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RESEARCH ARTICLE

The falling of a tree in the forest is the beginning of significant changes in the soil

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Abstract
Aims The aim of the project was to determine the vertical variability of soil under the influence of deadwood (DWD) in a temperate forest ecosystem.
Methods The laboratory analyses included soil layers of 0–5 cm, 5–10 cm, 10–20 cm and 20–40 cm, which were taken directly under the deadwood, as well as the forest litter layer and deadwood fragments. The control samples were taken 30 m away.
Results The decomposition processes of deadwood are associated with a 55% increase in soil organic carbon (SOC) deposition to a depth of -40 cm and a 36% increase in total nitrogen (N) content compared to soils without deadwood. DWD significantly increases exchangeable cations, especially at a depth of -5 cm to -20 cm. Deadwood contains slightly more hydrogen ($H^{+)}$ and aluminum ions (Al^{3+}) than forest litter, but soil acidification is related to pedogenic processes rather than decomposition of deadwood in hyperacid forest soils. The soil surface under deadwood with a high degree of decomposition is characterised by a lower bulk density (BD) value than the soil where only forest litter was present.
Conclusions Our studies suggest that the physicochemical properties of forest soils change under the influence of deadwood such that the deeper layers beneath the logs take on propertie8s that make them similar to the shallower layers without deadwood. To summarise, leaving deadwood in the forest has a positive effect on soil fertility by enriching the soil with nutrients (Ca^{2+}, K^{+}, Na^{+}, less Mg^{2+}) and improving its physical properties.

Keywords Coarse Woody Debris · Deadwood · Litter Decomposition · Soil Organic Carbon · Exchangeable Cations · Hyperacid Soils

Introduction

The moment a tree falls in the forest, the biochemical processes associated with its decomposition begin, which take place in the deadwood and in the soil. The decomposition of wood is a long-term process and takes between 10 and 100 years, depending on environmental conditions (Zielonka and Niklasson 2001), sometimes even over 300 years (Chen et al. 2005). The decomposition of deadwood is a key process

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in forest ecosystems that plays an important role in nutrient cycling (Cocciufa et al. 2014). Based on research and experiments, the factors causing coarse woody debris (CWD) decomposition have been described in detail. The decomposition of CWD has been shown to be important for habitat productivity, animal activity and tree seeding, and is a storehouse of carbon, water and nutrients (Harmon et al. 1986). Plant litters including dead leaves, stems, barks, flowers, fruits, and logs are the major sources of forest soil organic matter (SOM) (Osman 2013). The decomposition products of organic residues are absorbed into the litter and soil, they improve soil moisture in dry months and are resistant to destruction by fire (Page-Dumroese et al. 1991). It has been found that deadwood stores large amounts of water. Mosses play an important role in this process as they cover the dead stem and significantly increase its moisture content (Gutowski et al. 2004; Szukalska 2007). The rate of decomposition itself is the result of biotic factors and the locally created microclimate of the soil surface (Larsen et al. 1980; Swift and Boddy 1984; Breymeyer et al. 1998).

It is assumed that the most important abiotic factor influencing the rate of wood decomposition is moisture (Fravolini et al. 2016; Piaszczyk et al. 2022). Water determines the number of saprophytic fungi (Huang et al. 2022; Mayer et al. 2022) and is positively correlated with the number of decomposition taxa (Tarvainen et al. 2020; Hu et al. 2021). Among other abiotic factors related to the decomposition process of deadwood, its defragmentation by soil organisms is important. The fragmentation of the wood increases the availability of plant tissue for microorganisms and further biological decomposition is intensified (Harmon et al. 2000). Microorganisms are involved in the process of decomposition of deadwood and their activity determines the rate of decomposition. The most important biological role in wood decomposition is played by saprophytic fungi and bacteria, including cellulolytic and ligninolytic organisms, which determine the decomposition of lignin and cellulose by secreting enzymes (Wang et al. 2023). During the entire period of wood decomposition, white-rot fungi play the largest role, dominating the decomposition of hardwood and softwood (Arnstadt et al. 2016). Many factors have been found to influence the rate and intensity of development of the above groups, but the most important are pH and carbon and nitrogen content. Fungi grow much faster and more intensively than bacteria in soils with low pH values (Rousk and Bååth 2011). A high C/N ratio of the litter also favors fungi, as it increases the carbon content of the fungal hyphae colonizing the deadwood relative to the bacterial cells (Paustian and Schnurer 1987; Bakken 1985; Wallander et al. 2003). Organisms that decompose deadwood, such as fungi and bacteria, carry out wood decomposition processes and release organic carbon to the soil in the process (Bani et al. 2018; Piaszczyk et al. 2019). If little or no nitrogen is available, secondary metabolism occurs in conjunction with the degradation of lignin (Krajewski and Witomski 2005).

Some inferences may also come from research on nitrogen mineralization processes in litter. It has been found that even additional amounts of nitrogen (artificially or naturally introduced) do not cause significant and permanent changes in the chemical composition of litter, as they are likely to be leached out and mineralized very quickly (Frost and Hunter 2007; Sukovata et al. 2010). Long-term studies have shown that stem weight loss increases as soil nutrient content of the soil decreases. Fungi are responsible for this, which ensure the displacement of elements, especially between nutrient-poor soils and a rotting boot (Edelmann et al. 2023). Another important finding is that nutrient concentrations in decaying tree logs are sensitive to local microclimatic changes (Wang et al. 2022). Through leaching, the nutrients released during decomposition enter the soil with the rainwater. Three processes – defragmentation, decomposition and leaching – interact with each other and form a complex system for recycling CWD in forest ecosystems (Russell et al. 2015). The wood decomposition process shows considerable differences between tree species, especially between deciduous and coniferous species (Lasota et al. 2018).

The process of wood decomposition changes the physical, chemical and biochemical properties of forest soils (Błońska et al. 2017). During the decomposition process, 20 % of the carbon stored in deadwood is irretrievably lost in the form of CO_2 released into the atmosphere, while 1/3 of the carbon stored in the wood is released into the soil (Lagomarsino et al. 2021). Piaszczyk et al. (2019) pointed out that the most decomposed deadwood significantly influences the composition of the SOM. Previous studies found significant differences in dissolved organic carbon

(DOC) and nitrogen (N) concentrations in leachate from coniferous and deciduous trees. More DOC and N were released from decaying hornbeam and aspen wood, while the least DOC and TN were released into the soil from coniferous species, especially spruce (Błońska et al. 2019). SOC content, and thus the amount of organic matter, is a key factor influencing soil fertility in general (Zwydak et al. 2017; Ondrasek et al. 2019). However, current research on the effects of deadwood on soil does not explain the progression of physico-chemical transformations in soil from a vertical perspective. It is known that deadwood increases soil organic matter reserves in the upper soil layers (Wambsganss et al. 2017).

However, the extent to which deadwood alters the physicochemical properties of forest soils has not been determined. Previous research suggests that the effects of deadwood on soil decrease with depth (Nazari et al. 2023), but the limit of these effects has not been determined. The aim of our research was to determine the profound impact of deadwood on forest soil properties. We assume that the strongest impact of deadwood is in the superficial soil layers and has little impact at a depth of 20-40 cm. We assumed that deadwood leads to an increase in carbon accumulation in the near-surface layers of forest soils with a simultaneous increase in the content of basic cations.

Materials and methods

Study sites

The study plots were located in north-eastern Poland in the Masuria-Podlasie region, in the Białowieża Forest mesoregion (II.16) (Zielony and Kliczkowska 2012) (Table 1). The study area was formed during the Central Polish glaciation - the Warta Ice Age (170-120 thousand BP). Geologically, it is a poorly diversified, flat or slightly hilly plots covered with boulder clay, glacial fluvial sands and gravels, and outwash sands and gravels (Prusinkiewicz and Kowalkowski 1964; Fedorowicz et al. 1993). The study plots was dominated by podzols and brunic arenosols (IUSS working group WRB 2022). The analysed soils are characterised by a similar grain size, i.e. loamy sand. The climate of the Białowieża Forest is classified as a cool-temperate transitional climate. The average annual air temperature (1955-2001) was 6.8 °C. The average amount of precipitation is about 630 mm per year. The growing season is relatively short, lasting 205 days.

The investigation comprised 9 study plots. On each surface, a soil profile was dug directly at the location of the log. The most decomposed logs were included in the study (logs at the transition between the 4th and 5th degree of decomposition and logs in the 5th degree of decomposition). The degree of decomposition was determined according to the BioSoil methodology (2004): 4th degree - decomposed wood 26-75% of the wood was soft to very soft and 5th degree - very decomposed wood 76% - 100 % of the wood was soft. The sampling plan is shown in Figure 1. According to

Table 1 Location of the research plots

Plot number	Dominant tree species	Age of forest-forming species	Humus form	N	E
1	*Pinus sylvestris*	81	mor	52°43’49.1”	22°45’35.6”
2	*Quercus robur*	144	moder	52°40’05.8”	22°44’40.2”
3	*Quercus robur*	184	moder	52°40’16.6”	22°44’59.9”
4	*Quercus robur*	190	moder	52°45’13.6"	23°38’59.6"
5	*Picea abies*	69	mor	52°45’21.0"	23°38’24.7"
6	*Picea abies*	97	mor	52°42’58.4"	23°40’15.5"
7	*Quercus robur*	192	moder	52°43’04.9"	23°40’04.8"
8	*Pinus sylvestris*	182	moder	52°43’06.0"	23°39’15.8"
9	*Quercus robur*	182	moder	52°42’06.5”	23°41’09.4”

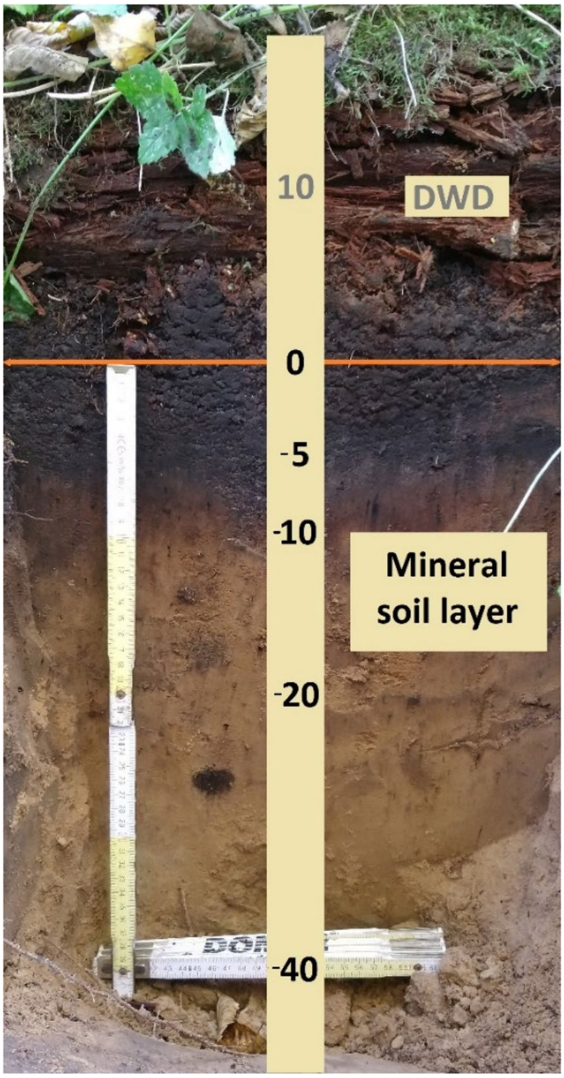


Fig. 1 Sampling scheme used in field surveys by *BioSoil (2004)*: https://www.icp-forests.org/documentation/Surveys/BD/DWD.html

the BioSoil soil module methodology (Forest Focus Regulation (EC) N 2152/2003), mineral soil samples for laboratory analyzes were taken from the following layers: 0-5, 5-10, 10-20, 20-40 cm. The control soil samples were taken in the same way at 30 m distance from log. Deadwood samples (DWD) weighing approximately 0.5 kg were taken from the center of a decomposed log, and litter samples (O) were taken from control plots. Samples with intact structure were collected in 100 cm^3 cylinders to determine bulk density. The deadwood surface variant is labeled with the DWD symbol, while the control surface variant is labeled with the no_DWD symbol.

Soil physiochemical properties analysis

The laboratory tests included wood samples and soil samples from mineral layers up to a depth of -40 cm. A total of 90 samples were taken for laboratory analysis. In all samples were determined: bulk density by the gravimetric method, pH($CaCl_2$) (PN-ISO10390:1997) by SevenCompact Duo pH/Cond S213, Mettler-Toledo Company, total organic carbon [SOC] (PN-ISO10694:2002), total nitrogen content [N] (PN-ISO13878:2002) by Vario Max cube CN, Elementar Company, exchangeable acidity [H_{ex}], exchangeable aluminum [Al^{3+}], hydrogen ions [H^+] (PB-12ed.3 01/07/2014) by Burette Dygital III 50ml, Brand Company, content of exchangeable cations (magnesium Mg^{2+}, potassium K^+, sodium Na^+ and calcium Ca^{2+}) (PB-05ed.3 01/07/2014) by ICP iCAP 7000 Series, Thermo Scientific Company. The content of total aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), potassium (K), phosphorus (P), manganese (Mn) was determined using the extraction method according to the PN-ISO 11466:2002 standard and the inductively coupled plasma optical emission spectrometry (ICP-OES) method. Sum of exchangeable cations [EC] (Lambers and Barrow 2020) and C/N ratio was calculated on the basis of the results obtained.

Statistical analysis

The statistical analyzes were performed with the program R (R Core Team 2023). The significance of the differences in the analyzed variables between the DWD, O, 0-5, 5-10, 10-20, 20-40 cm layers were determined using the Friedman ANOVA and the Nemenyi post-hoc test from the "PMCMRplus" package (Pohlert 2022). The significance of the differences in the same layers between outcrops with and without deadwood was determined using the Wilcoxon test from the "stats" package (R Core Team 2023). The correlation between the analyzed variables in outcrops with and without deadwood was determined using Spearman's rank correlation and visualization of the results in the "corrplot" package (Wei and Simko 2021). The simultaneous effect of the presence of deadwood and soil layer on SOC, N and EC content was calculated using linear mixed models (LMM), which allow additional control of the influence of random effects. The "lmer" function from the "lme4" package was used (Bates et al. 2015). A normal distribution was achieved by logarithmic transformation of the underlying data. The formula used was: lmer(variable~DWD*shift+(1|profile ID)). The results were considered statistically significant at $p<0.05$. The diversity of soil layers was represented using NMDS analysis in the "vegan" package (Oksanen et al. 2022).

Results

The highest SOC and N contents were found in deadwood samples (Fig. 2). The SOC content in the analysed wood was 380 g C kg^{-1} ±28 and was higher than in the forest litter (300 g C kg^{-1} ±23), but significant differences were found at a depth of 0-5 cm, 5-10 cm and 10-20 cm below the wood ($p<0.05$). The highest N contents were found in the deadwood and in the organic horizon of the control plot. The nitrogen content was at a similar level in these layers. The SOC and N content decreased significantly with depth. A significantly higher SOC content in the upper layers leads to a broad C/N ratio throughout the profile, and at a depth of -10 cm these changes are significant ($p<$ 0.05). Samples of deadwood and samples of organic horizons from control plots were characterized by the lowest bulk density. The BD of subsequent layers increased with depth, both in the plots with deadwood and in the control plots. The layer at a depth of 0-5 cm below the deadwood had a lower density than the corresponding layer in the control plot. A significantly lower density was found in the layers at a depth of 0-5 cm and 5-10 cm than in the deeper layers ($p<0.05$).

Deadwood increases the carbon reserve up to a depth of -40 cm by 55 % compared to a soil that is not affected by deadwood. For nitrogen, a 36 % higher reserve was found in soils with deadwood compared to the control plots (Table 2). The pH values of the samples from the tested variants were found to be less variable with depth. Wood samples and the samples from the organic horizons had a higher pH value than the lower layers.

Up to a depth of -20 cm, the EC content under the influence of deadwood is about twice as high as in the samples without DWD, while the changes in soil acidity are not significant (Table 3). The total calcium content in the 0-5 cm thick layer is significantly higher in the soils under soil influence of deadwood

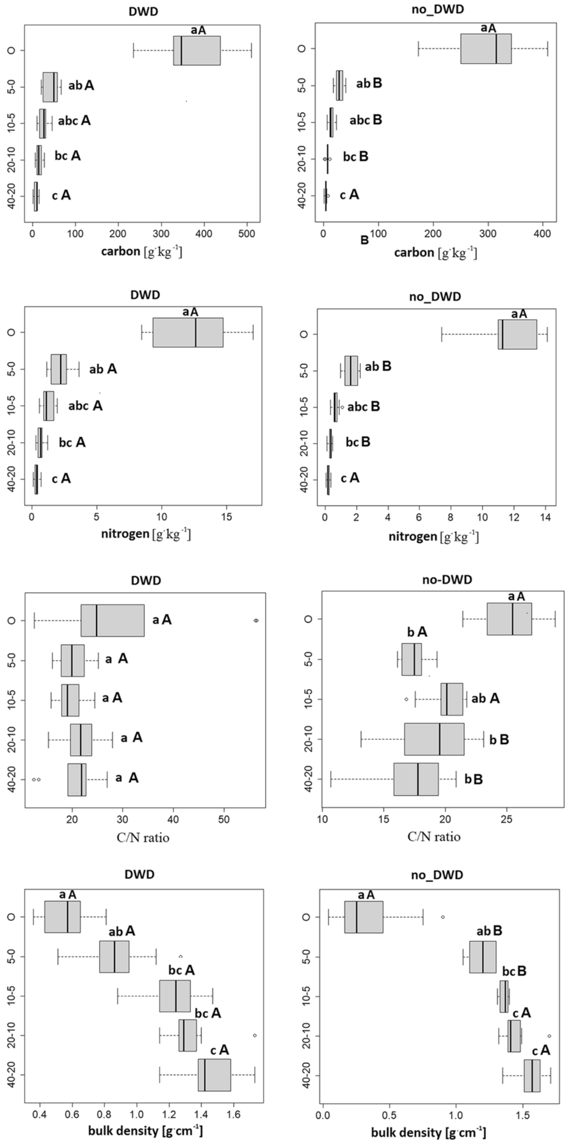


Fig. 2 Vertical distribution of carbon and nitrogen content [g*kg^{-1}],C/N ratio and BD in soils under the influence of deadwood [DWD] and without the influence of deadwood [no_DWD]. Different letters in the individual layers (a,b,c) indicate statistically significant differences based on Friedman's ANOVA and Nemenya's post-hoc test at $p<0.05$. Capital letters (A,B) - statistically significant differences in the same layers between DWD and no_DWD based on the Wilcoxon test ($p<0.05$)

Table 2 Average stock of necromass and SOC and N [kg*m^2] in soils exposed to the influence of deadwood [DWD] and without the influence of deadwood [no_DWD]. Different letters in the individual layers (a,b,c) indicate statistically significant differences based on Friedman's ANOVA and Nemenya's post-hoc test at $p<0.05$. Capital letters (A,B) - statistically significant differences in the same layers between DWD and no_DWD based on the Wilcoxon test ($p<0.05$). N/A - not applicable.

	DWD			No_DWD		
	SOC	N	pH	SOC	N	pH
O	694^{aA}	22^{aA}	4.0^{a}	51^{aB}	2.0^{aB}	4.4^{a}
±SE	147	4.8	0.7	14	0.6	0.7
0-5	18^{abc}	0.9^{bc}	3.7^{bc}	17^{a}	1.0^{a}	3.8^{b}
±SE	2.0	0.1	0.6	1.6	0.1	0.3
5-10	15^{bcA}	0.7^{bcA}	3.6^{b}	9.3^{abB}	0.5^{abB}	3.9^{ab}
±SE	2.0	0.1	0.4	1.1	0.0	0.3
10-20	20^{abA}	0.9^{abA}	3.9^{abc}	9.2^{abB}	0.5^{abB}	4.2^{ab}
±SE	2.8	0.1	0.2	1.2	0.0	0.3
20-40	11^{cA}	0.5^{c}	4.1^{ac}	5.6^{bB}	0.3^{b}	4.3^{a}
±SE	2.2	0.1	0.2	0.9	0.0	0.3
0-40	63^{A}	3.0^{A}	N/A	41^{B}	2.2^{B}	N/A
±SE	7.5	0.3	N/A	4.1	0.2	N/A

Table 3 Soil acidity and basic cation content (cmol(+)·kg^{-1}) in soils affected by deadwood [DWD] and in soils from control plots [no_DWD]. Different letters in each layer indicate statistically significant differences based on Friedman's ANOVA and Nemenya's post-hoc test at $p<0.05$. Capital letters (A,B) - statistically significant differences in the same layers between DWD and no_DWD based on the Wilcoxon test ($p<0.05$).

DWD	H_{ex}	H^+	Al^{3+}	K^+	Na^+	Ca^{2+}	Mg^{2+}	EC
O	3.2^{ab}	2.4^{a}	0.4^{a}	1.9^{a}	0.2^{a}	26^{a}	4.4^{a}	32^{a}
±SD	2.0	1.7	0.4	0.7	0.08	11	2.4	13
0-5	3.8^{ab}	1.0^{ab}	2.0^{ab}	0.3^{aA}	0.07^{abA}	2.5^{aA}	0.4^{a}	3.2^{aA}
±SD	2.2	0.8	1.5	0.1	0.08	1.0	0.1	1.1
5-10	3.6^{a}	0.9^{abA}	2.3^{b}	0.2^{abA}	0.04^{bA}	1.1^{abA}	0.2^{abA}	1.5^{abA}
±SD	1.4	0.8	1.1	0.1	0.02	0.7	0.1	0.9
10-20	$3.0.^{abA}$	0.3^{bcA}	2.1^{bA}	0.07^{bA}	0.04^{b}	0.4^{bA}	0.07^{bA}	0.6^{bA}
±SD	1.2	0.1	0.7	0.06	0.03	0.2	0.03	0.3
20-40	1.7^{b}	0.1^{cA}	1.3^{ab}	0.04^{b}	0.04^{bA}	0.3^{b}	0.06^{b}	0.4^{b}
±SD	0.8	0.09	0.7	0.04	0.04	0.2	0.05	0.3
No_DWD								
O	2.6^{ab}	1.9^{a}	0.2^{a}	2.1^{a}	0.2^{a}	26^{a}	4.6^{a}	33^{a}
±SD	1.6	0.1	0.3	0.8	0.1	7.1	1.6	9.1
0-5	3.1^{a}	0.6^{ab}	1.9^{b}	0.2^{abB}	0.02^{abB}	1.4^{abB}	0.3^{ab}	1.9^{abB}
±SD	1.0	0.4	0.9	0.07	0.02	1.0	0.2	1.3
5-10	2.4^{ab}	0.3^{bcB}	1.7^{b}	0.05^{bcB}	0.02^{bB}	0.4^{bcB}	0.07^{bcB}	0.5^{bcB}
±SD	0.7	0.2	0.5	0.03	0.01	0.3	0.05	0.4
10-20	1.4^{bcB}	0.04^{cB}	1.1^{bcB}	0.03^{cB}	0.02^{b}	0.1^{cB}	0.04^{cB}	0.2^{cB}
±SD	0.6	0.06	0.5	0.01	0.01	0.1	0.01	0.1
20-40	1.0^{c}	0.04^{cB}	0.8^{ac}	0.02^{c}	0.01^{bB}	0.2^{c}	0.04^{c}	0.2^{c}
±SD	0.5	0.06	0.4	0.01	0.01	0.1	0.02	0.1

than in the soils under the forest litter (Table 4). The other differences in cations content are statistically insignificant.

The analyzes confirmed the relationship between some of the properties of the studied soils (Fig. 3). A strong positive correlation was found between the

Table 4 Total metal content of soils affected (mg·kg^{-1}) by deadwood [DWD] and soils of control plots [no_DWD]. Different letters in each layer indicate statistically significant differences based on Friedman's ANOVA and Nemenya's post-hoc test at $p<0.05$. Capital letters (A,B) - statistically significant differences in the same layers between DWD and no_DWD based on the Wilcoxon test ($p<0.05$)

DWD	Al	Fe	Mg	Ca	K	P	Mn
O	1014^{aA}	1573^{a}	796^{a}	7696^{a}	1054^{a}	669^{aA}	1468^{a}
±SD	478	1172	399	3667	373	177	1223
0-5	3451^{ab}	3082^{ab}	459^{ab}	748^{abA}	486^{ab}	327^{b}	493^{ab}
±SD	1192	1449	174	258	138	121	366
5-10	3670^{abc}	3677^{abc}	447^{b}	435^{bc}	419^{bc}	296^{b}	221^{c}
±SD	1216	1150	175	192	108	130	184
10-20	4398^{bc}	3925^{c}	489^{ab}	319^{c}	388^{c}	320^{b}	217^{bc}
±SD	1064	1115	177	114	102	188	147
20-40	5115^{c}	4213^{bc}	565^{ab}	312^{c}	$436b^{c}$	329^{b}	167^{bc}
±SD	1367	1171	192	103	127	173	103
No_DWD							
O	1651^{aB}	2120^{a}	846^{a}	7597^{a}	1116^{a}	850^{aB}	1750^{a}
±SD	451	1212	260	1907	322	152	941
0-5	3513^{ab}	3352^{ab}	463^{b}	456^{abB}	409^{b}	305^{b}	376^{ab}
±SD	1234	1129	161	181	84	95	474
5-10	4387^{bc}	3954^{ab}	497^{bc}	303^{b}	388^{b}	315^{b}	305^{ab}
±SD	1652	1151	183	117	79	133	153
10-20	4916^{c}	4201^{b}	555^{abc}	309^{b}	423^{b}	350^{ab}	218^{ab}
±SD	1834	1197	207	133	113	162	91
20-40	4611^{bc}	4314^{b}	596^{ac}	304^{b}	472^{ab}	318^{b}	142^{b}
±SD	2097	854	177	97	112	192	76

carbon content and the total exchangeable bases. The bulk density was inversely related to the carbon and nitrogen content.

The NMDS analysis confirms significant changes in the properties of the soil layers under the influence of deadwood, in that the deeper layers under the log assume properties that make them similar to the higher layers in the variant without deadwood influence (Fig. 4).

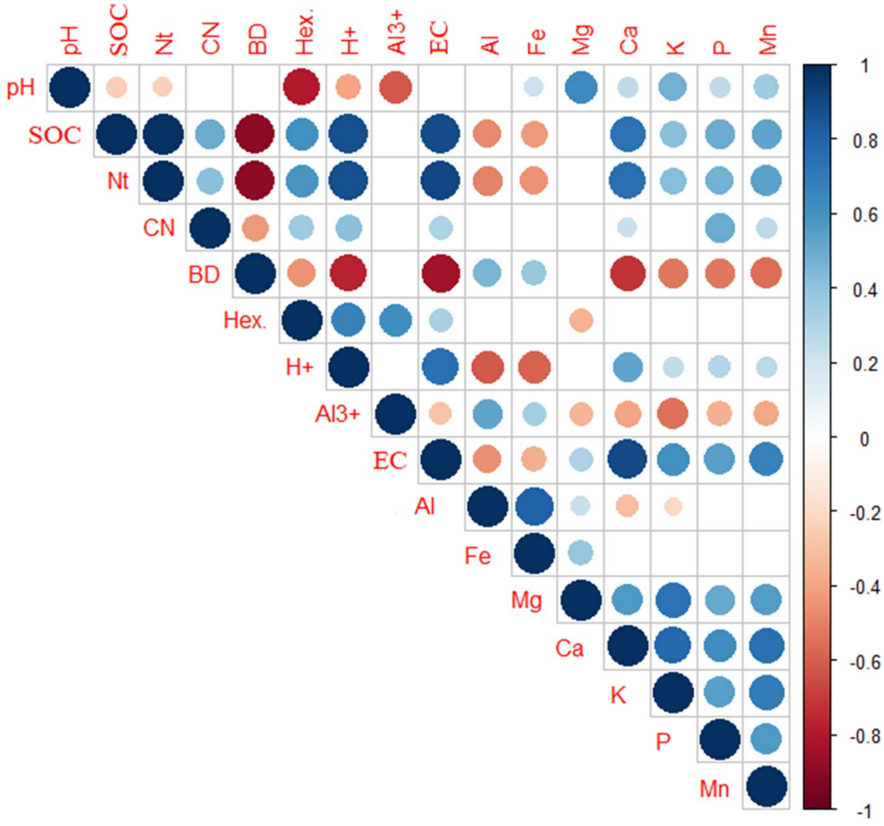
The regression analysis confirmed that deadwood significantly influences all investigated layers and basic soil properties (Table 5). Both factors together, i.e. the presence of deadwood and the soil layer, have a significant effect on the nitrogen content and the sum of exchangeable cations. The variance of fixed and random effects (SD) for: SOC was 0.085 (0.291) and 0.099 (0.315); N: 0.09194 (0.303) and 0.064 (0.254); EC: 0.242 (0.492) and 0.119 (0.344)

Discussion

Our research shows that deadwood (DWD) significantly affects forest soil properties, especially soil organic carbon (SOC) resources, exchangeable cation (EC) content, soil acidity (H_{ex}, Al^{3+}) and bulk density (BD). The significant changes affect soil layers down to a depth of -20 cm.

Decaying soil organic matter (SOM) is important for habitat productivity (Grigal and Vance 2000; Thiffault et al. 2011), and the rate of its decomposition is the result of biotic factors and the locally created microclimate of the soil surface (Larsen et al. 1980; Swift and Boddy 1984; Edmonds 1991). Our research shows that this increase is 55% down to a depth of -40 cm. The explanation for this condition could be the high acidity of the analysed soils, which affects the carbon and nitrogen cycle. All soils in our studies were hyperacid (3.61< pH <4.41). High soil acidity can enhance the accumulation of organic materials in surface soils by decreasing the soil microbial activities for SOM decomposition (Funakawa et al. 2014). These researchers pointed out the downward movement of DOC under high acidity conditions, which increases the accumulation of SOM in the form of organo-mineral complexes. The inhibitory effect of soil acidification on decomposition processes and soil carbon dynamics was also confirmed by Růžek et al.

Fig. 3 Correlations of physico-chemical properties of soils. Sperman's rank coefficient is only given in the case of a statistically significant relationship *p*<0,05



(2021). With increasing soil acidification, the solubility of many of its components, especially organic carbon, increases (Christ and David 1996; Anderson et al. 2000; Remeš and Kulhavý 2009). Our study shows that the exchangeable acidity (H_{ex}) in the 10-20 cm thick layer increased significantly due to DWD. This may indicate that soil acidification is related to pedogenic processes rather than wood decomposition. Some litter removal experiments, e.g. measurements within the DIRT (Detritus Input and Removal Treatments) project, have shown that soil pH decreases significantly in litter removal treatments compared to litter retention (Juhos et al. 2021). But in our studies, the presence of DWD was an additional natural factor. We found the greatest differences in pH of the soils studied in the O horizon, which is directly attributable to differences in the chemical composition of wood and litter (Kögel et al. 1988; Pettersen 1984). However, it should be noted that the pH differences in both the organic horizons and the mineral soil layers were not statistically significant. This is consistent with the results of studies on the decomposition properties of wood, where a constant decrease in pH from an initial 5.4 to 4.6 was observed in the final stage of decomposition (Kraigher et al. 2002).

Our studies also showed significant differences in the content of total N in soil layers down to a depth of -20 cm. Our research indicates an increase in the C/N ratio in the surface levels of the tested soils, which is the result of the impact of deadwood. However, using C/N as a general indicator of the nitrogen status of forests at the European scale, without explicit consideration of tree species, is too simplistic and may lead to misleading conclusions (Cools et al. 2014). Species composition influences the chemical, physical and biological properties of the soil in this influence is greatest in the topsoil (Augusto et al. 2002).

Our investigations also show that DWD, which is in an advanced stage of decomposition, contains slightly more H^+ and Al^{3+} cations than forest litter, but the differences were not significant in contrast to the mineral layers. Soils in the pH range <4.5 generally have lower concentrations of adsorbed Al^{3+}. This can be attributed to the lower availability of

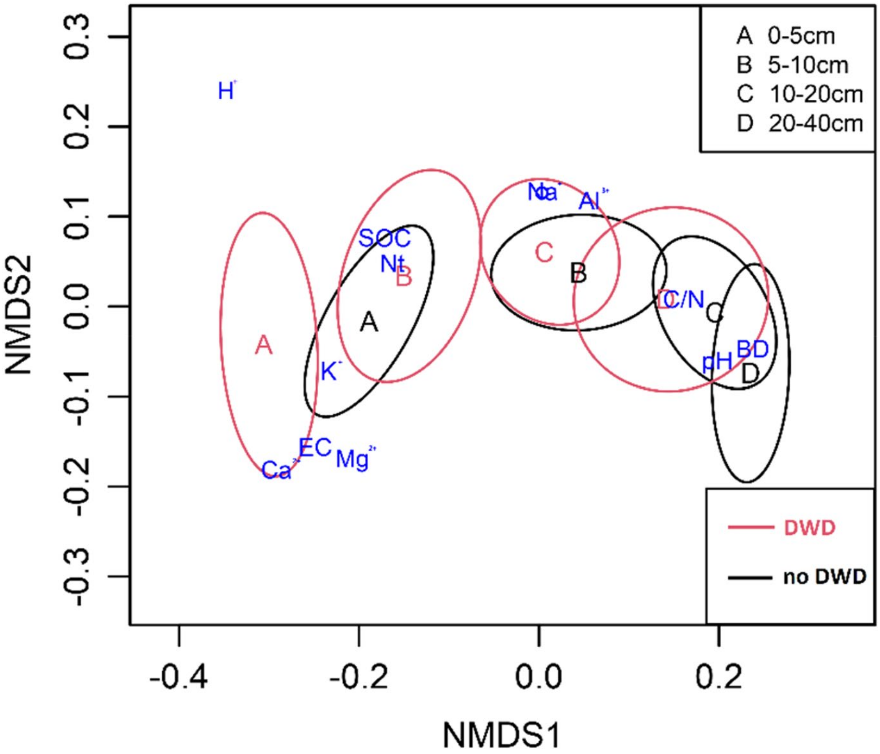


Fig. 4 NMDS analysis based on the Bray-Curtis distance (2D stress = 0.08), which shows the differences in the position of the centres (ellipse = 1SD) of the soil layers against the background of selected soil variables.

weather-resistant Al-containing minerals and the high proportion of weak organic acid (Rossa et al. 2008). The acidity of the soil and the Al^{3+} cations inhibit the activity of soil enzymes, which leads to an inhibition of nutrient circulation by microorganisms. Reduced SOM availability due to Al (and Fe) fixation can protect the SOC pool from microbial degradation in acidic forest soils (Kunito et al. 2016). It should be considered that fungi grow faster and more intensively in low pH soils compared to bacteria (Rousk and Bååth 2011). Fungi have been shown to alter their physical environment in acidic forest soils through the active translocation of metal cations from the mineral soil to the organic level (Clarholm and Skyllberg 2013). In our study, we found a significant difference in Al^{3+} content in the 10-20 cm thick layer, which may be related to increased Al^{3+} sorption by SOM. Our studies therefore confirm the observations of other researchers that deadwood is structurally and chemically different from litter and that its effects on the soil environment are different from those of leaves (Cotrufo et al. 2013). Previous work suggests a positive effect of litter on soil physicochemical properties, which may have implications for forest ecosystem resilience to climate change (Kuehne et al. 2008; Russell et al. 2015). Appropriate forestry practises, such as leaving deadwood in place, can help to maintain high carbon stocks in forest soils (Błońska et al. 2017; Piaszczyk et al. 2021). DWD is therefore a very important factor that slows down the carbon cycle in nature, especially in semi-natural forests. In the context of sustainable forest management, it is important to consider the role of deadwood in all forest ecosystems. In the face of climate change, maintaining the carbon balance in forest ecosystems is becoming crucial.

DWD is a source of nutrients released during decomposition processes (Stutz et al. 2017; Lasota et al. 2022; Piaszczyk et al. 2022). Jun-Hua et al. (2007) pointed out that soil moisture, organic matter content and exchangeable cations in the soil increase during forest succession and reach the highest value in the soil layer down to a depth of -15 cm (except for Na^{+}). They also pointed out that the most important factor determining the content of exchangeable cations in the soil is SOM. Furthermore, it has been shown that the factor that correlates most strongly with SOM is exchangeable Ca^{2+}

Table 5 Estimated values of soil layers parameters [95% Confidence Interval], ***$p<0{,}001$, **$0{,}001<p<0{,}009$, *$0{,}01<p<0{,}05$) and presence of deadwood on SOC, N and EC content based on LMM analysis (variable~DWD*layer+(1|ID plot))

Parameter	log(SOC)	log(N)	log(EC)
Intercept "O layer"	5,7***	2,4***	3,5***
	[5,4;6,0]	[2,2;2,7]	[3,1;3,9]
DWD	0,2	0,06	-0,06
	[-0,04;0,5]	[-0,2;0,3]	[-0,5;0,4]
0-5	-2,3***	-2,0***	-3,0***
	[-2,6;-2,1]	[-2,3;-1,7]	[-3,5;-2,5]
5-10	-3,0***	-2,9***	-4,4***
	[-3,3;-2,8]	[-3,2;-2,6	[-4,9;-4,0]
10-20	-3,7***	-3,6***	-5,0***
	[-4,0;-3,5]	[-3,9;-3,3]	[-5,5;-4,6]
20-40	-4,2***	-4,1***	-5,0***
	[-4,5;-4,0]	[-4,4;-3,8]	[-5,5;-4,5]
DWD*0-5	0,1	0,2	0,7*
	[-0,2;0,5]	[-0,2;0,6]	[0,05;1,4]
DWD*5-10	0,3	0,5*	1,2***
	[-0,08;0,7]	[0,1;0,9]	[0,6;1,9]
DWD*10-20	0,5*	0,6**	1,0**
	[0,1;0,9]	[0,2;1,0]	[0,3;1,6]
DWD*20-40	0,3	0,5*	0,5
	[-0,03;0,7]	[0,09;0,9]	[-0,2;1,1]

cations (Yao et al. 2022). Our research confirmed that DWD has a significant effect on the content and vertical distribution of exchangeable K^+, Na^+, Ca^{2+} and Mg^{2+} cations. The EC in forest litter and DWD was similar and was about 33 cmol(+)-kg^{-1}. However, the processes accompanying the decomposition of wood and the accumulation of cations in mineral soil are different from those accompanying the decomposition of forest litter. Our studies indicate significant differences in EC in mineral soil, but their content was similar in litter and DWD. We observed significant changes down to a depth of -20 cm, and the largest EC differences between DWD and without DWD occurred in the 5-10 cm layer. At this point, it is important to address research findings that indicate that most exchangeable cations are located in deeper soil layers, below -1.00 m, and that the higher the SOC content in the soil, the lower the Ca^{2+} and Mg^{2+} content (James et al. 2016). Our results indicate the release of exchangeable cations as a result of the decomposition of DWD. The importance of these processes is low in the initial phase of decomposition, but as decomposition progresses, the leaching layer increases (Harmon et al. 1986). Studies by Fekete et al. (2020) show that higher Ca values were measured in drier oak forests with higher SOC content than in wetter forests with lower SOC content. Ca^{2+}, Mg^{2+} and SOC also increased together in litter acidification experiments (Juhos et al. 2021; Tóth et al. 2011). Ca forms could therefore play an important role in SOC accumulation (Boiteau et al. 2020) and increase the stability of SOC compounds through several potential mechanisms (Rowley et al. 2018, 2021), however, these studies refer to alkaline soils. As previously mentioned, the soils we tested are hyperacid and prone to cation leaching and Al^{3+} activation. Therefore, the important role of soil SOM in buffering acids and retaining important cations in highly acidic forest soils is emphasised (Jiang et al. 2018). It should be noted that the quality of litter, which is influenced by species composition and ecosystem acidification, has little influence on the chemical composition of dissolved organic matter (DOM) (Ohno et al. 2007).

DWD also affects the physical properties of the soil and changes its structure. Our results showed that the soils under logs with heavily decomposed wood had a significant lower bulk density than the corresponding areas in control plots. The ability of the soil to store water (0-12 cm layer), which is correlated with the BD, depends on the decomposition rate of the organic residues (Ilek et al. 2017). Alexander (1980, 1988) and Huntington et al. (1989) indicated a strong correlation between SOM content and bulk density. This conclusion was confirmed in our study. In contrast to litter, DWD has a very specific surface area in relation to its volume (Stevens 1997). It therefore decomposes much more slowly than litter (Bujoczek 2012). Our research therefore indicates that leaving deadwood in the forest in the final phase of decomposition improves physical properties, decreasing BD. This in turn has a positive effect on the development of the new generation of the forest, especially on the growth parameters of seedlings of typical forest-forming species (Kormanek et al. 2015). The thickness of the litter layer can reduce the effects of extreme soil temperatures, which influences the microbial processing of litter and soil carbon (Fekete et al. 2016).

Conclusion

We show that DWD is a key component of biogeochemical cycles in forest ecosystems. DWD has a positive effect on the soil by increasing the accumulation of soil organic carbon and total nitrogen. The effect of strongly decaying wood is visible up to a depth of -20 cm under the log. Additionally, deadwood causes increases the content of exchangeable cations, especially in the upper layers of the soil. As a result of leaving the decomposing wood, changes in the physical properties of soils were noted, as evidenced by a reduction in bulk density. Our results indicate that leaving deadwood in forest ecosystems has a positive impact on soil condition, especially carbon sequestration.

Authors contributions The field work and soil samples were carried out by Karol Sokołowski. The laboratory analyses were carried out by Karol Sokołowski and the Natural Environmental Chemistry Laboratory, Forest Research Institute (PL). The first draft of the manuscript was written by Karol Sokołowski and Ewa Błońska. Statistical analyses were calculated by Radosław Gawryś. All authors edited earlier versions of the manuscript. All authors have read and approved the final version of the manuscript.

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Data availability The datasets generated during the current study are available from the corresponding author (k.sokolowski@ibles.waw.pl) on reasonable request.

Declarations

Competing interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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