

## ORIGINAL PAPER

# Leaving deadwood in the forest and the impact on the content of dissolved carbon, nitrogen and phosphorus in the forest soils

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## ABSTRACT

The aim of the study was to assess the losses of dissolved forms of DOC and selected nutrients, *i.e.* N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub>, as a result of their leaching into the soil under deadwood in selected forest reserves. The study was conducted in the following forest reserves of the Białowieża Forest: Władysław Szafer Landscape Reserve, Dębowy Grąd and Lipiny as well as outside these area in Koryciny Reserve. Soil samples were collected in the autumn of 2021 from litter (O) and mineral soils at a depth of 40 cm in several layers (0-5, 5-10, 10-2 and 20-40 cm). The pH in a soil solution of 0.01 CaCl<sub>2</sub>·dm<sup>-3</sup> (1:10) was measured potentiometrically and the total forms of P, K, Ca, Mg, Mn, Fe and Al were measured using ICP-OES. The water soluble forms of DOC, N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub> (1:5) were determined colorimetrically. Studies have shown that leaving deadwood impairs the slow release of DOC, nitrogen and phosphorus into the soil solution due to the high cellulose content in woody plant tissue. The process of DOC uptake into the soil solution also depended on the amount of carbon (TOC) and nitrogen (N<sub>tot</sub>) in the soil as well as the presence of ammonium (N-NH<sub>4</sub>) and phosphate (P-PO<sub>4</sub>) ions released during mineralisation of soil organic matter. It was shown that the dissolved forms of N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub> can form stable complexes with Al and Fe. Further, it was shown that the content of DOC in soils can be an indicator of carbon fixation and its possible losses as well as changes in the forest soil environment.

## KEY WORDS


deadwood, dissolved organic carbon (DOC), forest soils, nitrogen, phosphorus

## Introduction

Organic carbon is stored in soils and plays an important role in mitigating global climate change (Amelung *et al.*, 2020; Basile-Doelsch *et al.*, 2020). It is estimated that boreal and temperate forests worldwide store 20-30% of carbon in biomass and 50-60% in soil with a further 8% of carbon stored in deadwood (Pan *et al.*, 2011). Deadwood is an important source of carbon and nutrients in forest ecosystems and contributes to the biodiversity of natural habitats (Lassauce *et al.*, 2011). The carbon content of wood is estimated to be about 50% of its dry weight, and the weight loss of deadwood is caused by the following three processes: mineralization and CO<sub>2</sub>

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release, leaching and fragmentation (Harmion *et al.*, 1986). The decomposition of organic matter (DOM) and the release of its dissolved form is one of the most important elements of the C cycle in soil (Bolan *et al.*, 2011; Thieme *et al.*, 2019).

Quantification of DOM is often based on C content and DOM is often reported as dissolved organic carbon (DOC) (Bolan *et al.*, 2011). DOC is a small colloidal fraction of dissolved organic matter in soil retained on a 0.45- $\mu\text{m}$  sphere (Qualls *et al.*, 1991; Bolan *et al.*, 2011). DOC is a heterogeneous phase consisting of various acids, bases and compounds in varying degrees of decomposition with the largest fraction being humous substances (Qualls and Richardson, 2003). DOC is a mobile carbon source and affects the retention and movement of various nutrients. Depolymerization reactions of lignin structures during decomposition of deadwood contribute to the formation of compounds with lower molecular weight and higher solubility. DOC from deadwood can be leached into soils (Piaszczyk *et al.*, 2019; Wambsganss *et al.*, 2017). The main source of DOM in soils of temperate forests is leaching from the forest floor (Michalzik *et al.*, 2001) including aboveground plant structures, roots and microbial biomass (Gmach *et al.*, 2020). Rainwater transports DOC deep into the soil profile and partially immobilizes it in the mineral layers of the soil, while the content and composition of DOC changes with the water flow (Preussera *et al.*, 2021). According to Silveira (2005), DOC is very sensitive to environmental changes and can be an alternative tool for monitoring the impact of human activities on soil habitat quality. This trend is confirmed by studies conducted on forest soils (Błońska *et al.*, 2018; Hollands *et al.*, 2022). The authors showed that the intensity and type of management of agricultural land influence the concentration and distribution of stored soil carbon as well as the release and migration of DOC into groundwater. The main sources of DOC in forest soils are leaf litter, deadwood, humus and root exudates (Kalbitz *et al.*, 2000; Hollands *et al.*, 2022). Leaving deadwood on forest soils for an extended period of time is thought to promote the release of easily soluble forms of DOC and nutrients into the soil solution. These nutrients can provide an important nutrient pool for vegetation but at the same time increase the risk of losses through their leaching. Different uses of forest land, including leaving deadwood in natural forests, can affect the sequestration of soil organic carbon or its loss through leaching. In addition, the process of carbon dissolution can also release labile forms of macronutrients that can migrate into the soil and water environments (Burzyńska 2004, 2013).

It is assumed that when deadwood is left on forest soils for a long time decomposition processes take place and forms of DOC and macronutrients (nitrogen and phosphorus) dissolved, that can migrate in the soil and water environment. The process losing these components from forest soils can be a direct indicator of soil and forest habitat degradation.

The aim of this study was to assess the losses of dissolved forms of DOC and selected nutrients, *i.e.* N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub>, as a result of their leaching into the soil under deadwood in selected forest reserves in and outside the Białowieża Forest.

## Materials and methods

**RESEARCH AREA.** The study was conducted in the Hajnówka Forest District in the following reserves: Władysław Szafer Landscape Reserve (52.691732, 23.8357632; 52.698617, 23.815757; 52.700349, 23.868408), Dębowy Grąd (52.721489, 23.726108; 52.725693, 23.744072; 52.745772, 23.723280; 52.721489, 32.735982), and Lipiny (52.753853, 23.618982; 52.757660, 23.617617; 52.756790, 23.626887) including one outside the Białowieża Forest: the Koryciny reserve in Rudka Forest District (52.692337, 22.710309; 52.696536, 22.871981; 52.703524, 22.703380) (Fig. 1). The

Białowieża Forest is located in the continental biogeographical region zone of semiboreal forests and mixed forests (EEA, 2023). This is reflected in the species composition of the stands with a significant proportion of *Acer platanoides* L., *Carpinus betulus* L., *Quercus petraea* (Matt.) Liebl. and *Q. robur* L., as well as a high proportion of *Picea abies* (L.) Karst.

The characteristics of the studied reserves are listed in Table 1.

According to classifications of Poland into climatic regions, the Podlaskie Voivodeship is in the 4<sup>th</sup> climatic zone. The climate is a temperate transitional with continental influences. The average annual temperature is 7.5°C and the average annual precipitation is 598 mm. Precipitation

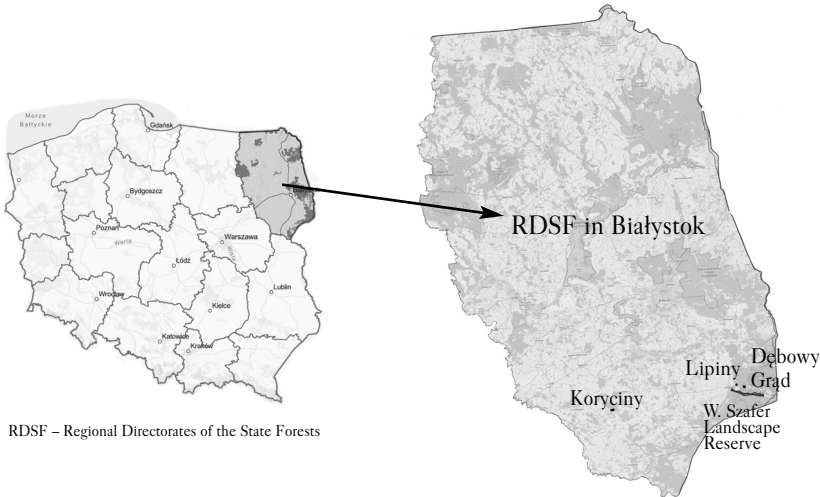


Fig. 1.

Location of Władysław Szafer Landscape Reserve, Dębowy Grąd, and Lipiny in Białowieża Forest, and Koryciny Reserve

Table 1.

Characteristics of the research areas in Białowieża Forest ('WS', 'LP', 'DG') and in Koryciny Reserve ('KOR')

Name of the reserve, symbol and total area (ha)	Commune (a) district (b)	Dominant tree species	Average age of trees	Number of samples	Type of soils (WRB)
'Władysław Szafer Landscape Reserve' 'WS' 1343.91 ha	a: Hajnówka b: Hajnówka	<i>Picea abies</i> (L.) Karst., <i>Quercus petraea</i> (Matt.) Liebl., <i>Q. robur</i> (L.), <i>Pinus sylvestris</i> (L.), <i>Betula pendula</i> Roth, <i>Ulmus minor</i> Mill.	123	60	Brunic Arenosols Epidistrict Cambisols
'Lipiny' 'LP' 56.28 ha	a: Hajnówka b: Hajnówka	<i>Q. petraea</i> , <i>Q. robur</i> , <i>Carpinus betulus</i> L.	110	30	Epidistrict Cambisols
'Dębowy Grąd' 'DG' 100.47 ha	a: Hajnówka b: Hajnówka	<i>Q. petraea</i> , <i>Q. robur</i> , <i>Picea abies</i> (L.) Karst.,	119	35	Albic Luvisols
'Koryciny' 'KOR' 87.72 ha	a: Grodzisk b: Rudka	<i>Q. petraea</i> , <i>C. betulus</i>	168	35	Brunic Arenosols Albic Luvisols

in September-December 2021 for the Podlaskie region was 180 mm, below the 1991-2020 average of 217 mm (IMGW, 2021).

Soil samples were collected in the autumn of 2021 from layers to a depth of 40 cm (0-5, 5-10, 10-20, 20-40 cm) and forest litter (O) with deadwood (variant: 1) and without deadwood (variant: 0). A total 160 soil samples were taken for study. The samples of variant 1 were taken directly from the remains of wood matter in the last phase of decomposition (phases: IV and V) (Gutowski *et al.*, 2004) and the control samples were taken up to 1.0 m away from the deadwood.

LABORATORY ANALYSIS. The soil samples taken for analysis were stored in an oven at 40°C and sieved with a 2-mm sieve with stones and roots removed by hand. Then the samples were divided into the two following components: (i) sieved samples for determination of pH in 0.01 mol CaCl<sub>2</sub>·dm<sup>-3</sup> (1:10) and concentration of total mineral nutrients with aqua regia (mixture of concentrated: 3HCl with HNO<sub>3</sub> in a ratio of 3:1) (PN-ISO 11466:2002) and water soluble forms of DOC, N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub> (1:5), and (ii) samples were ground in an agate mortar for the determination of carbon (TOC), nitrogen (N<sub>tot</sub>) and phosphorus (P<sub>tot</sub>). The following physicochemical parameters were determined in the soil solutions:

- soil acidity (pH) in 0.01 mol CaCl<sub>2</sub>·dm<sup>-3</sup> by the potentiometric method according to PN-EN ISO 10390:1997,
- total nitrogen (N<sub>tot</sub>) by the high temperature combustion method with TCD detection according to PN-ISO 13878:2002,
- total organic carbon (TOC) by the high temperature combustion method with TCD detection according to PN-ISO 10694:2002,
- total P, K, Ca, Mg, Mn, Fe and Al by the inductively coupled plasma excitation atomic emission spectrometry method (ICP-OES) according to PN-EN ISO 11885:2009,
- water-soluble forms of DOC, N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub> in distilled water solution (1:5) and determination by flow colorimetry (according to SKALAR, 2001 method).

All chemical analyses were performed in the accredited Laboratory of Environmental Chemistry (AB 740) of the Forest Research Institute in Sękocin Stary, Poland.

STATISTICAL ANALYSES. The normality of the distribution of the variables was tested with the Shapiro-Wilk test. A one-way analysis ANOVA was performed for the dissolved DOC and the content of N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub> in the forest soil from the reserves against the background of the type of deadwood. The significance of the differences between the mean contents of the components was assessed with the Tukey test at the significance level  $p < 0.05$ .

Linear Pearson correlation coefficients were calculated for the dissolved forms of DOC, N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub> as well as selected physicochemical parameters in forest soils. The significance of the linear Pearson correlation coefficients was tested at three significance levels  $p$ : 0.05; 0.01 and 0.001. Statistical analyses were performed using STATISTICA 13 software (Dell Inc., 2016).

## Results

Soils from the forest reserves were characterised by a wide range of acidic responses from very strongly acidic to moderately acidic (pH<sub>CaCl<sub>2</sub></sub>: 3.98-5.10) (Amelung *et al.*, 2018; Table 2). The analysis of linear Pearson correlations with pH and the content of dissolved forms of DOC, N and P has shown that there are no correlations between them. Only a weak positive value of the correlation coefficient ( $r=0.269$ ,  $p < 0.05$ ) was found between the pH value and N-NO<sub>3</sub>. It was

**Table 2.** Characteristics of the physicochemical properties in soils from the forest reserves in Białowięża Forest and in Korycińc Reserve (symbols of areas as in table 1)

Reserve	Layer [cm]	pH <sub>CaCl2</sub>	C/N [g·kg <sup>-1</sup> ]	TOC	N <sub>tot</sub>	P <sub>aot</sub>	K <sub>aot</sub>	Mg <sub>got</sub>	Ca <sub>got</sub>	Al <sub>aot</sub>	Fe <sub>aot</sub>	Mn <sub>aot</sub>
'WS' N=60	O	4.68 ± 0.75	32.45 ± 12.81	388.8 ± 97.6	11.73 ± 2.50	0.76 ± 0.24	1.09 ± 0.48	0.86 ± 0.31	9.23 ± 0.35	1.12 ± 0.59	1.13 ± 0.61	1.46 ± 0.53
	0-5	4.15 ± 0.73	18.88 ± 2.15	36.9 ± 14.1	1.95 ± 0.73	0.41 ± 0.73	0.51 ± 0.18	0.59 ± 0.16	0.85 ± 0.38	4.45 ± 1.00	4.42 ± 0.63	0.45 ± 0.32
	5-10	4.21 ± 0.84	19.79 ± 2.02	24.28 ± 0.9	1.23 ± 0.21	0.37 ± 0.11	0.48 ± 0.19	0.61 ± 0.19	0.73 ± 0.61	4.88 ± 1.11	4.46 ± 0.86	0.35 ± 0.19
	10-20	4.17 ± 0.44	21.26 ± 2.50	14.35 ± 6.0	0.67 ± 0.26	0.40 ± 0.14	0.43 ± 0.14	0.62 ± 0.15	0.62 ± 0.15	5.52 ± 1.26	4.67 ± 1.02	0.20 ± 0.16
	20-40	4.33 ± 0.38	20.59 ± 1.91	8.20 ± 4.3	0.39 ± 0.17	0.41 ± 0.18	0.45 ± 0.15	0.65 ± 0.18	0.38 ± 0.09	5.66 ± 1.48	4.66 ± 1.14	0.23 ± 0.12
'LP' N=30	0-40	4.21 ± 0.61	20.13 ± 2.28	20.9 ± 14.1	1.06 ± 0.73	0.40 ± 0.13	0.47 ± 0.16	0.62 ± 0.16	0.60 ± 0.41	5.13 ± 1.29	4.51 ± 0.96	0.33 ± 0.22
	O	4.04 ± 0.37	38.73 ± 18.58	378.6 ± 80.2	11.00 ± 3.85	0.72 ± 0.16	1.23 ± 0.54	0.67 ± 0.19	5.56 ± 1.83	1.38 ± 0.69	1.38 ± 0.67	1.53 ± 0.63
	0-5	3.71 ± 0.36	20.80 ± 4.00	42.4 ± 19.5	1.98 ± 0.68	0.42 ± 0.05	0.59 ± 0.17	0.46 ± 0.09	0.59 ± 0.17	3.61 ± 0.92	3.57 ± 0.73	0.24 ± 0.08
	5-10	3.81 ± 0.31	20.72 ± 2.28	19.7 ± 10.5	0.97 ± 0.55	0.46 ± 0.04	0.44 ± 0.74	0.46 ± 0.11	0.33 ± 0.14	4.13 ± 1.14	3.86 ± 0.72	0.23 ± 0.19
	10-20	4.08 ± 0.44	21.51 ± 2.97	11.38 ± 8.45	0.52 ± 0.35	0.50 ± 0.11	0.40 ± 0.75	0.49 ± 0.13	0.32 ± 0.14	4.70 ± 1.11	3.94 ± 0.74	0.23 ± 0.12
'DG' N=35	20-40	4.25 ± 0.40	20.65 ± 4.10	5.80 ± 3.2	0.27 ± 0.11	0.48 ± 0.17	0.43 ± 0.55	0.53 ± 0.05	0.31 ± 0.07	4.73 ± 0.66	3.86 ± 0.51	0.15 ± 0.09
	0-40	3.98 ± 0.40	20.92 ± 3.20	19.83 ± 18.1	0.93 ± 0.80	0.46 ± 0.10	0.47 ± 0.12	0.48 ± 0.10	0.38 ± 0.10	4.29 ± 1.03	3.81 ± 0.65	0.21 ± 0.12
	O	4.56 ± 0.63	32.27 ± 13.06	410.0 ± 67.8	13.83 ± 3.56	0.75 ± 0.24	0.97 ± 0.15	0.81 ± 0.18	10.66 ± 3.39	1.03 ± 0.59	1.30 ± 0.48	1.85 ± 1.60
	0-5	4.98 ± 0.80	14.70 ± 2.70	70.4 ± 36.2	5.10 ± 3.34	0.52 ± 0.18	0.61 ± 0.19	0.83 ± 0.37	5.40 ± 5.10	4.23 ± 1.14	3.75 ± 0.91	0.25 ± 0.32
	5-10	4.96 ± 0.90	13.54 ± 2.01	43.4 ± 33.3	3.31 ± 2.98	0.39 ± 0.09	0.53 ± 0.13	0.75 ± 0.38	2.95 ± 2.50	4.63 ± 2.07	4.27 ± 1.11	0.16 ± 0.13
'KOR' N=35	10-20	5.11 ± 1.03	12.53 ± 3.66	19.7 ± 17.2	1.55 ± 1.33	0.36 ± 0.24	0.53 ± 0.09	0.80 ± 0.04	3.66 ± 3.52	4.41 ± 1.07	4.15 ± 0.93	0.15 ± 0.12
	20-40	5.29 ± 1.19	15.4 ± 8.25	6.7 ± 7.2	0.46 ± 0.56	0.35 ± 0.12	0.61 ± 0.18	1.10 ± 0.95	3.65 ± 7.13	4.54 ± 2.00	4.94 ± 1.60	0.15 ± 0.01
	0-40	5.10 ± 0.94	14.05 ± 4.36	35.0 ± 24.1	2.61 ± 1.85	0.37 ± 0.19	0.57 ± 0.15	0.87 ± 0.56	3.91 ± 3.56	4.45 ± 1.55	4.27 ± 1.19	0.17 ± 0.18
	O	4.72 ± 0.65	23.0 ± 6.35	324.3 ± 41.0	12.62 ± 1.05	0.86 ± 0.15	1.43 ± 0.13	1.10 ± 0.36	10.02 ± 2.04	1.18 ± 0.20	1.46 ± 0.24	2.96 ± 1.26
	0-5	4.19 ± 0.33	16.65 ± 1.08	21.5 ± 4.3	1.22 ± 0.26	0.22 ± 0.02	0.49 ± 0.08	0.51 ± 0.01	0.76 ± 0.35	2.96 ± 0.32	3.62 ± 0.47	0.37 ± 0.25
'KOR' N=35	5-10	4.10 ± 0.07	17.77 ± 1.42	10.5 ± 3.0	0.60 ± 0.18	0.20 ± 0.05	0.46 ± 0.06	0.53 ± 0.08	0.38 ± 0.12	3.56 ± 0.30	4.08 ± 0.47	0.32 ± 0.15
	10-20	4.22 ± 0.09	15.92 ± 2.11	4.9 ± 2.4	0.30 ± 0.13	0.20 ± 0.06	0.51 ± 0.07	0.60 ± 0.07	0.36 ± 0.07	3.91 ± 0.47	4.03 ± 0.64	0.27 ± 0.14
	20-40	4.39 ± 0.25	12.84 ± 2.66	2.0 ± 1.5	0.14 ± 0.08	0.21 ± 0.10	0.58 ± 0.06	0.68 ± 0.12	0.38 ± 0.08	3.76 ± 0.81	4.14 ± 0.90	0.17 ± 0.10
	0-40	4.32 ± 0.40	16.05 ± 2.71	9.71 ± 8.09	0.56 ± 0.45	0.21 ± 0.06	0.51 ± 0.08	0.58 ± 0.11	0.47 ± 0.25	3.55 ± 0.61	3.95 ± 0.63	0.28 ± 0.18

found that pH measured in 0.01 mol CaCl<sub>2</sub>·dm<sup>-3</sup> had no effect on the release of the water soluble forms of DOC nor N-NH<sub>4</sub> or P-PO<sub>4</sub>.

The soils from the soils from studied reserves had different TOC contents depending on the location and depth of sampling. It was found that regardless of the location of the samples most DOC in the organic layer (O) ranged from 324.3 to 410.0 g TOC·kg<sup>-1</sup> were contained in the reserves 'KOR' and 'DG', respectively. The content in the soil varied and decreased with depth. The average content of TOC in the soil layer of 0-40 cm deep ranged from 9.71 to 35.0 g TOC·kg<sup>-1</sup> in the reserves 'KOR' and 'DG', respectively (Table 2).

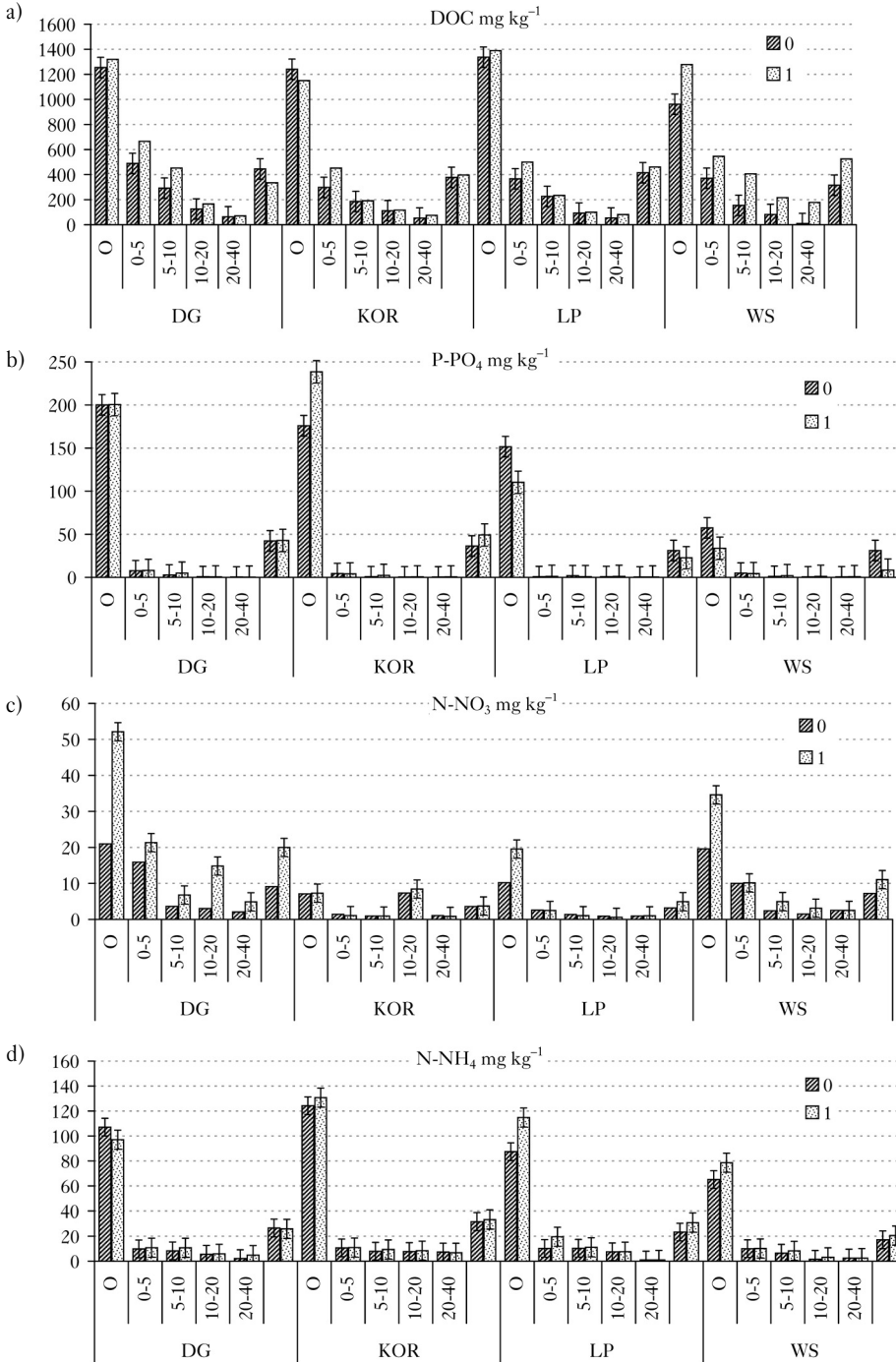
The content of DOC varied in the soils of the forest reserves and was highest in the organic layer (O) and in the uppermost 0-5 cm layer while decreasing with depth. The average content of DOC in the organic layer (O) ranged from 1118.65 mg·kg<sup>-1</sup> to 1363.30 mg·kg<sup>-1</sup> in the reserves 'WS' and 'LP' (Table 3). In the soil layer of 0-40 cm, the highest content of DOC was found in the reserves 'DG' and 'WS'. Leaving deadwood (variant 1) demonstrated a trend of increased release of DOC into the soil solution compared to the control variant (0) (Fig. 2a). This trend was found for most sites except for the organic layer (O) of the reserve 'KOR'. The linear Pearson correlations showed that the release of DOC into the soil solution depended mainly on the TOC ( $r=0.884$ ,  $p<0.001$ ), N<sub>tot</sub> ( $r=0.883$ ,  $p<0.001$ ) and K<sub>tot</sub> ( $r=0.722$ ,  $p<0.001$ ) content in the forest soil (Table 5).

**Table 3.**

Average DOC content of soluble forms of N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub> in soils of forest reserves in Białowieża Forest and in Koryciny Reserve (symbols of areas as in table 1)

Forest reserve	Layer [cm]	DOC	N-NO <sub>3</sub>	N-NH <sub>4</sub>	P-PO <sub>4</sub>
		[mg·kg <sup>-1</sup> ]			
'WS'	O	1118.90 ±354.10a	30.00 ±38.70a	74.48 ±40.30a	168.25 ±10.20a
	0-5	491.89 ±198.45	4.61 ±3.84	4.50 ±2.20	10.11 ±3.92
	5-10	328.65 ±204.48	4.16 ±3.87	7.70 ±2.39	1.74 ±1.00
	10-20	174.84 ±92.36	2.62 ±2.32	6.24 ±2.51	0.97 ±0.54
	20-40	141.03 ±97.20	2.50 ±1.94	5.81 ±1.95	0.74 ±0.53
	0-40	284.10 ±207.60b	3.47 ±3.20b	3.47 ±3.20b	2.00 ±1.90b
'LP'	O	1363.30 ±126.40a	14.89 ±11.10a	101.11 ±56.60a	130.90 ±48.90a
	0-5	433.05 ±179.23	2.48 ±2.00	10.76 ±1.18	5.50 ±3.75
	5-10	230.09 ±147.50	1.19 ±0.35	9.00 ±1.20	1.33 ±0.89
	10-20	96.23 ±60.76	0.72 ±0.40	7.60 ±0.88	0.41 ±0.27
	20-40	67.24 ±42.62	0.97 ±0.34	7.21 ±0.92	0.40 ±0.31
	0-40	206.65 ±186.20b	1.03 ±1.20b	8.64 ±1.70b	1.91 ±1.80b
'DG'	O	1291.71 ±91.50a	34.32 ±30.90a	101.36 ±38.10a	200.50 ±54.70a
	0-5	589.79 ±211.75	18.99 ±29.60	10.36 ±3.33	7.88 ±5.85
	5-10	383.59 ±242.12	10.69 ±17.01	9.68 ±4.76	3.93 ±3.49
	10-20	148.42 ±85.51	9.77 ±13.28	5.77 ±1.96	0.65 ±0.60
	20-40	67.41 ±50.19	3.68 ±5.48	4.54 ±2.75	0.31 ±0.29
	0-40	297.30 ±262.20b	10.78 ±18.30b	7.59 ±4.00b	3.19 ±4.50b
'KOR'	O	1240.73 ±51.80a	7.16 ±3.20a	126.40 ±54.30a	196.80 ±5.70a
	0-5	400.41 ±151.94	1.30 ±0.77	10.74 ±1.10	4.25 ±1.65
	5-10	189.18 ±146.14	0.94 ±0.33	8.45 ±1.12	1.23 ±1.06
	10-20	114.80 ±47.67	0.80 ±0.64	7.97 ±0.65	0.52 ±0.12
	20-40	67.49 ±28.26	1.00 ±0.50	7.14 ±1.24	0.50 ±0.18
	0-40	192.97 ±151.92b	1.01 ±0.58b	8.58 ±1.70b	1.62 ±1.80b

O – organic layer; a, b – significant differences between the average content of the nutrient in the organic layer (O) and the average from the 0-40 cm soil layer



**Fig. 2.**

DOC as well as N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub> content in soils of reserves in Białowieża Forest and in Koryciny Reserve (symbols of areas as in table 1)

1 - variant with deadwood, 0 - control variant

The soils of the forest reserves had different  $N_{\text{tot}}$  contents depending on the location of the objects and the depth of sampling. This nutrient was highest in the organic layer (O) which contained between 11.0 and 13.83  $N_{\text{tot}}$  in the 'LP' and 'DG' reserves. The content of this nutrient in the soil was much lower. The highest average content of  $N_{\text{tot}}$  from the layers at a depth of 0-40 cm was found in the 'DG' reserve (2.61 g  $N_{\text{tot}} \cdot \text{kg}^{-1}$ ) and the lowest in the soil of the reserve 'KOR' (0.56 g  $N_{\text{tot}} \cdot \text{kg}^{-1}$ ) (Table 2).

**Table 4.**

The type of deadwood (LS and IG) and content of soluble forms of DOC, N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub> in forest soils from reserves in Białowieża Forest and from Koryciny Reserve (symbols of areas as in table 1)

Forest reserve	A type of wood	Variant	[mg·kg <sup>-1</sup> ]			
			DOC	N-NO <sub>3</sub>	N-NH <sub>4</sub>	P-PO <sub>4</sub>
'WS'	LS	1	444.99 ±465.40	2.39 ±2.80	17.01 ±24.80	30.56 ±64.00
	IG	1	564.64 ±407.70	13.89 ±33.50	24.35 ±35.50	42.21 ±92.60
	–	0	325.53 ±432.10	5.89 ±10.60	18.52 ±33.10	28.30 ±72.90
'LP'	LS	1	–	–	–	–
	IG	1	448.85 ±492.40	4.90 ±9.30	30.04 ±54.50	23.10 ±47.70
	–	0	427.12 ±527.90	3.21 ±4.60	24.23 ±33.00	32.34 ±65.20
'DG'	LS	1	561.30 ±512.50	1.98 ±1.90	41.68 ±74.14	62.63 ±135.20
	IG	1	525.99 ±473.70	19.51 ±5.20	20.22 ±27.40	36.32 ±68.50
	–	0	444.69 ±47.30	15.97 ±26.50	27.35 ±1.50	42.33 ±82.40
'KOR'	LS	1	377.75 ±464.80	2.17 ±2.80	33.25 ±5.30	49.18 ±104.50
	IG	1	–	–	–	–
	–	0	414.91 ±450.70	2.27 ±2.90	31.58 ±53.25	36.40 ±72.20
All reserves	LS	1	437.25 ±443.30a	2.80 ±4.80a	25.27 ±42.90a	38.03 ±84.12a
	IG	1	526.03 ±441.00b	13.05 ±26.80b	24.74 ±38.90a	35.96 ±77.00a
	–	0	400.00 ±461.00a	6.11 ±14.00b	25.46 ±40.70a	33.49 ±70.00a

Forest type: LS – hardwood, IG – coniferous wood; Variant with deadwood (1), variant without deadwood (0)  
a, b – statistically significant differences between means

**Table 5.**

Pearson linear correlations between the content of selected physicochemical soil properties and the content of dissolved forms of DOC, N-NO<sub>3</sub>, N-NH<sub>4</sub> and P-PO<sub>4</sub> in soils from forest reserves of Władysław Szafer Landscape Reserve, Dębowy-Grąd, and Lipiny in Białowieża Forest and areas outside this reserve in Koryciny Reserve

Parameter	Linear correlations of Pearson (r)			
	DOC	N-NO <sub>3</sub>	N-NH <sub>4</sub>	P-PO <sub>4</sub>
pH <sub>CaCl2</sub>	–	0.269*	–	–
TOC	0.884***	0.457**	0.821***	0.870***
N <sub>tot</sub>	0.883***	0.514**	0.849***	0.849***
C/N	0.539**	0.200*	0.396*	0.497**
P <sub>tot</sub>	0.633**	0.633***	0.602***	0.662***
K <sub>tot</sub>	0.722***	0.440***	0.757***	0.796***
Mg <sub>tot</sub>	0.247**	0.287*	0.294*	0.349***
Ca <sub>tot</sub>	0.673***	–0.218*	0.633***	0.733***
Al <sub>tot</sub>	–0.635***	–0.635***	–0.609***	–0.633***
Fe <sub>tot</sub>	0.722***	–0.260*	–0.644***	–0.673***
Mn <sub>tot</sub>	0.672***	0.433**	0.646***	0.662***
DOC	–	0.428***	0.799***	0.813***

\*, \*\*, and \*\*\* significant correlation at  $p=0.05$ , 0.01 and 0.001 level



The content of water-dissolved  $\text{N-NO}_3$  varied depending on the depth of the soil samples and the reserve. The majority of this nutrient was in the litter (O) and the least amount in the soil layer at a depth of 20-40 cm. The average  $\text{N-NO}_3$  content in the forest litter ranged from 7.16 to 34.32  $\text{mg N-NO}_3 \cdot \text{kg}^{-1}$  in the 'KOR' and 'DG' reserves. Leaving deadwood on the soil surface for many years promoted the release of water-soluble forms of  $\text{N-NO}_3$  mainly in the litter and topsoil. In deeper soil layers of 10-40 cm, the content of this nutrient was relatively low ( $<4.0 \text{ mg N-NO}_3 \cdot \text{kg}^{-1}$ ) (Table 3 and Fig. 2c). When assessing the influence of the type of deadwood on the leaching of water-soluble forms of  $\text{N-NO}_3$  into the soil solution, it was found that significantly more  $\text{N-NO}_3$  penetrated the soil from coniferous wood as well as in the control variant (0) than from hardwood (Table 4).

Statistical analysis of linear Pearson correlations between  $\text{N-NO}_3$  content and mineral nutrients of forest soils showed mostly weak positive values ( $r < 0.600$ ) except for elements such as  $\text{P}_{\text{tot}}$  ( $r=0.633, p < 0.001$ ) and  $\text{Al}_{\text{tot}}$  ( $r=-0.635, p < 0.001$ ). Negative values of linear correlation coefficients between  $\text{N-NO}_3$  and  $\text{Al}_{\text{tot}}$ ,  $\text{Ca}_{\text{tot}}$  and  $\text{Fe}_{\text{tot}}$  could indicate a reduced release of nitrate nitrogen into the soil solution with a simultaneous increase in the content of these nutrients in the studied forest soils (Table 5).

The content of water-dissolved  $\text{N-NH}_4$  in forest reserve soils was several times higher than that of  $\text{N-NO}_3$ , especially in the (O) layer, with a gradual decrease with depth (Table 3). The average  $\text{N-NH}_4$  content in the organic layer (O) ranged from 74.48 to 126.40  $\text{mg} \cdot \text{kg}^{-1}$  in the 'WS' and 'KOR' reserves, respectively. The average content of this nutrient in soil layers of 0-40 cm deep was in the range of 3.47-8.64  $\text{mg N-NH}_4 \cdot \text{kg}^{-1}$  and from 3.47 to 8.64  $\text{g N-NH}_4 \cdot \text{kg}^{-1}$  in the 'WS' and 'LP' reserves (Table 3). Similar to  $\text{N-NO}_3$ , there was no increased movement of nitrogen of both forms into deeper layers in the soil. Moreover, leaving deadwood on forest land and its type of trees (IG-coniferous wood and LS-hardwood) did not have a significant impact on the release of  $\text{N-NH}_4$  into the soil solution (Table 4 and Fig. 2d). Pearson linear correlation showed that the process of release of soluble  $\text{N-NH}_4$  forms into soil solution was dependent on soil in  $\text{N}_{\text{tot}}$  ( $r=0.842, p < 0.001$ ),  $\text{TOC}$  ( $r=0.821, p < 0.001$ ),  $\text{DOC}$  ( $r=0.699, p < 0.001$ ) and  $\text{K}_{\text{tot}}$  ( $r=0.757, p < 0.001$ ). A different response to the reduction of soluble forms of  $\text{N-NH}_4$  is expected in the case of higher levels of  $\text{Al}_{\text{tot}}$  ( $r=-0.609, p < 0.001$ ) and  $\text{Fe}$  ( $r=-0.644, p < 0.001$ ) in the soil (Table 5).

The total  $\text{P}_{\text{tot}}$  content in the studied soils ranged from 0.21-0.42  $\text{g P}_{\text{tot}} \cdot \text{kg}^{-1}$  for the reserves 'KOR' and 'LP' (Table 2). The organic layer (O) contained the least amount of this nutrient (0.72-0.86  $\text{g P}_{\text{tot}} \cdot \text{kg}^{-1}$ ). The  $\text{P}_{\text{tot}}$  content in the soil was not very high, regardless of reserve and layer (Table 2). The contents of total nutrients in the soils from the forest reserves studied is shown in Table 2.

The organic layer (O) contained the most soluble form of  $\text{P-PO}_4$ , and its average content ranged from 130.9 to 200.50  $\text{mg P-PO}_4 \cdot \text{kg}^{-1}$  in the forest soils in the reserves 'LP' and 'DG', respectively. On the other hand, the content of this nutrient in deeper soil layers was low regardless of the location and varied between 0.31-10.11  $\text{mg P-PO}_4 \cdot \text{kg}^{-1}$ . The influence of leaving deadwood on the release of water-soluble  $\text{P-PO}_4$  into the soil solution could also not be proven (Table 4).

The evaluation of the linear Pearson correlations between the  $\text{P-PO}_4$  content and the mineral nutrients in the investigated forest soils revealed highly significant positive correlation coefficients ( $r > 0.800, p < 0.001$ ) for  $\text{P-PO}_4$  as well as  $\text{TOC}$ ,  $\text{N}_{\text{tot}}$  and  $\text{DOC}$ . The release of  $\text{P-PO}_4$  into soil solution was thus significantly dependent on the content of these nutrient in the forest soil. The process of releasing the soluble form of  $\text{P-PO}_4$  into the soil solution may be slowed down by the content of certain nutrients, *i.e.*  $\text{Al}_{\text{tot}}$  and  $\text{Fe}_{\text{tot}}$ . This tendency is evident from the negative values of Pearson linear correlation coefficients (Table 5).

## Discussion

The study hypothesis was that when deadwood is left on forest soils for a long period of time decomposition processes take place and release forms of organic carbon (DOC) and macroelements dissolved in water (nitrogen and phosphorus) can be washed deep into the soil layers. The process related to the loss of these nutrients from forest soils may be a direct indicator of soil and forest habitat degradation. The research was conducted in three forest reserves of the Białowieża Forest which were old forests aged 110-168 years. The studies showed that DOC and dissolved forms of N and P, were deposited mainly in the forest litter (O).

According to Hansson *et al.* (2010) and Michalzik *et al.* (2001), the organic matter (O) is the main component of DOC, and the mineral soil absorbs it. Kalbitz and Kaiser (2008) and Wang *et al.* (2019) have shown that DOC penetrates deeply into the soil in forest ecosystems. In light of the study by the aforementioned authors, the release of these nutrients into the soil solution in the case of the Białowieża Forest reserves was probably caused by absorption processes occurring due to an acidic soil reaction ( $\text{pH}_{\text{CaCl}_2}$ : 3.98-5.10).

Leaving deadwood on the forest reserve soils for many years contributed to the release of low amounts of DOC and water soluble forms of N and P compared to the control group (0) without deadwood. The study also showed weak movement of these nutrients into the soil up to a depth of 40 cm which could indicate the possibility of their uptake by forest plants during the growing season. The slow release of water soluble forms of DOC and macronutrients from deadwood residues may be caused by the high cellulose content which has been confirmed in studies by other authors. Russell *et al.* (2014) and Guo *et al.* (2021) showed that the slow decomposition rate of deadwood is related to the lignin content of wood residues which limits the enzymatic degradation of non-lignin macroparticles. Lignin-derived aromatic compounds are probably the most stable components of DOM, while plant-derived carbohydrates are more easily degraded (Kalbitz and Kaiser, 2008).

Forest soils have a wide variation in the chemical composition of DOM and exhibit different properties depending on the tree species (Thieme *et al.*, 2019). It is estimated that certain tree species, *i.e.* *Quercus petraea*, *Q. robur*, *Carpinus betulus*, and *Betula pendula* Roth. from which the deadwood came, contained between 40-60% cellulose.

From this study, it appears that the type of deadwood (hardwood and softwood) has an influence on the amount of DOC released into the soil solution and is higher for softwood. Studies on the influence of the type of deadwood on the rate of its decomposition and the release of DOC are not clear. According to studies by Weedon *et al.* (2009) and Hermann *et al.* (2015), most conifers decompose more slowly than hardwoods due to the higher content of compounds such as lignin, resin and wax in conifers (Li *et al.*, 2007; Lukac and Godbold, 2011). Some studies (Bantle *et al.*, 2014; Froeberg *et al.*, 2010) have shown that coniferous forests have higher concentrations of DOC than temperate deciduous forests. According to Thieme *et al.* (2019), coniferous forests have higher concentrations of DOC, lignin and protein molecules and fewer tannin-like molecules in litter runoff compared to deciduous forests.

The study was focused on assessing the influence of soil acidity, TOC content and some mineral nutrients in forest soils in northern Poland on the release of DOC, nitrogen and phosphorus into the soil solution. Dissolved organic matter (DOM) in soil plays an important role in the biogeochemistry of carbon, nitrogen and phosphorus, in pedogenesis and the transport of pollutants in soil (Kalbitz, *et al.* 2000). It was found that pH measured in 0.01 mol  $\text{CaCl}_2 \cdot \text{dm}^{-3}$  had no effect on the release of the water soluble forms of DOC,  $\text{N-NH}_4$  and  $\text{P-PO}_4$ . Based on the analysis of Pearson's linear correlation between these nutrients, it was shown that the content

of DOC in forest soils depends on TOC content,  $N_{\text{tot}}$ ,  $P\text{-PO}_4$ , and  $N\text{-NH}_4$  as well as  $K_{\text{tot}}$  and  $Fe_{\text{tot}}$ . Both nitrogen and phosphorus are released from the soil during the mineralization of soil organic matter (SOM), while  $K_{\text{tot}}$  and  $Fe_{\text{tot}}$  can stabilize the content of DOC in the forest soils studied. According to Yano *et al.* (2000), the processes of absorption and stabilization of SOM in soil depend on the chemical composition of DOM.

Negative values of linear Pearson correlations were also found between  $Al_{\text{tot}}$  and the content of dissolved forms of DOC,  $N\text{-NO}_3$ ,  $N\text{-NH}_4$  and  $P\text{-PO}_4$  and between  $Fe_{\text{tot}}$  and the content of  $P\text{-PO}_4$ ,  $N\text{-NH}_4$  and  $N\text{-NO}_3$  in the forest soils. Negative values of these coefficients could indicate that Al and Fe bind the soluble forms of these nutrients and form stable soil complexes. Soils of the forest reserves studied were characterized by a wide range of acidity levels, from very strongly acidic to moderately acidic ( $pH_{\text{CaCl}_2}$ : 3.98-5.10). Similar results were also obtained by Kaiser and Kalbitz (2012). Kupka and Gruba (2022) showed increased DOC absorption at low pH which is probably due to the protonation of soluble organic substances (saturation of the functional groups with  $H^+$  ions). Studies have shown that the content of DOC in soils may be an indicator of carbon sequestration or potential carbon losses in the forest soil environment.

## Conclusions

- ✦ Forest litter was the main source of dissolved forms of C (DOC) and of nutrients (N and P) available to vegetation, while mineral soil was low in these regardless of stratum. The release of these nutrients into the soil solution was probably low due to absorption processes taking place at acidic pH ( $pH_{\text{CaCl}_2}$ : 3.98-5.10).
- ✦ Leaving deadwood affected the slow release of DOC as well as nitrogen ( $N\text{-NO}_3$  and  $N\text{-NH}_4$ ) and phosphorus ( $P\text{-PO}_4$ ) into the soil solution possibly due to the high cellulose content in woody plant tissues.
- ✦ The release of DOC into the soil solution depended on the total amount of carbon (TOC) and nitrogen ( $N_{\text{tot}}$ ) in the soil as well as on the presence of ammonium ( $N\text{-NH}_4$ ) and phosphate ions ( $P\text{-PO}_4$ ) released from soil organic matter during mineralization.
- ✦ Negative values of Pearson linear correlation coefficients between the content of  $Fe_{\text{tot}}$  and  $Al_{\text{tot}}$  and the dissolved forms of nitrogen and phosphorus ( $N\text{-NO}_3$ ,  $N\text{-NH}_4$  and  $P\text{-PO}_4$ ) could indicate that Al and Fe bind the soluble forms of these nutrients to form stable soil complexes.
- ✦ Studies have shown that the content of DOC in soils may be an indicator of carbon sequestration or potential carbon losses in the forest soil environment.

## Autors' contributions

I.B. – data collection and analysis, methodology, statistical analysis, manuscript writing; K.S. – participation in manuscript writing, manuscript improving, formal analysis.

## Conflicts of interest

The authors 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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## STRESZCZENIE

## Pozostawianie martwego drewna a zawartość rozpuszczonych form węgla, azotu i fosforu w glebach leśnych

Badania prowadzono w północnej Polsce (woj. podlaskie) na terenie Puszczy Białowieskiej (w 3 rezerwatach leśnych w Nadleśnictwie Hajnówka: Dębowy Grąd „DG”, Lipiny „LP” i Rezerwat Krajobrazowy Władysława Szafera „WS”), a także poza jej obszarem: na terenie Nadleśnictwa Rudka w rezerwacie Koryciny „KOR”.

Obiekty doświadczalne były zlokalizowane na różnych typach gleb (wg WRB): gleba płowa typowa („DG”), gleba brunatna wylugowana („LP”), gleba rdzawa właściwa i brunatna wylugowana („WS”) oraz gleba rdzawa typowa i płowa typowa („KOR”).

Drzewostany leśne były w wieku od 110 do 168 lat, a w ich składzie dominowały *Quercus petraea* (Matt.) Liebl., *Q. robur* L., *Fraxinus excelsior* L., *Picea abies* (L.) Karst., *Acer platanoides* L., *Betula pendula* Roth, *Carpinus betulus* L., *Pinus silvestris* L. i *Ulmus minor* Mill.

W terminie wrzesień-listopad 2021 r. pobrano próbki ściółki leśnej (O) oraz gleby z warstw 0-5, 5-10, 10-20 i 20-40 cm. Pobrano je w wariancie z martwym drewnem (wariant 1) oraz na stanowiskach kontrolnych bez martwego drewna (wariant 0), zlokalizowanych w sąsiedztwie obiektów z martwym drewnem. Po wysuszeniu i przygotowaniu do badań zmierzono kwasowość próbek w roztworze 0,01 M  $\text{CaCl}_2$   $\text{pH}_{\text{CaCl}_2}$  z gleby (1:10) metodą potencjometryczną. Przygotowano: (i) roztwór wody królewskiej ( $3\text{HCl} \times \text{HNO}_3$  w stosunku: 3:1), w którym oznaczono całkowitą zawartość P, K, Ca, Mg, Mn, Fe i Al metodą emisyjnej spektrometrii atomowej ze wzbudzeniem w plazmie indukcyjnie sprzężonej (ICP-OES) oraz (ii) wyciąg wodny z gleby (1:5), w którym zbadano zawartość rozpuszczonych form DOC,  $\text{N-NO}_3$ ,  $\text{N-NH}_4$  i  $\text{P-PO}_4$  metodą kolorymetrii przepływowej. Dodatkowo w glebie zmierzono całkowitą zawartość TOC i  $\text{N}_{\text{tot}}$  metodą wysokotemperaturowego spalania z detekcją TCD.

Na podstawie badań wykazano, że głównym źródłem DOC oraz rozpuszczonych form azotu ( $\text{N-NO}_3$  i  $\text{N-NH}_4$ ) i fosforu fosforanowego ( $\text{P-PO}_4$ ) była ściółka leśna, zaś glebę do głębokości 40 cm cechowała ich mała zawartość (tab. 1 i 2; ryc. 1a-d). Otrzymane wyniki mogą wskazywać na sorbowanie tych makroskładników przez glebę, co zachodzi przy jej kwaśnym odczynie ( $\text{pH}_{\text{CaCl}_2}$ : 3,98-5,10) oraz przy obecności glinu i żelaza (tab. 1). Wykazano, że wieloletnie pozostawianie martwego drewna w rezerwatach leśnych Puszczy Białowieskiej wpływało na powolne uruchamianie rozpuszczonych form DOC, a także azotu ( $\text{N-NO}_3$  i  $\text{N-NH}_4$ ) i fosforu ( $\text{P-PO}_4$ ) do roztworu glebowego. Istotnie więcej DOC i azotu azotanowego uwalniało się do roztworu glebowego spod martwego drewna iglastego niż liściastego (tab. 3). Można przypuszczać, że znaczna zawartość celulozy w zdrewniałych tkankach drewna liściastego była czynnikiem ograniczającym tempo uwalniania tych składników do roztworu glebowego.

Przenikanie DOC do roztworu glebowego było uzależnione od zasobności gleby w węgiel całkowity (TOC) i azot ( $\text{N}_{\text{tot}}$ ) oraz zawartości jonów amonowych ( $\text{N-NH}_4$ ) i fosforanowych ( $\text{P-PO}_4$ ) uwalnianych z glebowej materii organicznej podczas jej mineralizacji (tab. 4).

Na podstawie badań można wnioskować, że zawartość DOC może być indykatorem akumulacji węgla i składników mineralnych w glebie lub ich ewentualnych strat spowodowanych wywymianiem, a także wskaźnikiem stanu degradacji gleb leśnych.