, United States of America

HIGHLIGHTS

- Stumps were a CO_2 source with flux values ranging 0.14 to 227.5 μmol CO_2 m^{-2} s^{-1}.
- Stump CH_4 flux was largely positive (81 %), ranging −0.32 to 201.6 nmol CH_4 m^{-2} s^{-1}.
- Sprouting did not affect gas flux despite decreasing stump surface temperature.
- Genus differences most strongly affected CO_2 and CH_4 flux.

GRAPHICAL ABSTRACT



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ABSTRACT

Cut stumps can be temporary hot spots of carbon emissions due to connections to decaying root systems. Drivers of variation in stump decomposition have yet to be clearly identified, including interactions with stump sprouting, an important regeneration pathway after harvest in temperate deciduous forests. The aim of this study was to identify the effects of sprouting relative to other abiotic and biotic factors on carbon emissions from cut stumps. We measured carbon dioxide (CO_2) and methane (CH_4) flux from the surface of cut stumps 0–4 years following a canopy gap harvest in an upland mixed-oak forest in the southern Appalachians, U.S. Stumps were a CO_2 source for all years with flux values ranging from 0.14 to 227.5 μmol CO_2 m^{-2} s^{-1}. Instantaneous CH_4 flux was largely positive (81 %) and ranged from −0.32 to 201.6 nmol CH_4 m^{-2} s^{-1}. Sprouting did not affect CO_2 or CH_4 flux despite decreasing stump surface temperature and increasing wood moisture. Both CO_2 and CH_4 flux were stable over time since harvest and differed most strongly by genus. Using an average annual C-CO_2 emission rate of 2.6 kg C m^{-2} of stump surface yr^{-1} and preharvest basal area (42 m^2 ha^{-1}), the annual C-CO_2 loss from stumps was estimated to be 109 kg C ha^{-1} yr^{-1} (16.6 and 800.2 kg C ha^{-1} yr^{-1} 95CI) near-term to gap harvest. Understanding factors influencing the variability in carbon emissions from stump decomposition is critical as we test sustainable forest management approaches that optimize climate change adaptation and mitigation.

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* Corresponding author.
E-mail address: mlschult@ncsu.edu (M.L. Arteman).

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1. Introduction

Dead woody material (DWM) is an important forest carbon pool and could account for up to 18 % of the total ecosystem carbon in temperate systems (Pregitzer and Euskirchen, 2004). While the U.S. national down dead wood inventory does not categorize stumps separately (Woodall et al., 2019), stumps make up 23, 25, and 33 % of the total deadwood pool in Swiss, German, and Austrian forests respectively based on their National Forest Inventories (Didion and Abegg, 2022; Niese, 2013; Schnell and Hennig, 2019) – the vast majority of which originated from cutting. Stumps, distinguished from other DWM due to their connection to a decaying belowground root system (Didion and Abegg, 2022), serve many roles in an ecosystem, such as soil development and nutrient hot spots (Sucre and Fox, 2009), micro-habitats for fungi, microbes, invertebrates, and vertebrates (Harmon et al., 1986), and long-term carbon storage (Melin et al., 2009).

DWM carbon loss as carbon dioxide (CO_2) can be substantial, ca 25 % of net primary productivity, where DWM is abundant (Cai et al., 2016). Carbon loss from DWM is commonly modeled as a negative exponential decay function over time (Russell et al., 2015), with residence times of 32–84 years for hardwoods in the eastern U.S. (Russell et al., 2014). Higher hardwood decay rates are found in the warmer southeast. Complete collapse of large wood volume was observed in ca 16 years in a southern Appalachian clearcut (Mattson and Swank, 2014) compared to ca 30 years in a northeastern clearcut (Gore and Patterson III, 1986). Up to two-thirds of log wood mass is lost to the atmosphere as CO_2 and one-third becomes wood fragments entering the forest floor and soil carbon pools (Mattson and Swank, 2014). Stump surfaces, however, have been found to have higher CO_2 flux rates than logs (Forrester et al., 2015) and surrounding soil (Noh et al., 2019), making them a hot spot of CO_2 production near-term ($<$ 10 years) to disturbance. Higher stump CO_2 flux rates from stumps were observed than stump wood decay rates alone in felled fire-killed Spanish black pine (*Pinus nigra*), likely due to additions of CO_2 originating from the belowground portions of stumps, roots, and soil that were diffused upwards (Martínez-García et al., 2015). CO_2 flux from stumps follows a non-linear response with time after harvest including an initial increase as the roots die and decomposers colonize the wood, followed by rapid increase in flux and peak, and finally a decline with low, continued flux rates (Bormann, 1961; Harmon et al., 2000, Harmon et al., 1986; Read et al., 2022; Rinne-Garmston et al., 2019). The carbon loss from DWM could be oversimplified in models (Fraver et al., 2013), potentially discounting a delayed pulse from stumps following disturbance.

Many significant biotic factors have been identified as drivers of CO_2 flux from DWM including decay class (Gough et al., 2007; Rinne-Garmston et al., 2019), angiosperms versus gymnosperms (Covey et al., 2016; Herrmann et al., 2015; Weedon et al., 2009), diameter (Martínez-García et al., 2015), and microbial and fungal communities (Mali et al., 2019; Mieszkin et al., 2021). The importance of these factors varies by system and can change over time (van der Wal et al., 2015). Hardwood trees are faster to decompose than conifers as characterized by differing wood structural and chemical properties and resulting differences in microbial and fungal communities (Harmon et al., 2020; Russell et al., 2014). Within hardwood species, DWM decay rates (Mattson et al., 1987; Russell et al., 2014) and CO_2 flux (Forrester et al., 2015; Jomura et al., 2007; Liu et al., 2006) can vary considerably, however, there is little evidence of patterns in CO_2 flux differences by species (Shorohova and Kapitsa, 2016; Swift et al., 1976).

Decomposition of DWM, including stumps, is an established source of CO_2, while much less is known about trace greenhouse gases such as methane (CH_4). Methane flux is more variable than CO_2, such that DWM can be a CH_4 sink or a source (Covey and Megonigal, 2019; Martinez and Ardón, 2021; Perreault et al., 2021; Warner et al., 2017). Methane production by methanogens (archaea) occurs mainly in anerobic conditions, though recent studies have found saprotrophic fungi contributed to methanogenesis under aerobic conditions in DWM (Lenhart et al., 2012; Mukhin and Voronin, 2007). Counteracting CH_4 production, methane-oxidizing microbes simultaneously consume CH_4 in aerobic and anaerobic environments, contributing to a lower and variable net CH_4 flux. Recently, a study in coastal forested wetlands found snags to be a significant but variable source of CH_4 with similar environmental drivers to soil CH_4 flux but often oppositely correlated (Martinez and Ardón, 2021). A large release of gases trapped in heartwood was observed in stumps up to 10 days after harvest (Gorgolewski, 2022). More studies describing temporal patterns in varied ecosystems and conditions are needed to establish common drivers of CH_4 flux from DWM.

Microenvironmental conditions strongly influence gas flux and are commonly used in scaling instantaneous measurements (Bond-Lamberty et al., 2002; Gough et al., 2007). Wood temperature relationships with CO_2 flux from DWM are well established as positive and exponential (Forrester et al., 2012; Jomura et al., 2008). Wood moisture, another common factor included in model building, shows a unimodal response where CO_2 flux is limited by low moisture (Chambers et al., 2001) and suppressed by high moisture (Bond-Lamberty et al., 2002; Olajuyigbe et al., 2012; Progar et al., 2000). Methane flux relationships are more complex since CH_4 production and consumption both have a similar unimodal response to moisture and positive response to temperature (Mukhortova et al., 2021). CO_2 flux from stump surfaces specifically have been modeled using temperature alone (Cheng et al., 2023; Forrester et al., 2015; Martínez-García et al., 2015; Noh et al., 2019), though that is not always successful (Read et al., 2022).

Canopy openings, natural or harvested, can speed up rates of DWM decomposition (Forrester et al., 2012; Harmon et al., 2020), especially for buried wood (Finér et al., 2016), through increases in temperature due to light (Raymond et al., 2006). Effects of elevated temperature may be bounded by low moisture for DWM on the soil surface (Finér et al., 2016). Canopy opening size and aspect also affects these changes in the microenvironment, where larger openings and more southern facing aspects (in the northern hemisphere) experience higher light levels (Prévost and Raymond, 2012). The few studies comparing canopy gap effects on gas flux from DWM found increased CO_2 flux in the openings compared to closed canopy conditions near-term to harvest (Forrester et al., 2012), but no difference between gap sizes (0.1 and 0.4 ha; Read et al., 2023).

In hardwood-dominated systems, stump sprouts serve as a major regeneration pathway for second-growth forests, quickly capturing the overstory after harvest (Elliott et al., 1997; Shure et al., 2006; Ward and Williams, 2018; Yan et al., 2010) or natural disturbance (Clinton and Baker, 2000). Sprouting and sprout vigor are a function of stump size, species, and available light (Atwood et al., 2009; Boring et al., 1981; Del Tredici, 2001; Keyser and Zarnoch, 2014; Nieves et al., 2022; Putz et al., 1983; Zhang et al., 2018), factors that also directly or indirectly affect decomposition. In addition, a portion of the roots from the decaying stump continues to support the new sprouts (Fraser et al., 2007) potentially reducing carbon emissions from root decomposition or contributing carbon emissions through autotrophic respiration diffusion into the stump. Stump sprouting may also influence the microenvironment of the decomposing stump due to shading soon after harvest. Uncertainties around the magnitude and direction of factors influencing gas flux from stumps, including sprouting, need to be better understood to more accurately assess their contributions to total ecosystem carbon loss.

The aim of this study is to identify the effects of sprouting and other factors on carbon emissions from cut stumps and document the temporal processes 4 years post-harvest in a southern Appalachian mixed-hardwood forest. Decay class was held relatively constant due to uniform harvest timing of canopy gaps. Species differences in stump carbon emissions is unquantified for this mixed hardwood system, where currently there is weak evidence for differences in deadwood gas flux response by species (Liu et al., 2006; Mattson et al., 1987). Our specific objectives were to 1) evaluate the effect of stump sprouting on CO_2 and

CH_4 flux relative to other biotic (species, size) and abiotic (wood temperature and moisture, gap size) variables, 2) quantify change in gas flux from stumps over time since harvest, and 3) quantify the cumulative carbon emissions on an area basis. We hypothesized that sprouting would decrease gas flux due to reduced root decomposition and stump surface temperature. We also expected gas flux differences among deciduous hardwood species similar to decomposition rates, where species explains the most variance (Mattson et al., 1987). As sustainable forest management approaches are tested to optimize climate change adaptation and mitigation, it is critical to understand factors influencing the variability in carbon emissions, including from stump decomposition.

2. Methods

2.1. Study area

The study site is a second-growth upland hardwood forest dominated (in rank order by basal area) by tulip-poplar (*Liriodendron tulipifera*), chestnut oak (*Quercus montana*), northern red oak (*Q. rubra*), red maple (*Acer rubrum*), white oak (*Q. alba*), and hickory (*Carya tomentosa, C. ovalis, C. cordiformis,* and *C. glabra*) with mean ages ranging from 95 to 150 years old (Grover et al., 2023) and located in the Pisgah National Forest, Buncombe County, NC, USA (35°28′N, 82°40′W). Positioned within the Blue Ridge Physiographic Province of the Southern Appalachian Mountains, the site elevation ranges between 700 and 1070 m. The geology is predominantly felsic to mafic high-grade metamorphic biotite and granitic gneisses (Hadley and Nelson, 1971). The soils are shallow to very deep, well-drained, moderately to extremely acidic Inceptisols and Ultisols, ranging in texture from fine sandy loam to gravelly loam with steep 10–90 % slopes (Soil Survey Staff et al., 2023). Average annual precipitation is evenly distributed throughout the year, totaling to 130 cm. Monthly average temperatures range – from 3.8° to 8.6 °C in January, to 15.9° to 28.3 °C in July (NOAA, 2021). In spring of 2019, experimental canopy gaps were harvested by hand-felling trees within the gap boundaries and removing them with skidders. Openings of two sizes were created, large and small, with a mean canopy opening of 1 and 0.2 ha respectively.

2.2. Stump sprout inventory

To characterize the site-wide importance of sprouting post-harvest, trees representative of sizes and species dominant at the study site were identified, measured, and tagged preharvest as described in Grover et al. (2023). Selected trees were as evenly distributed across 21 plots as species and size availability and tree health (trees with heart rot were not selected) allowed. Each plot accounted for 2–7 % of the total sample size. The cut stumps (n = 220) were revisited in December 2020 – January 2021, two growing seasons post-harvest, to measure stump diameter and height, presence or absence of sprouts, height of tallest sprout, and number of stems per stump or number of stems in one quarter of the stump (if large numbers of sprouts occurred).

2.3. Intensive stump measurements

A subset of three small gaps (0.15–0.25 ha) and three large gaps (0.95–1.09 ha) with S to SW facing aspects were selected for intensive stump measurements. In each gap, 4–6 freshly cut stumps of dominant species were selected (n = 29). Oak species and hickory species were grouped into their respective genera due to similarities in wood anatomy within genus. Genera hereafter refers to four groups: red maple, hickory, tulip-poplar, and oak. Oak species includes *Q. alba* (n = 1)*, Q. coccinea* (n = 1)*, Q. montana* (n = 2)*, Q. rubra* (n = 3)*, Q. velutina* (n = 2). Hickory was not identified to species. In August 2020, 1 YST (year since treatment), photosynthesis (P_{max}) was measured using a LI-6800 portable photosynthesis analyzer (Li-Cor Inc., Lincoln, NE) on a healthy leaf from the top one-third of the tallest sprout on a subset of stumps. Settings included 1500 μmol m^{-2} s^{-1} light (PAR), 400 ppm CO_2, and ambient temperature and humidity.

Wood samples were taken from the surface of stumps (n = 25) with a chain saw in February 2023, 4 YST, to measure wood density. Sample volume was measured using the water displacement method. Wood density was calculated as dry weight in grams over wet volume in cm^3. A genus-level average value was used for the four stumps that were too small or unsafe to sample. Published values of species-specific green wood density were used as initial values (USDA Forest Service, 1999). Decay coefficients (k) were calculated for each stump using:

$$\frac{X}{X_o} = e^{-kt}$$

where, X is the wood density at time t and X_0 is the initial wood density (Olson, 1963). Wood density for years 1–3 was calculated using the stump-specific k value. Change in wood density was calculated as the difference between wood density at 4 YST and initial wood density (X_0), where larger values represent more wood density loss.

To measure gas flux, PVC collars (D = 20 cm, H = 2.5 cm) were installed on the cut surface of the stumps and sealed with silicon caulk (Fig. 1). Collars were initially attached in May 2019, 0 YST, and reattached to the same spot with a new application of caulk when necessary. The CO_2 flux was measured nearly monthly from June 2019 to Dec 2021 (n = 20) and several times in July/August 2022 (n = 1) and 2023 (n = 3) (Table S1). In total CO_2 flux was measured 24 times. Methane was measured a total of 12 times from January 2021 to August 2023. From 2019 to 2020, CO_2 flux was measured using an LI-8100 infrared gas analyzer and an 8100–103 survey chamber (Li-Cor Inc., Lincoln, NE). In 2021 and after, CO_2 and CH_4 flux were measured using a LI-7810 trace gas analyzer and an 8100-01S smart chamber (Li-Cor Inc., Lincoln, NE). The two units were compared side-by-side and showed CO_2 flux difference of 2 % and thus were considered equivalent. For each measurement round, measurements were conducted in one day or two consecutive days, between 0800 and 1600 h, the order was randomized by plot. Litter was removed from the collars before measurements. Measurements were taken for 90 s with a dead band of 10 s. Raw observations were individually inspected and processed in SoilFluxPro software (Li-Cor Inc., Lincoln, NE) using best-fit linear or non-linear models with flux CV ≤ 2. During gas flux measurements, instantaneous stump surface temperature and wood moisture content (v/v %) were measured using a Traceable digital pocket thermometer (Cole-Parmer, Vernon Hills, IL) and a wood moisture meter (Protimeter TimberMaster, St. Marys, PA) inserted a ~ 1 cm into the stump surface, near to collars.

Stump surface temperature was also measured continuously, logged every 3 h, using iButton temperature loggers (Maxim Integrated Products Inc., Sunnyvale, CA) covered with an ad hoc custom fabricated solar shield. Ad hoc shields may have positive temperature bias during daytime hours, especially in open conditions (Terando et al., 2017). Direct comparisons of instantaneous and continuous temperature (Supplemental Material) showed that the continuous temperatures were an accurate representation of stump surface temperatures with no evidence of positive temperature bias. The daily average of continuous temperature was calculated for individual stumps. Where individual continuous stump data were missing (34 % of total observations) due to sensor damage from moisture or rodents, they were estimated using the strong linear relationship between daily individual and daily overall average stump temperature, R^2 ranging 0.94–0.99. Average growing season (DOY 130–270) temperature was calculated per stump. To compare stump surface temperature over time, average growing season air temperature (Candler 1 W, NOAA) was subtracted from stump surface temperature (T_{stump} - T_{air}) to account for known patterns in air temperature over time.

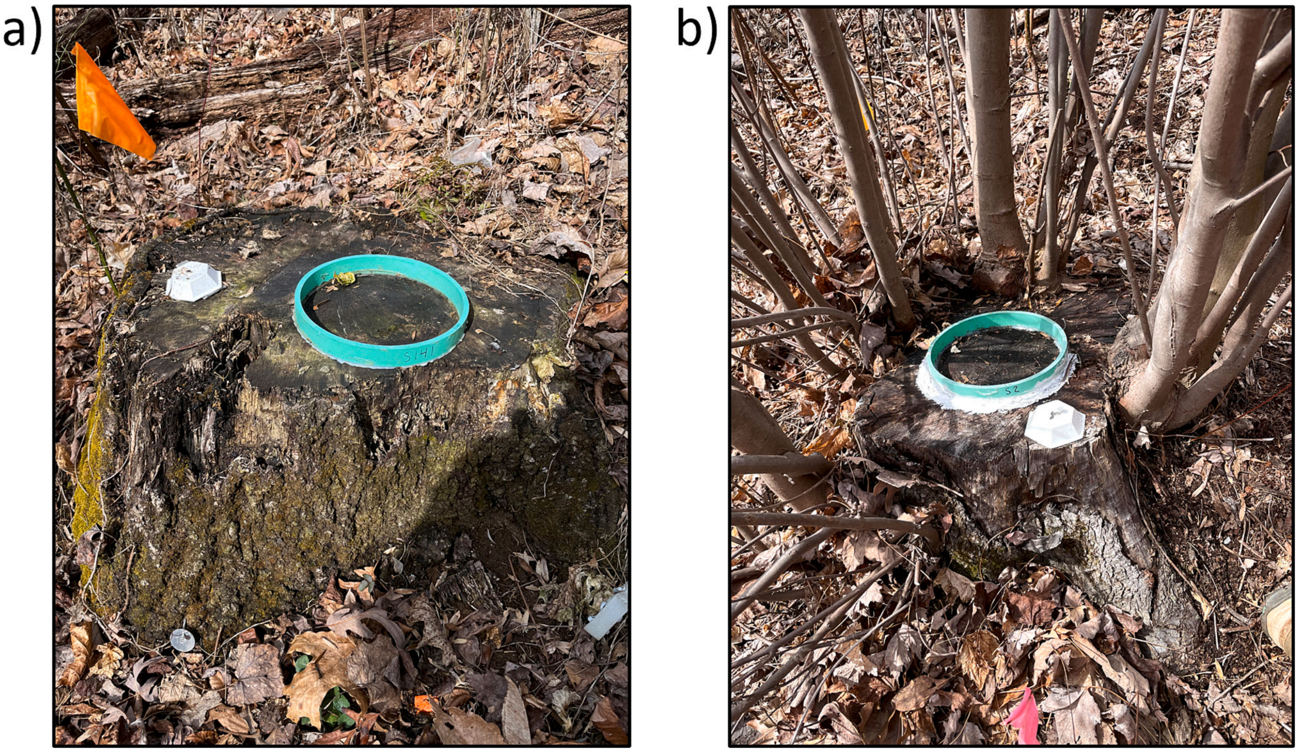

Fig. 1. Gas flux from a) non-sprouting and b) sprouting stumps was measured by placing a chamber on a collar (20 cm diameter) sealed to the stump surface with caulk. Continuous stump surface temperature was measured with sensors under white solar shields. Photos taken in February 2023, four growing seasons post-harvest.

2.4. Analysis

2.4.1. Statistics

In the larger stump assessment ($n = 220$), we used sprout presence (2 YST) as a binary response variable in a generalized linear mixed model with a binomial distribution and logit link function to test for differences by gap size, stump diameter, stump height, and their interaction as fixed effects, with plot nested within gap size included as a random effect. The model was run separately for each genus. Red maple could not be included since all stumps had sprouts present. For sprouting stumps only ($n = 162$), we tested for differences in maximum sprout height using a linear mixed model with gap size, distance from gap center, stump diameter, stump height, and their interactions as fixed effects and plot nested within gap size as a random effect. The model was run separately for each genus. Manual backwards selection removed higher level interactions with $P > 0.05$.

In assessing intensively measured stumps, growing season averages (DOY 130–270) of CO_2 and CH_4 instantaneous flux for each year per stump (experimental unit, $n = 29$) were used as response variables. For CH_4, one stump (*Q. velutina*) was excluded from the analysis due to outlying flux values, 1.5 times the interquartile range above the third quartile by genus. A sprouting index (value 0 to 1) was calculated by adding together normalized sprout count (0–1) and normalized max sprout height (0–1) and dividing by 2. Non-sprouting stumps had a sprouting index value of 0. A generalized linear mixed model included fixed effects of genus, gap size, stump diameter, wood density, sprouting index, distance from gap edge, and year. Plot was included as a random effect. Year was included as repeated measures using an AR(1) covariance structure. Stump diameter was included in the model to control for effects of diameter on sprouting. Within year, growing season average temperature and moisture differences by sprout presence were tested with an ANOVA. For 2020 (1 YST), a linear model was used to evaluate the effect of sprouting vigor on growing season average CO_2 flux using three continuous variables: sprout stem density, maximum sprout height, and P_{max} for all species combined. All analyses were done using JMP statistical software (JMP Pro 15, SAS Institute Inc., Cary, NC).

2.4.2. Upscaling

To estimate daily CO_2 flux, models including temperature and moisture were compared using data from all stump gas flux measurements. Preliminary analysis using all stump data showed first order exponential models including temperature variables had similar AIC and adj R^2 as models also including moisture variables (Table S2). Furthermore, moisture variables were not significant (all $P > 0.3$) parameters in any model. The temperature parameter that produced individual models with $P < 0.1$ was chosen. The relationship between instantaneous stump CO_2 flux and temperature was fitted using a first-order exponential model:

$$R_{stump} = e^{a} \text{ x } e^{bT} \tag{1}$$

where R_{stump} is modeled CO_2 flux (μmol m^{-2} s^{-1}), a and b are fitted parameters, and T is the instantaneous temperature (°C). R_{stump} values were multiplied by a factor of 1.0368 to convert to units of g C m^{-2} d^{-1}. Models were developed for each genera and year (0 YST, 1 YST, and 2–4 YST) using the base ‘lm’ function in R (R Core Team, 2022). Preliminary analysis showed that individual stump and year level models ranged widely in R^2 (0.00–0.92) and P (<0.001–0.95), 19 % with $R^2 < 0.1$ and 45 % with $P > 0.1$. Multiple data point combinations for models showed that genera by year produced the finest groupings of data that provided all models with $P < 0.1$ (Table S3). Daily average continuous stump surface temperature was used as model input for scaling. Daily C flux values were summed to annual and cumulative C flux from CO_2 per stump.

To predict CH_4 flux, models including temperature and moisture were compared using data from all stumps. Preliminary analysis showed first order exponential models including temperature only had the lowest AIC (Table S4).

3. Results

3.1. Sprouting

In the larger stump assessment, red maple and tulip-poplar stump sprout presence was nearly 100 %, oak 57 %, and hickory 55 % across the site, two years post-harvest (Table 1). Hickory showed a significant interaction between gap size and stump height ($P = 0.029$, Table S6) where probability of sprouting decreased as stump height increased with a sharper decline in the large gaps. The significant interaction between gap size and stump diameter ($P = 0.003$, Table S6) for oaks showed the probability of sprouting decreased sharply for stumps larger than 60 cm diameter in the large gaps, whereas in the small gaps diameter had little effect. The probability of sprouting for tulip-poplar was not affected by the fixed effects (all $P > 0.3$, Table S6). Max sprout height was negatively affected by stump height for tulip-poplar ($P = 0.032$, Table S7). No other significant differences were observed for distance from gap center, gap size, stump diameter, or stump height in the other genera (all $P > 0.1$, Table S7).

For intensively measured stumps, gas flux and microenvironmental variables were measured repeatedly throughout 4 years post-harvest (Fig. 2). Sprouts were present on 22 of 29 stumps, varying by genus like the larger sampling (Table 2). The surfaces of stumps with sprouts were cooler than non-sprouting stump surfaces 0, 1, 2, and 4 YST ($P < 0.05$) with an average of 0.9 °C lower instantaneous temperature (Table 3). This pattern also holds using continuous data when corrected for differences in air temperature across years (Fig. 3). Wood moisture increased over time on average. During the growing season 4 YST, sprouting stumps had 19.5 % higher instantaneous moisture content than non-sprouting stumps ($P < 0.05$), which reflected patterns across all years (Table 3). For sprouting stumps, the effect of sprout vigor on CO_2 flux was evaluated at 1 YST using continuous variables of sprout density, max sprout height, and P_{max}. When accounting for diameter in the model, there was no significant linear relationship between CO_2 flux and sprout density ($P = 0.36$) and max sprout height ($P = 0.28$, Fig. 4a, b). CO_2 flux had a negative linear relationship with P_{max} ($P = 0.058$, Fig. 4c).

3.2. Instantaneous CO_2 and CH_4 flux over time

Instantaneous CO_2 flux values from stumps ranged from 0.14 to 227.5 μmol CO_2 m^{-2} s^{-1} (Fig. S1). Instantaneous CH_4 flux values were largely positive, where only 19 % of the values were negative, ranging −0.32 to 201.6 nmol CH_4 m^{-2} s^{-1} (Fig. S1). We did not see that sprouting influenced growing season CO_2 or CH_4 flux ($P = 0.654$ and $P = 0.244$; Table 4) and neither flux changed significantly with time ($P = 0.872$ and $P = 0.969$). Genus was the only significant factor affecting mean growing season instantaneous CO_2 flux ($P = 0.029$, Table 4). Red maple had 3 times higher average CO_2 flux rates than tulip-poplar (Table 5). Red maple had the highest CO_2 flux, followed by hickory, oak, and tulip-poplar (Fig. 5a).

Factors affecting growing season mean instantaneous CH_4 flux included genus, gap size, and distance from gap edge ($P < 0.05$, Table 4). While we lack sufficient sample size to explore further, this appears to be driven solely by increased CH_4 flux from hickory stumps ($n = 5$) near to the center of large gaps (Fig. 6). Our sampling lacked individual hickory stumps near the center of small gaps, as such for hickory here the factors of large gaps and distance from gap edge are correlated. On average, hickory had an order of magnitude higher mean CH_4 flux than the other genera (Fig. 5b; Table 5).

Table 1
Stump sprouting probability two years post-harvest for 220 individuals. Where sprouts were present ($n = 162$), mean preharvest diameter at breast height (range), mean stem count of sprouts, mean height of largest sprout is reported.

Genus	n	DBH (cm)	Sprout Presence	Sprout Count	Max Sprout Ht (m)
Red maple *(Acer rubrum)*	40	43 (17–75)	100 %	43	3.1
Tulip-poplar *(Liriodendron tulipifera)*	52	63 (20–103)	94 %	34	2.6
Oak (*Quercus* spp.)	99	68 (34–147)	57 %	30	1.7
Hickory (*Carya* spp.)	29	44 (20–84)	55 %	19	1.4

3.3. Cumulative CO_2 and CH_4 flux

To predict daily CO_2 flux in order to scale to the full growing season, a first-order exponential model including temperature (eq. 1) was fit for each genus and year grouping. The strength of relationships (R^2) ranged from 0.06 to 0.32 with a mean of 0.17 across years (Table S3). The scaled annual carbon flux from CO_2 showed trends similar to the instantaneous growing season averages by year and genus (Fig. 7a; Table 5). Cumulatively since harvest (0–4 yrs), individual stumps emitted 13.2 kg C per m^2 of stump surface on average. Red maple (24.6 kg C m^{-2}) had over three times higher C loss than oak (8.4 kg C m^{-2}) and tulip-poplar (7.6 kg C m^{-2}), with hickory (18.3 kg C m^{-2}) in between (Fig. 7b).

For CH_4 flux, the best-fit model for all data was a first order exponential relationship with temperature ($R^2 = 0.016$). Overall, the models we evaluated did not describe the data trends well with genus-specific model R^2 ranging of 0.002–0.134 (Table S5). As such, CH_4 flux values were not upscaled. Measurements at a higher temporal resolution may help to improve modeling efforts of this carbon loss.

4. Discussion

4.1. CO_2 and CH_4 flux over time

On average, growing season instantaneous CO_2 flux was relatively stable across years ($P = 0.872$), with the highest values occurring 1 YST. Modeled annual CO_2 flux using daily temperature data showed the same pattern. This observed trend of decline in CO_2 flux after 1 YST more closely resembles the exponential decay response used to model DWM carbon loss (Fraver et al., 2013) than the delayed pulse in carbon loss approximately 3–8 years after harvest observed in studies of stumps at more northern sites (Forrester et al., 2015; Read et al., 2022). Measurements in future years, e.g., 5–10 years post-harvest, are required to verify a further decline in CO_2 flux over time. Instantaneous CO_2 flux values were always positive but variable among stumps (Fig. S1). Our CO_2 flux values are similar to those from stumps in a red spruce (*Picea rubens)* forest 1–8 YST with values ranging 0.7 to 44.9 μmol CO_2 m^{-2} s^{-1} (Read et al., 2022) and a deciduous hardwood system 1–7 years following harvest with values ranging 3.5 to 44.1 μmol CO_2 m^{-2} s^{-1} (Forrester et al., 2015). In a thinned conifer plantation, Cheng et al. (2023) found an increase in stump CO_2 flux between 1- and 3 years post-harvest with a maximum of approximately 56 μmol CO_2 m^{-2} s^{-1}. While our average values are comparable to other studies of stump and log CO_2 flux, our maximum instantaneous values were above the range others have reported. All values above 100 μmol CO_2 m^{-2} s^{-1} were from five stumps (3 red maples, 1 hickory, 1 red oak) differing in sprouting, plot, and gap size (Fig. S1). These maximum values are comparable to values measured on active ant mounds, hot spots of forest soil CO_2 emission (Risch et al., 2005). As such, our measurement timing could have overlapped with an episodic burst in fungal, microbial, or insect activity below the stump surface unrelated to daily temperature or resulted from inputs from living sprout tissue. Additionally, gap harvest may have reduced fungal species richness due to variable or extreme microclimates of stumps, and thus reduced competition between fungal species and increased decomposition rates (Perreault et al., 2023).

Instantaneous CH_4 flux values were 81 % positive. Twenty-one

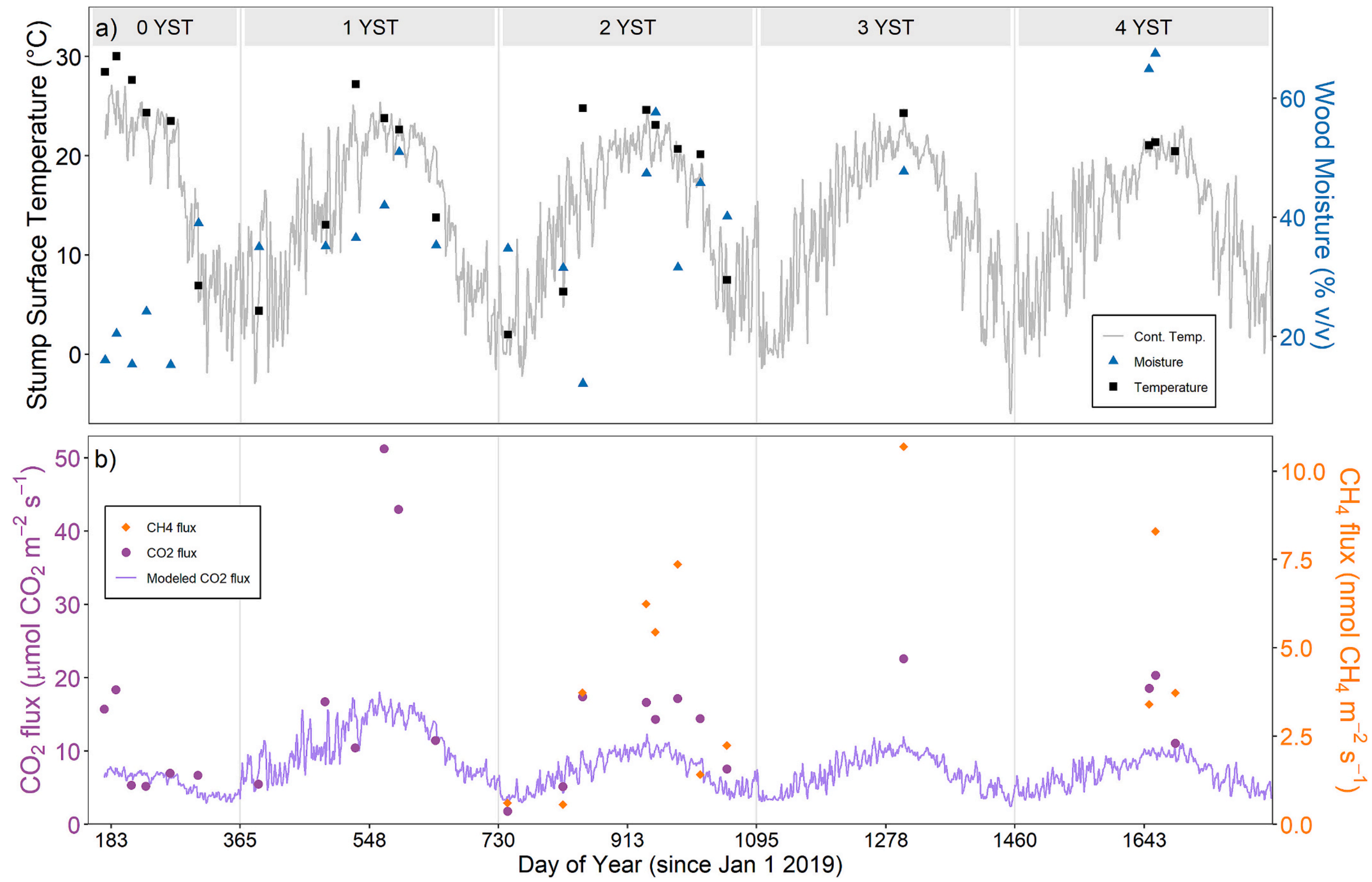

Fig. 2. Mean instantaneous values ($n = 29$) of a) stump surface temperature and moisture, and b) stump CO_2 and CH_4 flux. Continuous stump surface temperature was averaged daily (grey line). Modeled CO_2 flux was estimated using daily average temperature for each stump, mean shown here (purple line).

Table 2
Subset of stumps (n = 29) selected for repeated measurements to characterize carbon emissions. Stump age (range), preharvest diameter at breast height (range), percentage of stumps that are sprouting, wood density (SE) measured 4 YST, and wood density loss (SE) 4 YST for each genus. Tukey HSD ordered letters show differences between genera for wood density metrics ($P < 0.0001$).

Genus	n	Age	DBH	Sprout	Wood density	Wood density loss
		years	cm	%	g cm^{-3}	g cm^{-3}
Red maple	6	98	32	100 %	0.259	0.231
		(56–150)	(27–46)		(0.032) B	(0.023) AB
Hickory	5	132	39	60 %	0.355	0.286
		(86–186)	(17–57)		(0.036) B	(0.025) A
Tulip-poplar	9	97	49	100 %	0.232	0.168
		(73–111)	(31–69)		(0.026) B	(0.019) BC
Oak	9	127	57	44 %	0.456	0.127
		(84–225)	(27–84)		(0.026) A	(0.019) C

stumps (72 %) had a growing season average CH_4 flux between −1 and 1 nmol CH_4 m^{-2} s^{-1}. All values above 25 nmol CH_4 m^{-2} s^{-1} came from five individual stumps, different than those individuals with high CO_2 flux (Fig. S1). To our knowledge, these CH_4 values are among the first in situ measurements to be reported for stumps, thus limiting direct comparisons. In sugar maple (*A. saccharum*) stumps, average values of 2834 nmol CH_4 m^{-2} s^{-1} have been recorded minutes after harvest, which then dropped to an average of 1.9 nmol CH_4 m^{-2} s^{-1} after one year (Gorgolewski, 2022). Downed deadwood has been showed to have variable CH_4 flux (ranging −3.5 to 3.5 nmol CH_4 m^{-2} s^{-1}; Warner et al., 2017) and can serve as an average net CH_4 source (ranging −3.73 to 22.8 mg CH_4 kg DDW^{-1} s^{-1}; Perreault et al., 2021). Standing dead snags located in wetland soils had highly variable CH_4 flux values ranging from −55.41 to 53.68 nmol CH_4 m^{-2} s^{-1} (Martinez and Ardón, 2021). We found no correlation between CO_2 and CH_4 flux (Fig. S2), similar to Mukhortova et al. (2021). While CH_4 contributions of trees can be significant at the stand-scale, even in upland areas (Gorgolewski et al., 2022; Warner et al., 2017), further research is needed across sites to quantify the magnitude and direction over time of CH_4 fluxes from DWM, including stumps.

4.2. Sprouting effects

Sprouting was prevalent within the mature mixed-oak site, occurring on 74 % of the stumps post-harvest (162 of 220). The probability of sprouting was lower for larger diameter oak stumps, similar to Nieves et al. (2022). Other studies have observed that stumps receiving more light have higher rates of biomass growth for some deciduous hardwood species (Keyser and Zarnoch, 2014), e.g. at the northern or center portion of gaps and larger gaps (Zhang et al., 2018). We did not observe this pattern with max sprout height, though light might have been similar across gap size and distance from edge due to the large size of the openings studied here. Zhang et al. (2018) studied gaps ranging 0.098 ha to 0.018 ha in size. Keyser and Zarnoch (Keyser and Zarnoch, 2014) had a larger sample size (e.g. red maple $n = 596$) and evaluated stumps after 10–40 % basal area reduction.

Sprouting altered microenvironmental factors thought to affect stump decomposition. We expected sprouting to reduce stump gas flux similar to shading effects on DWM, where logs in canopy gaps have higher CO_2 flux rates than closed canopy (Forrester et al., 2012; Read et al., 2023). As hypothesized, sprouting reduced the surface temperature of stumps, but we found sprouting had no effect on growing season

Table 3

Sprouting as a binary response effect on growing season stump microenvironment. *P* and means are reported by year since treatment (YST) for stump surface temperature and moisture from instantaneous measurements. The difference between sprouting and non-sprouting stumps was reported to show directional response. Letters from Tukey HSD test show significant differences where $P < 0.05$. Bold *P* are <0.05.

		0 YST		1 YST		2 YST		3 YST	4 YST	
Temperature (°C)	*P*	0.027		0.008		0.045		0.350	0.017	
	sprouting	22.8	B	20.6	B	19.8	B	19.9	18.8	B
	non-sprouting	24.0	A	22.0	A	20.8	A	20.2	19.4	A
	difference	−1.2		−1.4		−1.0		−0.3	−0.7	
	P	0.100		0.143		0.099		0.484	0.041	
	sprouting	19.4		43.5		48.6		49.7	73.5	A
	non-sprouting	15.1		33.5		36.4		41.7	54.0	B
Moisture (v/v %)	difference	4.3		10.0		12.2		8.0	19.5	

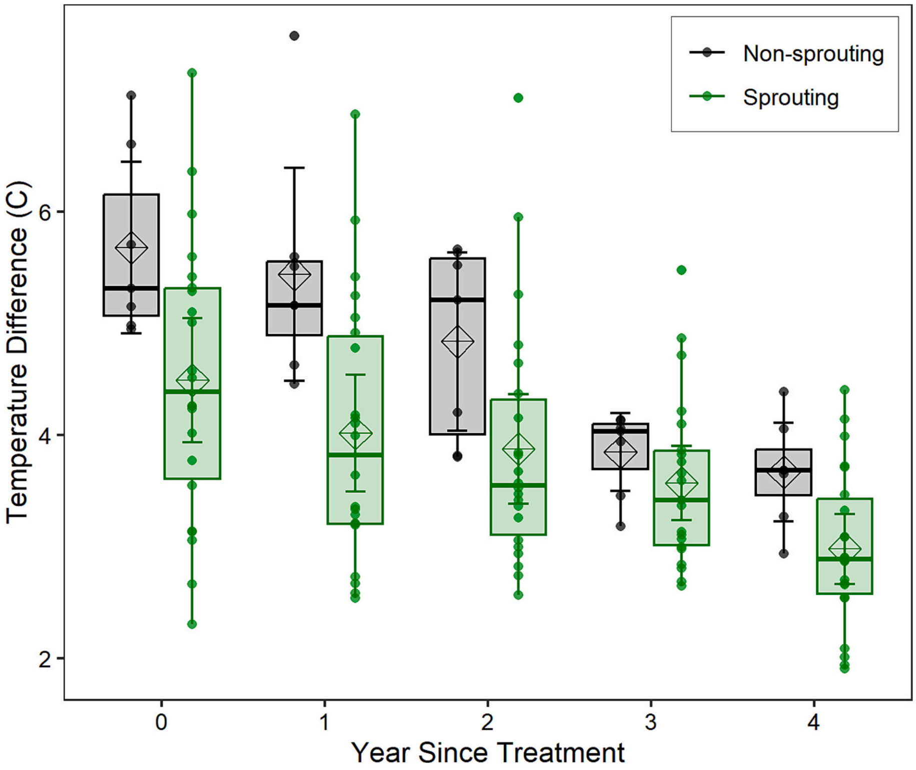

Fig. 3. The difference in growing season daily average stump surface temperature and air temperature ($T_{stump} - T_{air}$) for sprouting and non-sprouting stumps decreased over time as vegetation in gaps regrew. Mean (diamonds) and 95 % confidence limits overlaid on boxes (median and 25 % and 75 % quartiles). Individual stump means of $T_{stump} - T_{air}$ shown as points.

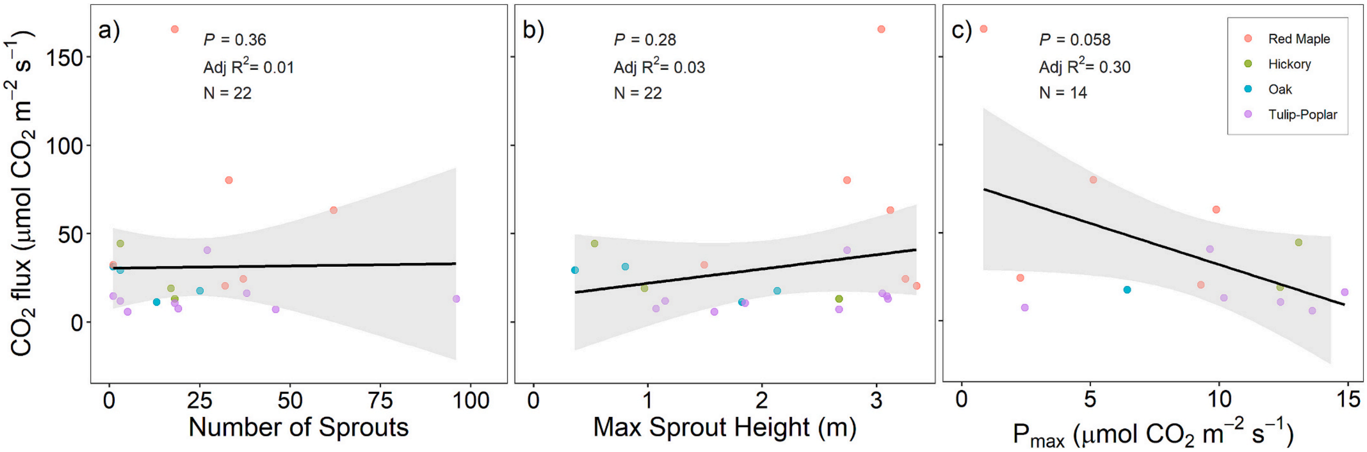

Fig. 4. Variables describing sprouting vigor poorly predicted instantaneous growing season CO_2 flux for individual stumps 1 YST, excluding non-sprouting stumps. *P* and adjusted R^2 reported for linear regressions that also account for diameter.

Table 4

Model summary for fixed effects on growing season mean instantaneous gas flux from stumps. Year was included as a repeated measure. Year included 0–4 YST and 2–4 YST when testing CO_2 flux and CH_4 flux respectively. $P < 0.05$ are in bold. Genus means comparisons are shown in Table 5.

	CO_2			CH_4		
Fixed effects	DF	F ratio	Prob > F	DF	F ratio	Prob > F
Genus	3	3.628	0.0287	3	8.281	0.0001
Gap size	1	0.138	0.7144	1	5.947	0.0281
Stump diameter	1	1.779	0.1975	1	0.198	0.6585
Sprout Index	1	0.207	0.6541	1	1.387	0.2435
Wood density	1	0.261	0.6107	1	0.799	0.3750
Distance from edge	1	0.427	0.5213	1	9.452	0.0035
Year	1	0.026	0.8718	1	0.002	0.9688

mean instantaneous CO_2 and CH_4 flux. These observations may have in part been confounded, since the most significant patterns of both gas flux and sprouting were by genus. We lacked adequate sample distribution to test sprouting effect on gas flux within red maple and tulip-poplar since nearly all stumps were sprouting. However, sprout vigor as three continuous metrics also showed no significant ($P > 0.05$) relationships with CO_2 flux. During this period 1 YST, the largest difference in vegetation cover between sprouting and non-sprouting stumps was observed, as the sprouts were well-developed while the competing vegetation was not as vigorous yet (personal observation). Sprout vigor has been shown to be positively related to carbon reserves at the time of cutting (Kays and Canham, 1991; Schier and Zasada, 1973). Non-structural carbohydrate reserves are preferentially utilized by fungi (Hulme and Shields, 1970) potentially making sprouting an indicator of increased decomposition rates, counter to our hypotheses. In addition, autotrophic respiration of sprouts could contribute to CO_2 loss by diffusion through stump tissue. The measured decrease in stump temperature and potential increase in carbon reserves and autotrophic respiration for sprouting stumps could in combination have little effect on CO_2 flux rates. Our measured sprout vigor variables did not show a significant effect on CO_2 flux from stump surfaces. Future exploration of sprout physiology, stump coarse root decomposition, stump root grafting, wood chemical composition, and fungal and microbial communities may provide insights into the influence of species and sprouting on stump decomposition.

4.3. Species effects

Across years, differences between genera were the most pronounced, as hypothesized, with a stump surface CO_2 flux rank order of red maple, hickory, oak, and tulip-poplar. While differences between coniferous and hardwood DWM decay rates are well defined (Kahl et al., 2017), species differences within hardwoods have been found to be a minor factor for CO_2 flux from DWM (Jomura et al., 2007; Liu et al., 2006), including stumps specifically (Forrester et al., 2015). Values of southern Appalachian DWM decay rates between species studied here are largely similar but show that oak is variable by species (k = 0.05–0.17), and that hickory decays more quickly (k = 0.166) than tulip-poplar (k = 0.107) and red maple (k = 0.081) (Mattson et al., 1987). In stumps, we found that hickory and red maple had more wood density loss by 4 YST than oak, with tulip-poplar in between (Table 2). Though the rank order of wood density loss did not align directly with CO_2 flux it helps explain trends, similar to Mattson et al. (1987). The variables measured in our study cannot fully account for the strong differences in stump surface CO_2 flux between genera. Factors such as wood decaying fungal and microbial community composition, wood chemistry, root grafting with neighboring unharvested trees, or sapwood and heartwood proportions

Table 5

Growing season mean (SE) instantaneous gas flux. Ordered letters from Tukey HSD test show significant differences by genus.

		0 YST	1 YST	2 YST	3 YST	4 YST	Average	
CO_2 (μmol m^{-2} s^{-2})	Red maple	14.9	64.4	29.2	34.1	18.2	32.7 (5.9)	A
	Hickory	14.4	29.2	24.5	43.6	24.0	27.7 (6.5)	AB
	Tulip-poplar	7.9	14.3	6.2	11.0	12.4	10.1 (4.8)	B
	Oak	7.6	30.0	11.6	16.2	15.0	16.1 (4.8)	AB
CH_4 (nmol m^{-2} s^{-1})	Red maple	–	–	2.4	1.0	0.2	1.5 (2.7)	B
	Hickory	–	–	13.4	16.9	15.1	16.5 (3.0)	A
	Tulip-poplar	–	–	0.04	0.2	1.4	0.4 (2.2)	B
	Oak	–	–	0.3	0.8	5.7	2.0 (2.4)	B

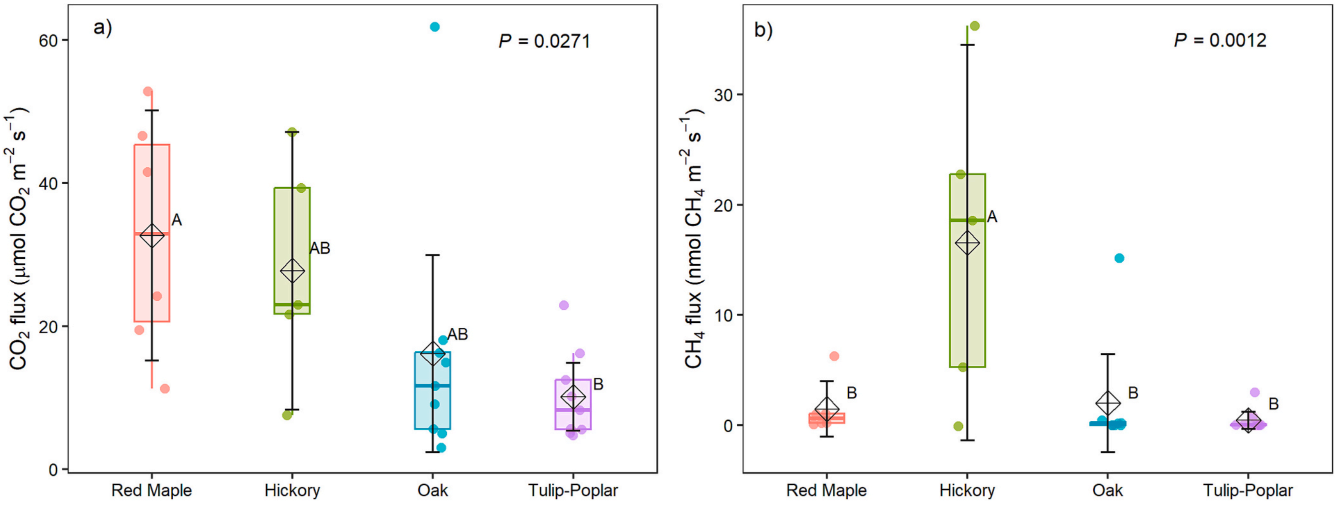

Fig. 5. Growing season mean instantaneous gas flux (DOY 130–270) and 95 % confidence limits (black). Letters from Tukey HSD test show significant differences between genera, P values shown. Individual stump means shown as points. Boxes show median and 25 % and 75 % quartiles.

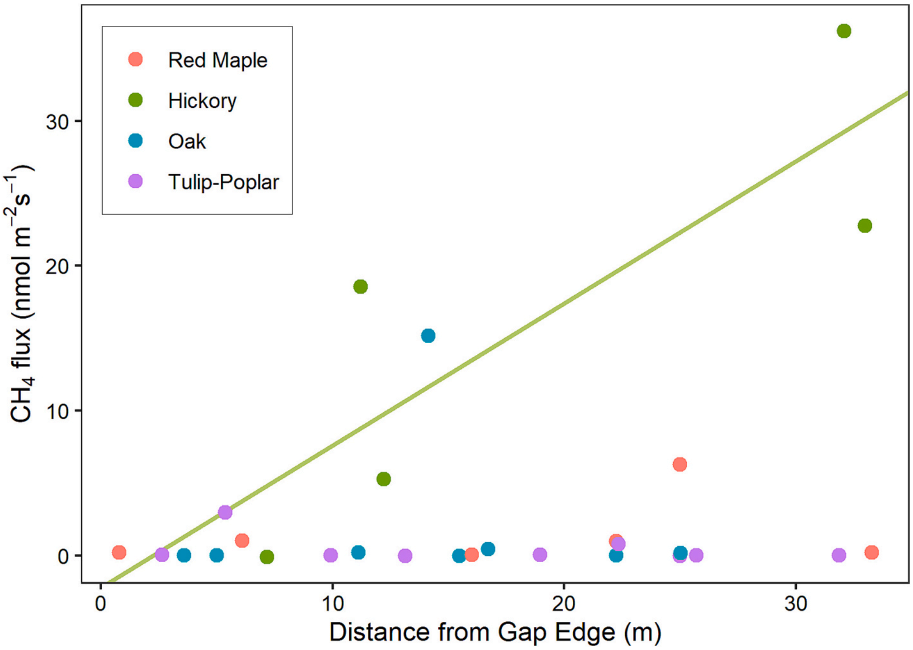

Fig. 6. Growing season mean instantaneous CH_4 flux for each stump (2–4 YST). Gap edge is located at 0 m and increasing values of distance extend into the harvested gap, nearer to gap center. Linear regression shown for hickory ($R^2 = 0.71$, $P = 0.07$). Linear regressions for other genera were not significant: red maple ($R^2 = 0.08$, $P = 0.58$), oak ($R^2 = 0.00$, $P = 0.99$), tulip-poplar ($R^2 = 0.16$, $P = 0.29$).

within the collars were not considered here and may be useful to elucidate differences between species in future work. No other variables strongly influenced CO_2 flux, including no effect of gap size (Read et al., 2023). We found no differences in gas flux by stump size, contrary to Martínez-García et al. (2015) that found an increase in respiration with stump size across cut stumps in three sites recently burned by wildfire.

Growing season mean instantaneous CH_4 flux was most strongly influenced by genus. Within logs, larger diameter, least decayed, hardwood species have been found to have the highest values of CH_4 concentrations, with oak and birch (*Betula*) species having higher values than pine (*Pinus*) and ash (*Fraxinus*) species (Covey et al., 2016). We found that CH_4 flux from hickory was higher than other genera and increased with distance from gap edge ($P < 0.01$). Increasing distance from gap edge could potentially serve as an integrated factor for distance from non-harvested interspecific stems and thus could have reduced root grafting or simply increased light and temperature. It is unclear, however, how this may have affected hickory stumps differently than other genera. Further work including larger sample sizes would be necessary to draw more robust conclusions.

4.4. Estimating annual carbon emissions

Temperature alone resulted in the best model to describe patterns of surface carbon flux from CO_2 (Cheng et al., 2023; Forrester et al., 2015; Martínez-García et al., 2015; Noh et al., 2019), albeit the fits were not very strong. For oak and tulip-poplar, the relationships with temperature were stronger 2–4 YST compared to 0–1 YST (Table S3). Earlier on, drivers other than temperature may have had stronger influence on CO_2 flux, i.e. low wood moisture and lag time in establishment of the microbial and fungal communities. Methane flux had poor fits with the predictor variables we assessed. Larger sample sizes and additional and more frequent measurements, such as continuous monitoring of wood moisture (Green et al., 2022) and soil and internal stump temperature (Martínez-García et al., 2015) may refine gas flux relationships with microenvironmental drivers, e.g. lag times with moisture or temperature, threshold responses with moisture, and quadratic relationships with temperature (Mukhortova et al., 2021).

By multiplying our reported average annual C-CO_2 emission rate of 2.6 kg C m^{-2} of stump surface yr^{-1} by an average site pre-harvest basal area, 42 m^2 ha^{-1} (Grover et al., 2023), we estimated the annual C-CO_2 loss from stumps to be approximately 0.11 Mg C ha^{-1} yr^{-1} (0.02 and 0.80 Mg C ha^{-1} yr^{-1} 95 % confidence limits) near-term to harvest in harvested areas. Non-stump DWM decomposition, i.e., downed deadwood and logging slash biomass estimated with line transects and hardwood decay rates from literature, was approximately 0.81 Mg C ha^{-1} at the study site (Arteman, 2024). Stump surface C-CO_2 emission rate was 13.5 % of carbon loss from other DWM, proportional to their respective biomass. While we lack comparative measurements of CH_4, DWM may have a pulse of CH_4 emission near-term the harvest but then serve as a CH_4 sink, like soil (Gorgolewski, 2022). DWM contributions to forest methane budgets has been shown to be small, approximately 1.8 % (Gorgolewski, 2022) and 1 % (Warner et al., 2017). In harvested stands with less residual logging debris, stumps may make up a larger portion of the total deadwood pool and carbon flux. Compared to an average rate of within-gap soil respiration of 11 Mg C ha^{-1} yr^{-1} at the study site (McCarthy, 2023), stump surface carbon emission would make up 1 % of that from soil near-term to harvest. Similarly, in a pine plantation in subtropical China stump surface carbon emission values were minor compared to soil, however, the addition of carbon released from stump surfaces determined the significant difference in total respiration between 1 and 3-years since thinning treatments (Cheng et al., 2023).

Stump harvesting for conifers, e.g. Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), is conducted in some European countries to reduce greenhouse gas emissions from stump decomposition while producing biofuel to substitute for fossil fuel consumption (Persson and Egnell, 2018). Stumps may also be harvested to reduce disease for the next rotation (Persson and Egnell, 2018). But in many places, such as eastern deciduous forests, the practice is unlikely due to the importance of stumps in the natural regeneration process, the additional disturbance to the soil resulting in competing vegetation, and lack of economic benefit. While the tradeoffs of reducing carbon emission by removing stumps have not been quantified in these systems, our results indicate that fluxes even when high are small relative to other carbon losses at the stand scale.

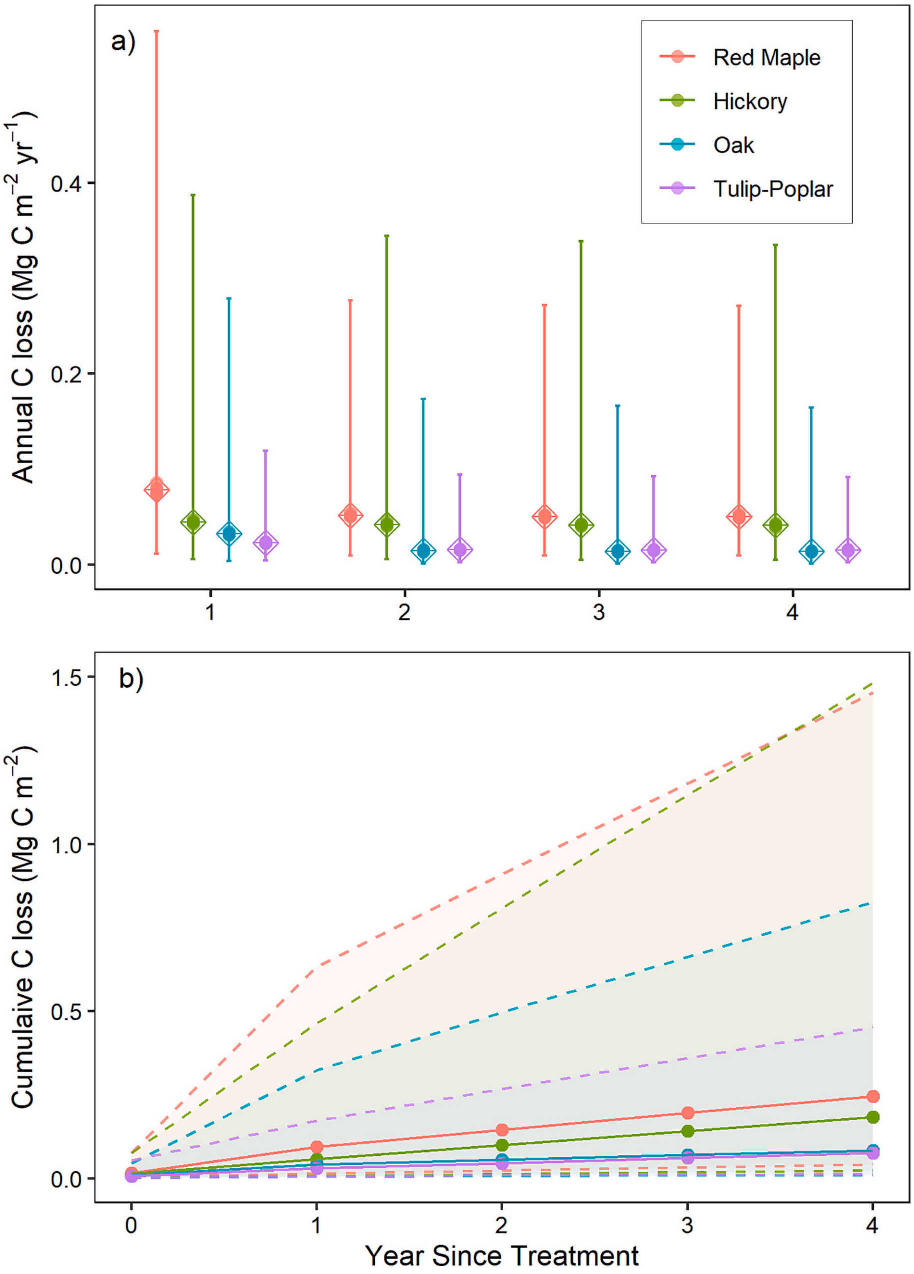

Fig. 7. a) Mean and 95 % confidence limits of modeled daily C loss rates from stump surface CO_2 flux summed annually over time since harvest. Modeled values from individual stumps shown as points. b) Cumulative mean annual C loss from stump CO_2 flux by genus over time since harvest. Dash lines show cumulative 95 % confidence limits across years.

5. Conclusions

Stumps are an important component of the DWM pool in managed forest ecosystems, though carbon flux relationships with driving factors are an ongoing area of research. We examined the relationships between sprouting and other factors found to affect carbon emission from cut stumps, as sprouting is prevalent in temperate hardwood systems. Differences in both CO_2 and CH_4 flux from stump surfaces were most prevalent by species. Stump sprouting altered microenvironmental variables as expected but did not affect CO_2 and CH_4 flux. Studies explaining fine-scale variability of the sources of forest carbon loss over time and space are critical steps toward meeting the challenge of modeling detrital carbon dynamics at larger and longer scales and informing climate-smart forest management.

CRediT authorship contribution statement

Morgan L. Arteman: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Jodi A. Forrester:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Tara L. Keyser:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jodi Forrester reports financial support was provided by National Institute of Food and Agriculture. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179059.

Data availability

Data will be made available on request.

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