Ann. For. Res. 65(2): 47-56, 2022
https://doi.org/10.15287/afr.2022.2386

ANNALS OF FOREST RESEARCH
www.afrjournal.org

Emissions of CO_2 from downed logs of different species and the surrounding soil in temperate forest

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Błońska E., Piaszczyk W., Lasota J., 2022. Emissions of CO_2 from downed logs of different species and the surrounding soil in temperate forest. Ann. For. Res. 65(2): 47-56.

Abstract The decomposition of deadwood plays a very important role in the functioning of the forest ecosystem. The present study was conducted with the objectives to: (1) determine the amount of deadwood respiration depending on species and degree of decomposition; (2) determine the extent of the impact of decomposing wood on the amount of respiration in surrounding soil; (3) find a relationship between the amount of respiration and the chemical fractional composition of soil organic matter. Our research has shown that respiration of decaying wood samples was 2-3 times lower compared to soil, regardless of the type of wood and the degree of wood decomposition. The conducted analyses confirmed the influence of the species of wood and the degree of decomposition on the respiration rate in wood samples. More decomposed wood (4th and 5th degree of decomposition) releases more CO_2 compared to less decomposed wood and the highest CO_2 emissions were recorded for aspen and alder wood. Better understanding of the mechanisms and factors affecting CO_2 emissions in forest ecosystem can help reduce climate change.

Keywords: deadwood; decay rate; forest ecosystem; soil organic matter; temperate forest.

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Manuscript: February 25, 2022; revised November 11, 2022; accepted December 28, 2022.

Introduction

Decomposition is the process whereby dead organic material is broken down to its constituent parts, ultimately to carbon dioxide (CO_2) and inorganic ions such as ammonium, calcium (Ca^{2+}), potassium (K^+), and other elements originally assimilated by the organisms (Robertson & Paul 2000, Chapin et al. 2011). Decomposition is an essential process in forest ecosystem functioning plays the crucial role in the breakdown of organic matter recycling nutrients that have been used by plants and animals (Rawlik et al. 2021). An important factor regulating the decomposition process is activity and composition of the microorganisms involved in that process (Xu et al. 2014, Feng et al. 2017). The decomposition process determines the amount of soil organic carbon (SOC) in the ecosystem and contributes to the total ecosystem respiration determining the net emission of carbon dioxide (CO_2) from the ecosystem to the atmosphere (Ravn et al. 2020).

Deadwood is a natural and essential component of forest ecosystems. Regardless of the form and amount of deadwood in the forest ecosystem, both standing and lying, deadwood performs important functions: it modifies habitat conditions, affects species diversity and the condition of plant, animal and fungal species, and modifies the circulation of elements in the forest ecosystem (Pichler et al. 2011, Cocciufa et al. 2014, Błońska et al. 2017, Piaszczyk et al. 2019a).

Decomposition of deadwood is a result of microbial respiration, physical fragmentation, leaching, and biological transformation (Russell et al. 2015). The knowledge about the CO_2 emission during deadwood decomposition process is very important because the amount of carbon stored in deadwood is equivalent to about 8 per cent of the global forest carbon stocks (Pan et al. 2011). Seibold et al. (2019) indicated that wood decomposition is driven by temperature, precipitation and the decomposer community.

Climate warming could accelerate wood decomposition by increasing microbial activity and insect-mediated wood decomposition, particularly in regions in which moisture is not limiting (Pietsch et al. 2018). The importance of wood species in the decomposition process turned out to be a very important factor and a very significant feature that determines the susceptibility of wood to decomposition is lignin content (Piaszczyk et al. 2022). The wood of more easily degradable species is colonised by a larger number of fungi, with diverse biochemical capacities (Kahl et al. 2017). Piaszczyk et al. (2019b) demonstrated the significance of the progress of the deadwood decay process and deadwood species in the formation of soil enzymatic activity. In certain cases, the increase of in tested parameters was greatest in most decomposed logs.

During the decomposition of a log, approximately 70% of the C is respired to the atmosphere by microbial activities (Chambers & Schimel 2001). The current estimate of carbon amount releases to the atmosphere during decomposition of deadwood is incomplete. The dynamics of wood respiration are still poorly understood in comparison to other fluxes of forest respiration (Rinne-Garmston et al. 2019). Therefore, it is very important to understand the factors that determine the rate of deadwood respiration. The present study was conducted with the objectives to: (1) determine the amount of deadwood respiration depending on species and degree of decomposition; (2) determine the extent of the impact of decomposing wood on the amount of respiration in surrounding soil; (3) find a relationship between the amount of respiration and the chemical fractional composition of soil organic matter. Logs of different species at different decomposition stages were selected for the analysis.

Materials and Methods

Experimental design

The investigation was conducted in the Czarna Rózga Reserve in Central Poland (50°59’37N; 20°1’5E). The study area is characterized by the following conditions of climate: the average annual rainfall is 649 mm, the average annual temperatures amount to 7.4°C and the length of the vegetation season lasts 200–210 days. Logs of the common hornbeam (*Carpinus betulus*), common alder (*Alnus glutinosa*), common aspen (*Populus tremula*) and silver fir (*Abies alba*) at different decomposition stages (III, IV and V) were selected for the analysis. The log research plots were located on Gleysols and Cambisols with sandy loam texture.

The decay classification of the logs was based on the hardness of the trunk. The decay classes (DC) of the logs were estimated according to the classification of dead trees in Maser et al. (1979). Three replicate logs were sampled for each combination of decay class and species. We selected logs with diameter between 25 and 35 cm to ensure direct comparability of observations. Wood samples measuring 7 × 7 × 7 cm for laboratory analysis were taken from the midpoint of each log. The soil samples (0.5 kg) were collected directly under the log from 0 to 10 cm depth using a small spade. Additionally soil samples were taken from different distances (0.1 m, 0.5 m, 1 m) from the logs from 0 to 10 cm depth after removed of litter. In total 144 soil and 36 deadwood samples were collected in the field in August 2017.

Measurement of wood and soil CO_2 respiration

The amount of carbon dioxide (CO_2) released from the wood and soil was assessed by performing closed chamber incubation with sodium hydroxide (NaOH). Field moist samples were weighed in 50 g amount and placed in 1 L plastic jars (Alef & Nannipieri 1995). Production of CO_2 was estimated using NaOH traps. A total of 50 mL polyethylene containers filled with 30mL of 1.0 M NaOH were placed in the 1 L jars on the soil surface. The jars were tightly sealed for one week in an incubator at 25 °C. Released CO_2 reacted with NaOH. Two portions of 5 mL of NaOH were titrated with 0.5 M HCl (automatic titrator, Mettler Toledo, Inc.) to pH 8.3 and to pH 3.7, respectively. Titration to pH 8.3 neutralised excess NaOH. From 8.3 to 3.7 was titrated Na_2CO_3 (Hopkins 2008, Kupka et al. 2021). As the wood and soil samples were carbonate free, there was no need to add barium chloride solution to precipitate carbonates.

Laboratory analysis

Soil and deadwood samples obtained in the field were dried and sieved through 2.0-mm mesh. In soils and deadwood samples, the basic properties were determined. Using the potentiometric method, the pH of the samples was analysed in H_2O. Carbon (Ct) and nitrogen (N) contents were measured with an elemental analyser (LECO CNS TrueMac Analyzer, Leco, St. Joseph, MI, USA). Using the method of Kononowa and Bielczikowa, fractional composition of humus was determined in which extraction is performed in a mixture of 0.1 M NaOH and 0.1 M Na4P2O7 (Dziadowiec & Gonet 1999). In order to obtain a humic acid (HA) and fulvic acid (FA) fraction, the chemical fraction was conducted. Base cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) were extracted using ammonium acetate and determined by inductively-coupled plasma analysis (ICP-OES Thermo iCAP 6500 DUO, Thermo Fisher Scientific, Cambridge, UK).

Statistical analysis

The normality of the distribution of the variables was tested with the Shapiro–Wilk test. Levene's test was used to evaluate the homogeneity of variances. We tested the differences between the distances using ANOVA and Tukey's HSD (honest significant difference) test. The two-way ANOVA was used to evaluate differences between mean values of soil and deadwood properties of different species, decomposition stages and distance from logs. General linear model (GLM) was used to investigate the effect of the species, decay class and distance on soil properties. Principal component analysis (PCA) method was used to evaluate the relationships between soil and deadwood properties. Differences with $P < 0.05$ were considered statistically significant. All analyses were performed in Statistica 12 software (StatSoft 2012).

Results

In the course of the research, differences in the tested properties were noted depending on the type of wood, the degree of decomposition and the distance from deadwood (Table 1). The analyzed logs differed significantly in their properties compared with the soil directly below them and in their immediate vicinity. Log samples especially those in the 5th degree of decomposition, are characterized by a significantly higher content of C, P, K, Mg and Na. The conducted analysis confirmed the importance of the species in shaping the pH, N, Ca and Mg content (Table 1).

Table 1 Basic physicochemical properties of wood and soil in relation to rate of wood decomposition (DC - III, IV and V), wood species and distance from log (cm).

Species	DC	Dist	pH	N	Ct	P	Ca	K	Mg	Na	Cp	C_{HA}	C_{FA}
Aspen	III	log	4.70±0.62	0.16±0.07	45.35±0.24	32.29±20.55	16.71±7.91	0.55±0.31	2.19±1.46	0.11±0.03	-	-	-
		0	4.09±0.24	0.97±0.89	16.38±13.88	29.66±25.48	12.30±15.46	0.31±0.22	1.45±1.73	0.13±0.15	6.92±4.08	6.33±4.21	0.60±0.29
		10	4.11±0.34	0.81±0.77	14.31±13.29	21.99±16.58	13.90±19.45	0.24±0.26	1.13±1.33	0.08±0.07	6.20±4.25	5.50±4.56	0.71±0.31
		50	4.28±0.42	0.91±1.07	16.44±19.30	28.85±31.56	16.58±24.80	0.30±0.39	1.37±1.83	0.07±0.06	6.30±4.80	5.85±4.62	0.45±0.24
		100	4.20±0.32	0.76±0.97	14.41±18.94	24.96±30.49	15.64±25.23	0.26±0.36	1.37±2.05	0.07±0.07	5.55±4.67	4.92±4.59	0.64±0.52
	IV	log	4.44±0.37	0.66±0.17	45.99±1.79^{a}	88.43±7.11^{a}	20.19±7.47	1.98±0.98^{a}	2.94±0.34^{a}	0.12±0.03^{a}	-	-	-
		0	4.36±0.76	0.59±0.44	9.89±7.76^{b}	28.77±24.44^{b}	12.54±16.11	0.17±0.18^{b}	1.45±1.43^{ab}	0.05±0.02^{b}	4.81±2.90	0.96±0.51	3.85±2.40
		10	4.21±0.34	0.37±0.09	5.64±1.65^{b}	21.07±5.43^{b}	5.69±4.47	0.10±0.03^{b}	0.65±0.20^{b}	0.03±0.01^{b}	3.51±0.96	0.68±0.13	2.83±0.83
		50	4.03±0.34	0.33±0.08	5.17±1.61^{b}	15.47±2.88^{b}	4.64±4.93	0.06±0.03^{b}	0.44±0.19^{b}	0.03±0.01^{b}	3.33±0.75	0.70±0.09	2.63±0.66
		100	3.99±0.16	0.38±0.17	5.91±2.87^{b}	23.96±8.46^{b}	5.72±3.68	0.08±0.03^{b}	0.62±0.29^{b}	0.04±0.03^{b}	3.97±1.31	0.78±0.17	3.18±1.14
	V	log	5.00±0.46	0.88±0.14^{a}	46.42±0.86	169.26±65.04^{a}	29.95±15.66	1.80±0.68^{a}	4.69±1.30^{a}	0.18±0.03	12.09±0.99^{a}	2.34±1.70	9.75±2.66^{a}
		0	4.51±1.32	0.88±0.49^{ab}	17.14±10.78	37.59±17.12^{b}	13.37±3.12	0.44±0.35^{b}	1.51±0.94^{ab}	0.12±0.11	8.21±4.38^{ab}	3.06±2.95	5.15±2.86^{ab}
		10	4.61±1.35	0.45±0.16^{b}	8.16±4.11	19.93±8.86^{b}	7.77±5.24	0.17±0.09^{b}	0.76±0.36^{b}	0.05±0.03	4.11±1.23^{b}	1.50±1.15	2.62±1.29^{b}
		50	4.37±1.22	0.30±0.07^{b}	5.38±1.52	12.39±5.74^{b}	5.40±6.56	0.29±0.33^{b}	1.07±0.80^{b}	0.11±0.12	3.50±0.37^{b}	1.40±1.06	2.10±0.88^{b}
		100	4.05±0.63	0.27±0.08^{b}	4.32±0.92	11.80±6.38^{b}	3.97±4.60	0.16±0.15^{b}	0.95±0.71^{b}	0.10±0.10	3.45±0.55^{b}	1.11±0.63	2.34±1.17^{b}
Alder	III	log	4.56±0.99	0.36±0.16	47.00±0.43^{a}	27.32±4.39^{a}	12.14±7.36	1.92±2.13^{a}	2.23±0.62	0.13±0.04	-	-	-
		0	4.81±1.01	0.57±0.14	8.28±2.43^{b}	18.17±2.28^{b}	14.77±14.34	0.17±0.11^{b}	1.07±0.66	0.05±0.01	5.97±2.99	3.48±1.57	2.49±2.17
		10	5.04±1.17	0.52±0.20	7.46±3.14^{b}	15.79±0.76^{b}	16.20±16.25	0.10±0.09^{b}	1.09±0.89	0.05±0.02	5.38±2.92	3.15±1.18	2.24±2.06
		50	4.99±1.05	0.50±0.26	7.21±3.92^{b}	15.72±1.64^{b}	16.01±16.42	0.11±0.07^{b}	1.03±0.95	0.05±0.02	5.51±3.78	3.53±1.66	1.98±2.13
		100	5.21±1.21	0.53±0.23	7.59±3.45^{b}	18.59±1.82^{b}	15.58±15.74	0.11±0.02^{b}	1.04±0.93	0.04±0.02	5.75±3.65	4.12±1.51	1.63±2.18
	IV	log	4.20±0.35	0.49±0.18	46.32±0.14^{a}	70.64±57.71	17.87±4.34	1.92±0.98^{a}	2.59±0.50^{a}	0.26±0.26	-	-	-
		0	5.51±1.22	1.06±0.78	16.70±14.02^{b}	31.50±19.29	28.20±3.05	0.21±0.16^{b}	1.90±0.84^{ab}	0.12±0.09	6.70±4.55	1.12±0.50	5.48±4.11
		10	5.67±1.28	0.61±0.27	8.65±4.26^{b}	23.40±14.52	23.08±3.92	0.09±0.02^{b}	1.27±0.16^{b}	0.09±0.08	4.43±1.83	0.74±0.22	3.69±1.61
		50	5.62±0.98	0.70±0.40	10.17±6.61^{b}	27.65±18.01	24.84±3.26	0.14±0.11^{b}	1.40±0.32^{b}	0.09±0.07	4.52±1.98	0.77±0.21	3.75±1.77
		100	5.77±0.77	0.62±0.23	8.45±3.64^{b}	16.93±4.49	25.10±3.43	0.09±0.02^{b}	1.26±0.15^{b}	0.10±0.08	4.23±1.41	0.72±0.17	3.51±1.25
	V	log	4.71±0.65	1.10±0.35	46.12±0.50^{a}	163.75±64.15^{a}	29.90±19.48	1.62±0.84^{a}	3.28±0.72^{a}	0.19±0.10	14.13±3.35	4.90±2.80	9.23±4.89
		0	5.34±1.18	0.82±0.26	12.28±3.71^{b}	26.09±4.17^{b}	27.79±17.75	0.16±0.09^{b}	1.59±0.64^{b}	0.07±0.03	6.73±2.58	3.82±2.73	2.91±1.06
		10	5.36±1.14	0.87±0.26	12.93±3.88^{b}	30.10±5.58^{b}	29.60±15.98	0.21±0.08^{b}	1.66±0.70^{b}	0.08±0.05	7.06±3.02	3.61±2.79	3.45±1.32
		50	5.18±1.25	0.83±0.23	12.12±2.63^{b}	24.97±6.96^{b}	26.32±15.47	0.18±0.06^{b}	1.44±0.56^{b}	0.07±0.04	7.05±3.49	3.56±2.58	3.49±1.92
		100	4.91±1.38	0.99±0.33	14.92±4.62^{b}	31.10±5.61^{b}	25.44±16.90	0.21±0.07^{b}	1.58±0.54^{b}	0.07±0.04	8.65±4.99	4.92±3.96	3.74±2.86
Fir	III	log	3.95±0.45	0.10±0.02^{b}	47.19±2.23^{a}	20.93±6.57	6.11±0.60^{a}	0.69±0.61	0.78±0.40^{a}	0.10±0.01	-	-	-
		0	3.59±0.06	0.53±0.15^{a}	10.02±2.64^{b}	12.58±4.74	2.07±0.93^{b}	0.19±0.18	0.38±0.16^{ab}	0.05±0.01	5.41±1.10	3.93±2.05	1.48±1.17
		10	3.60±0.02	0.41±0.02^{a}	7.70±0.18^{b}	9.44±3.40	1.02±1.08^{b}	0.08±0.08	0.25±0.04^{b}	0.06±0.05	4.44±1.20	3.16±2.30	1.28±1.13
		50	3.63±0.13	0.29±0.06^{a}	5.65±0.87^{b}	8.87±1.08	0.78±0.89^{b}	0.07±0.04	0.17±0.05^{b}	0.05±0.03	3.65±0.92	2.93±1.94	0.73±1.03
		100	3.67±0.02	0.33±0.16^{ab}	6.68±2.49^{b}	9.65±1.46	0.81±0.76^{b}	0.05±0.04	0.16±0.05^{b}	0.04±0.03	4.00±1.86	3.26±2.43	0.74±0.67

Species	DC	Dist	pH	N	Ct	P	Ca	K	Mg	Na	Cp	C_{HA}	C_{FA}
Fir	IV	log	4.36±0.33	0.27±0.12	47.35±0.49^{a}	94.00±55.11^{a}	9.71±4.24	1.25±0.50^{a}	1.12±0.49	0.12±0.08	-	-	-
		0	4.36±0.52	0.37±0.12	6.18±3.95^{b}	27.25±10.36^{b}	5.41±4.86	0.16±0.06^{b}	0.35±0.21	0.03±0.01	3.32±1.16	1.47±1.61	1.84±0.45
		10	4.38±0.60	0.41±0.25	6.39±3.10^{b}	27.04±18.22^{b}	6.66±6.77	0.20±0.08^{b}	0.48±0.50	0.04±0.02	3.17±0.39	1.29±1.13	1.88±1.28
		50	4.19±0.44	0.28±0.12	4.04±0.98^{b}	19.86±7.97^{b}	3.69±3.00	0.12±0.03^{b}	0.29±0.22	0.03±0.02	2.68±0.56	1.08±0.76	1.61±1.31
		100	4.39±0.66	0.26±0.12	3.90±0.92^{b}	14.75±6.89^{b}	5.44±6.06	0.10±0.04^{b}	0.35±0.31	0.03±0.01	2.54±0.70	1.00±0.65	1.55±1.31
	V	log	3.99±0.31	0.73±0.11	47.53±1.26^{a}	79.94±21.36^{a}	17.77±4.69	0.89±0.11^{a}	2.21±0.36^{a}	0.14±0.04	15.70±2.19^{a}	10.21±4.28	5.49±4.28
		0	3.78±0.21	0.96±0.18	20.55±6.83^{b}	25.71±10.84^{b}	7.46±1.10	0.21±0.06^{b}	0.76±0.16^{b}	0.12±0.08	7.99±6.04^{ab}	6.34±7.36	1.65±1.35
		10	3.67±0.27	0.62±0.19	12.79±3.20^{b}	23.17±15.93^{b}	5.17±2.98	0.13±0.12^{b}	0.63±0.22^{b}	0.10±0.04	6.64±2.31^{b}	5.13±3.00	1.51±1.46
		50	3.73±0.27	0.66±0.37	14.09±10.49^{b}	17.55±6.72^{b}	4.06±2.58	0.12±0.06^{b}	0.54±0.15^{b}	0.11±0.10	6.73±4.71^{b}	5.35±3.99	1.38±0.96
		100	3.73±0.25	0.53±0.22	9.99±3.83^{b}	15.87±9.89^{b}	3.97±3.85	0.08±0.08^{b}	0.48±0.24^{b}	0.07±0.03	5.32±1.73^{b}	3.61±1.73	1.72±1.46
Hornbeam	III	log	4.39±0.23	0.31±0.12	45.30±0.42	33.27±4.24	16.21±4.72	1.04±0.51	3.01±0.41	0.23±0.17	-	-	-
		0	4.48±0.20	0.89±1.14	16.80±22.93	26.44±29.76	15.13±17.10	0.37±0.48	1.75±2.64	0.10±0.09	5.65±5.69	5.07±6.10	0.58±0.46
		10	4.55±0.35	0.90±1.20	16.23±22.65	30.69±38.96	17.49±20.64	0.23±0.30	1.35±2.02	0.06±0.04	5.56±5.85	5.10±6.17	0.46±0.46
		50	4.48±0.08	0.88±1.11	15.69±20.63	22.37±26.10	19.27±23.28	0.18±0.19	1.25±1.87	0.06±0.03	5.63±5.35	4.99±5.44	0.64±0.37
		100	4.53±0.10	0.89±1.08	14.92±18.78	28.04±37.50	20.89±25.16	0.22±0.27	1.69±2.33	0.08±0.05	5.32±4.11	4.64±4.01	0.68±0.59
	IV	log	4.93±0.24	0.59±0.11	44.70±2.01	88.34±7.71^{a}	42.57±32.08	1.33±0.41^{a}	5.53±5.12	0.14±0.07	-	-	-
		0	4.55±0.13	1.62±0.73	27.82±11.61	65.96±21.75^{ab}	27.51±6.22	0.48±0.15^{b}	2.47±0.88	0.12±0.07	11.26±4.71	7.38±5.49	3.88±2.09
		10	4.43±0.30	1.23±0.76	21.40±14.39	42.86±10.87^{b}	21.45±6.80	0.27±0.11^{b}	1.76±0.68	0.11±0.11	9.05±5.10	6.58±6.15	2.47±1.39
		50	5.32±1.13	0.91±0.69	15.48±13.90	29.22±9.60^{b}	23.21±7.98	0.21±0.17^{b}	1.51±0.74	0.08±0.06	7.51±5.97	5.51±6.51	2.01±0.67
		100	5.63±1.41	0.94±0.73	15.59±14.55	27.71±14.37^{b}	24.07±3.19	0.25±0.27^{b}	1.55±0.86	0.08±0.04	7.59±6.32	5.79±7.38	1.80±1.06
	V	log	5.53±0.16	0.55±0.26	45.60±0.35^{a}	78.21±36.08^{a}	29.17±13.60	0.67±0.53	3.28±3.13	0.17±0.04	14.10±3.47^{a}	5.89±2.87	8.21±2.89^{a}
		0	5.79±0.63	0.54±0.31	7.65±3.92^{b}	20.15±14.92^{ab}	21.24±16.67	0.15±0.13	1.50±1.25	0.09±0.01	4.18±0.92^{b}	3.26±0.42	0.92±0.52^{b}
		10	5.48±0.95	0.49±0.20	6.90±2.34^{b}	14.05±5.01^{b}	16.50±9.67	0.11±0.05	1.11±0.78	0.07±0.02	3.95±0.42^{b}	3.13±0.42	0.83±0.43^{b}
		50	5.29±0.79	0.39±0.08	5.33±0.74^{b}	10.89±3.82^{b}	11.70±4.76	0.08±0.05	0.84±0.42	0.07±0.03	3.55±0.44^{b}	3.04±1.02	0.51±0.58^{b}
		100	4.94±1.19	0.39±0.07	5.83±2.04^{b}	11.20±2.64^{b}	9.27±5.01	0.08±0.07	0.65±0.53	0.05±0.01	3.62±0.46^{b}	3.22±1.04	0.40±0.64^{b}
Species			***	*	ns	ns	***	ns	***	ns	ns	ns	ns
DC			*	ns	ns	***	ns	ns	ns	ns	ns	ns	ns
Distance			ns	ns	***	***	*	***	***	***	ns	ns	ns
Species x DC			ns	***	***	**	*	ns	ns	*	ns	ns	ns
Species x Distance			ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
DC x Distance			ns	ns	ns	***	ns	ns	ns	ns	ns	ns	ns
Species x DC x Distance			ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

mean±standard deviation; * - $p \leq 0.05$, ** - $p \leq 0.01$, *** - $p \leq 0.001$, ns – not significant; different lowercase alphabets in the upper index mean significant differences of parameters depending on the distance from the logs; Ct – organic carbon content (%), N – nitrogen content (%), Ca, K, Mg and Na content (cmol(+).kg-1), Cp - pyrophosphate extractable carbon (%), CHA - carbon in humic acid (%), C_{FA} - carbon in fulvic acid (%)

The degree of wood decomposition was significant for the pH value and the content of P. The content of Ct, P, K, Mg and Na was significantly influenced by the distance from the log ($p \leq 0.001$). Distance was less important in shaping the Ca content ($p \leq 0.05$). The type of species and decay class have interactive effect on the content of N, Cp, P, Ca and Na while decay class and distance has interactive effect on P content (Table 1). Wood species, decay class and distance had no statistically significant influence on the concentrations of Cp, C in fulvic acid (FA) and humic acid (HA) (Table 1). There is a tendency that all SOM fractions have decreased significantly with the distance from logs. The highest values of Cp, CHA and CFA were recorded in the soil directly under the log.

Significant differences in respiration were noted within the tested samples (Figure 1). In the case of most of the studied species, the degree of deadwood decomposition was characterized by significantly lower respiration. 2 to 3 times higher respiration was recorded in the soil compared with the deadwood.

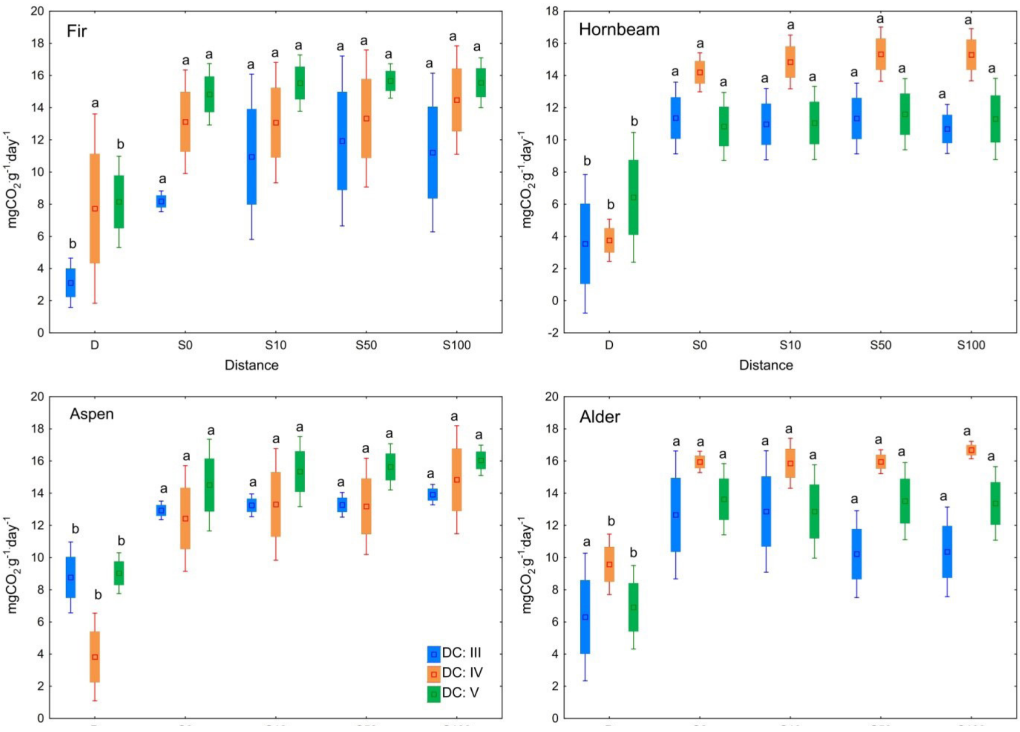

Figure 1 The CO_2 respiration ($mgCO_2.g^{-1}.day^{-1}$) in relation to rate of wood decomposition (III, IV and V) and wood species plotted against the distance (cm) from the wood log, letters (a, b) mean significant differences between distance.

The GLM analysis performed confirmed the significant importance of decay classes, species and distance in shaping the respiration of the tested samples (Table 2). As deadwood decomposition progressed, respiration increased. In most of the tested wood species (except aspen), the samples in the fourth and fifth degree of decomposition were characterized by the highest respiration. The type of species and distance has interactive effect on respiration ($p \leq 0.001$) (Table 2).

The respiration has strongly correlated with the pH, content of P, Ca, Mg and Na. Additionally, respiration was strongly correlated with Cp and CFA (Table 3).

A projection of the variables on the factor plane demonstrated correlation between the wood and soil properties and respiration (Figure 2). Two main factors had a significant total impact (66.72 %) on the variance of the variables. Factor 1 accounted for 52.89 % of the variance of the examined properties, whereas factor 2 explained for 13.83 % of the variance (Figure 2). Factor 1 is related to the organic matter fractions and respiration, while factor 2 is related to the acidity. The conducted PCA analysis confirmed the relationship between respiration and SOM fractions, the content of N, P and the content of basic cations (Ca, Mg and K) (Figure 2).

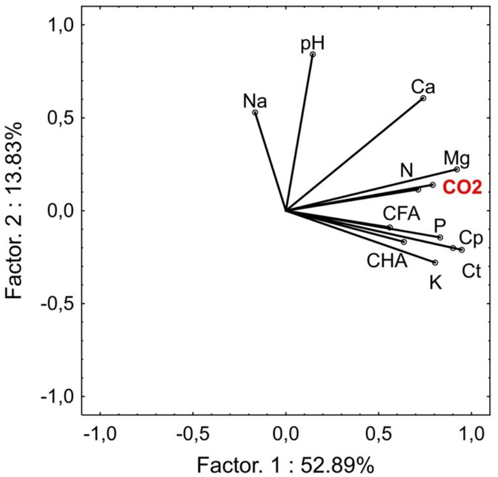

Figure 2 Diagram of PCA with projection of variables on a plane of the first and second factor (Ct - organic carbon content, Cp - pyrophosphate extractable carbon, C_{HA} - carbon in humic acid, C_{FA} - carbon in fulvic acid).

Table 2 Summary of general linear model (GLM) analysis of the effect of decay class (DC), wood species and distance from log on CO_2 respiration.

	F	*p*
DC	15.153	**0.0001**
Species	4.397	**0.0056**
Distance	45.752	**0.0000**
DC*Species	5.259	**0.0001**
DC*Distance	0.516	0.8423
Species*Distance	0.399	0.9614
DC*Species*Distance	0.456	0.9857

Note: Significance effect (P < .05) are shown in bold

Discussion

Our research shows the differences in the amount of respiration between deadwood and the soil beneath it and in its vicinity. Higher respiration was noted in the soil compared with the deadwood. Respiration of decaying wood samples was 2-3 times lower compared to soil, regardless of the type of wood and the degree of wood decomposition. The factors influencing the rate of the decomposition process and the respiration process may be the quality of the substrate, especially its chemical composition (Tuomi et al. 2011). The noted differences can be related to the physical and chemical properties of wood and soil. Earlier studies indicate differences in the content of C, N and P in wood and soil, which was expressed by the C/N/P stoichiometry (Piaszczyk et al. 2019). The soil samples were characterized by narrower C/N/P stoichiometry compared to that of deadwood. The C/N/P in soil ranged from 395/27/1 to 1592/81/1, while in deadwood it ranged from 2950/45/1 to 16906/38/1. In our research, we found clear differences in the content of basic cations in decaying wood and soil. The wood samples were characterized by a higher content of Ca, K, Mg and Na, regardless of the type of wood and the degree of decomposition.

Other factors reported to affect the decomposition process include microorganisms activity especially fungal diversity and community structure (Valentin et al. 2014). Early studies confirm that decaying wood has an important contribution to the overall fungal diversity because a large fraction of all the species were found to exclusively inhabit wood thus, wood specialised species are lost from managed forests where decaying wood is absent (Mäkipää et al. 2017). In addition, bacteria are considered to play a minor role in wood decomposition (Clausen 1996).

Table 3 Correlation between CO2 respiration and basic physicochemical properties.

	pH	N	Ct	P	Ca	K	Mg	Na	Cp	C_{HA}	C_{FA}
CO_2 respiration	0.18*	0.13	0.12	0.18*	0.21*	0.05	0.18*	0.18*	0.19*	0.02	0.34*

Note: * correlation significant with *p<0.05*; Ct - organic carbon content, Cp - pyrophosphate extractable carbon, C_{HA} - carbon in humic acid, C_{FA} - carbon in fulvic acid

In our study, we did not determine the amount and diversity of microorganisms, but based on the results of previous studies, we can conclude that factor play a significant role in shaping deadwood and soil respiration. Our results indicate the possibility of leaving deadwood in forest ecosystems without fear of excessive CO_2 emissions to the atmosphere. During the decomposition of deadwood, significantly lower amounts of CO_2 are released compared with the soil. Considering the time it takes for the deadwood to completely decompose and the intensity of the decomposition processes, there will not be CO_2 intensive emissions. In fresh habitats, the total time required for fine woody debris decomposition among the different species was estimated to be 4–10 years for deciduous species and 6–11 years for conifers while under boggy habitat conditions, this period was extended to 7–11 years (deciduous species) and 17–20 years (coniferous species) (Piaszczyk et al. 2022). The results concern pieces of wood several centimeters long. In the case of huge logs, the decomposition period will increase several times.

The performed GLM analysis confirmed the importance of the wood species and its degree of decomposition in influencing respiration. The research covered deciduous and coniferous species, which differ in the chemical composition of the wood. The walls of wood cells are composed of three principal chemical materials, cellulose, hemicelluloses and lignin, all of which are polymeric. The concentration of slowly decomposing lignin plays a role in the pace of the decomposing process.

Hornbeam wood and, to a lesser extent, fir wood had significantly lower respiration. The highest CO_2 emissions were recorded for aspen and alder wood. Species that are more susceptible to the degradation include those without heartwood and those with a lower content of secondary metabolites. Hornbeam wood is heavy and hard, which slows down the decomposition processes.

Coniferous wood contains toxic substances that limit the number of organisms in the decomposing wood (Harmon et al. 1986). According to Kögel-Knabner (2002), deciduous and coniferous species differ in the quality of hemicellulose, lignin degradation and presence of resins. Piaszczyk et al. (2022) demonstrated the importance of lignin content in influencing the mass decline of wood. With a lower lignin content, the decomposition process was faster.

The wood of more easily degradable species is colonised by a larger number of fungi, with diverse biochemical capacities, which may result in higher enzymatic activity (Piaszczyk et al. 2019b). With regard to the degree of wood decomposition, the highest respiration was determined in wood samples at the fourth and fifth degree of decomposition and in the soil affected by them. With the decomposition of deadwood, its physical, chemical and biochemical properties change (Błońska et al. 2019). Kahl et al. (2017) have further confirmed a positive correlation of wood decay rate with enzymatic activity and species diversity of fungi colonising wood. The most occurrences of mycorrhizal fungi in dead wood have been reported for the last decay phases of dead wood (Ottosson et al. 2014).

During the decay of a Norway spruce log, the fungal community in the log becomes increasingly a species that is rich and more similar to fungal communities found from soil (Mäkipää et al. 2017). According to these authors the increase in fungal species richness in wood during the decay is associated with the gain of mycorrhizal and some soil-saprotroph species such as *Gymnomyces monosporus*, *Piloderma fallax*, *P. sphaerosporum*, *Tylospora sp.*, and *Russula decolorans.*

Although we found a significant difference between the amount of carbon dioxide emitted from deadwood compared with the soil, we did not find a significant difference in the intensity of respiration in the gradient of distance to the log over a distance of up to 100 cm. The exception was the soil in the immediate vicinity of the alder wood logs (under the logs and 10 cm from the log), there was a tendency for soil respiration increase. Directly under the logs, the enrichment of easily soluble carbon of fulvic acids, phosphorus and also alkaline cations was noted. The enrichment of the soil under the logs undoubtedly results from the process of washing by rainwater and the displacement of dissolved substances with water, which was confirmed in previous studies (Zalamea et al. 2016, Lasota et al. 2018). It should be remembered that in natural conditions, as a result of changes in thermal and humidity conditions, as well as differences in microhabitat conditions affecting insolation, fluctuations in the process of microbiological decomposition of wood and associated respiration occur. The influence of these environmental factors on the rate and dynamics of wood decomposition in the forest environment has been documented in a number of studies (Harmon et al. 1986, Olajuyigbe et al. 2012, Herrmann and Bauhus 2013). In our experiment, we studied respiration under controlled conditions (temperature, humidity), reflecting the potential flux of CO_2 released under optimal conditions.

Conclusions

We conclude that deadwood releases 2-3 times less CO_2 into the atmosphere during the decomposition process compared with the soil. More decomposed wood (4^{th} and 5^{th} degree of decomposition) releases more CO_2 compared to less decomposed wood. Hornbeam wood and, to a lesser extent, fir wood had significantly lower respiration. The highest CO_2 emissions were recorded for aspen and alder wood. The future challenge is to determine the amount of CO_2 released by a larger number of wood species depending on the habitat conditions, and above all, thermal conditions and rainfall.

Acknowledgements

The research was financed by the National Science Centre, Poland: decision no. DEC 2016/21/D/NZ9/01333 and DEC 2020/39/B/NZ9/00372.

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