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Short-Term Effects of Controlled Heathland Burning on Macro- and Microelements Accumulation in *Calluna vulgaris*

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ABSTRACT

In order to protect, improve the condition and renew the heathland, foresters recommend controlled burning aimed at eliminating competing species, removing dead shoots, and stimulating *Calluna vulgaris* to grow. The aim of the research was to assess the impact of heath burning on the accumulation of nutrients in the shoots and roots of *C. vulgaris.* The results of our research indicate that the fire did not cause statistically significant changes in active acidity and exchangeable acidity in the surface layers of the soil compared to the control area. The heathland soils were nutrient-poor, with phosphorus being the most deficient element. The acidic pH of soils (pH<5.0) limited the bioavailability of macronutrients to plants. Spring burning of the heathland caused statistically significant differences in the content of N, P, K, Mg, Ca and Mn in the surface layer (A), N, P, K, Cu and Fe in the B layer and P, Mg, Cu and Fe in the C layer of the soil compared to the control surface. The macronutrient content in live shoots and roots was very low, except for calcium. The high content of Ca resulted from the functioning of *C. vulgaris* under stress conditions related to phosphorus deficiency in the soil and aging of the heath. In the short-term assessment, controlled burning of the heathland caused statistically significant differences in the content of N, P, K, Mg, Zn, Cu and Mn in shoots ($p<0.01$) and Mn in roots ($p<0.05$). The fire significantly ($p<0.01$) changed the values of the ratios between important nutrients (N/P, K/Mg and Fe/Mn) in the shoots of *C. vulgaris* compared to the control area.

Keywords: heathland protection, fire, soil, shoot, roots, accumulation of nutrients.

INTRODUCTION

The functioning of plants depends on the content and bioavailability of nutrients contained in the surface and near-to-surface layers of the soil. For their proper growth and development, an appropriate pool of both macro- and micronutrients is necessary [Ostrowska and Porębska 2002]. Among the macronutrients, nitrogen, phosphorus, potassium, magnesium and calcium play a significant role, determining the production of biomass. Considering the micronutrients, zinc, copper, manganese and iron are worth mentioning as without them the proper growth of plants is disturbed. If these elements are to be taken up by plants, they must be present in the soil in mobile, easily digestible forms. And this, in turn, depends on numerous factors, including the pH of the soil and the organic matter contained in it [Jonczak and Parzych 2015]. Macronutrients are bioavailable and readily taken up by plants at pH 6.0-8.0 (8.5) and micronutrients at soil pH 4.0-5.5 (6.0). The exception is manganese, which is also absorbable at pH~8. Depending on the pH and the content of organic matter in the soil, the bioavailability of nutrients for plants changes.

Soils on moors are nutrient-poor and highly acidic [Marcos et al., 2009], and these conditions are tolerated by *Calluna vulgaris*. The occurrence of other plant species on heathlands is most often limited by nitrogen and phosphorus deficiency in the soil [Fernández 2002]. Long-term nutrient deficiencies in the soil contribute to the inhibition of plant growth and development, as well as accelerate the death of older shoots [Tessier and Raynal 2003; Parzych 2010]. However, sometimes an increase in soil fertility associated with the inflow of atmospheric nitrogen with rain, snow or fog is observed [Barker et al., 2004; Parzych et al., 2008]. Increased nitrogen deposition affects the structure and functioning of heathlands, especially those characterized by exceptionally low nitrogen and phosphorus content in the soil [Stevens et al., 2016; Taboada et al., 2016]. Periodic increase in soil fertility is conducive to the entry of species competing with *C. vulgaris*, most often grasses (e.g. *Molinia caerulea*), which eventually may weaken the functioning of *C. vulgaris* as a result of taking a significant amount of nutrients from the soil [Power et al., 2001; Marcos et al. 2003; Härdtle et al., 2006]. Ultimately, the rapid encroachment of grasses can lead to overgrowth and loss of heathland [Scandrett and Gimingham 1991]. Therefore, in order to protect and improve the condition of heathland, foresters recommend mowing or controlled burning procedures to eliminate competitive species, remove excess dead shoots and stimulate *C. vulgaris* to produce new shoots and grow. Currently, controlled burning treatments are considered an irreplaceable tool for the protection of heathland and are practiced in different European countries, including Austria, the Czech Republic, Estonia, Germany, Poland, Romania, Switzerland, Sweden [Forgeard and Frenot 1996; Niemeyer et al., 2005; Calvo et al., 2007; Valkó et al., 2014].

Controlled burning of the heath is inevitably associated with the impact on the physicochemical properties of the soil. According to the scientific literature, fires can modify not only the pH of the soil [Han et al., 2021], but also the content and form of nutrients accumulated in the surface and near-to-surface layers of the soil [Schaller et al., 2015; Abney et al., 2017; Jonczak et al., 2019, Torres Rojas et al., 2020; Rustowska 2022], and thus affect the mobility and bioavailability of macro- and micronutrients for plants.

The main objective of the study was to assess the impact of controlled heathland burnout on the content of macro- and micronutrients in soil, shoots and roots of *C. vulgaris* in dry heathland ecosystems. This goal was accomplished by cyclical sampling of soil and *C. vulgaris*, performing a number of chemical analyses and interpreting the obtained results.

MATERIALS AND METHODS

Research area

The research covered heaths located in northern Poland, in Tuchola Forest, in the Tuchola Forestry Inspectorate (53.65829, 18.03409), (Figure 1). The area formed more than 10,000 years ago during the last glaciation in Poland, called the Baltic Glaciation. The region is characterized by a lowland, lakeside landscape, dominated by pine forests. In smaller

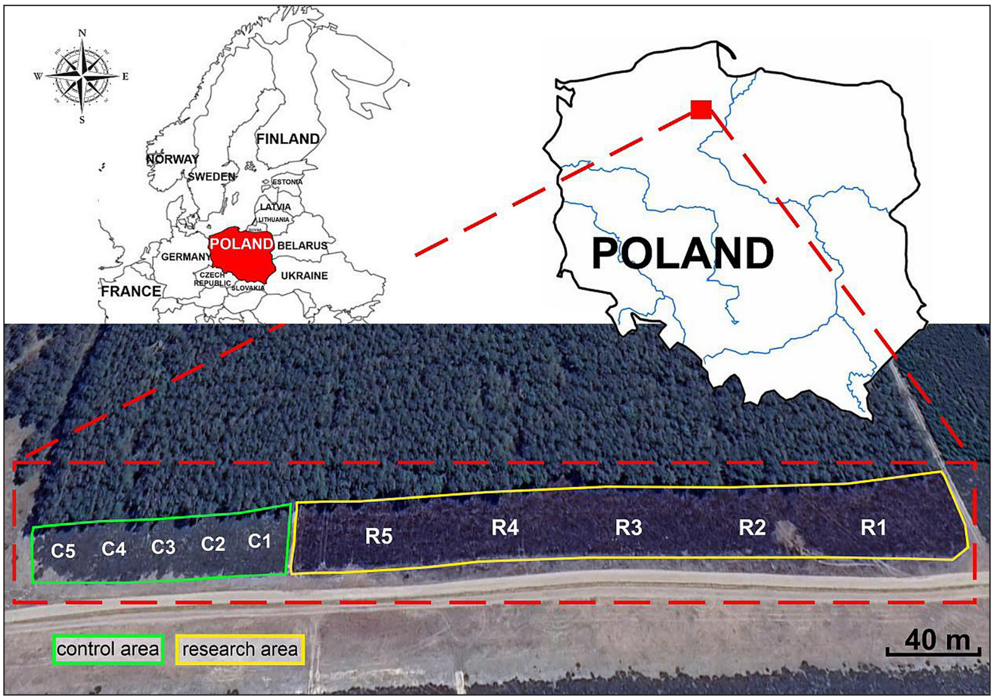

Figure 1. Location of the research area (sampling points: C1–C5 – control area, R1–R5 – research area)

quantities, there are deciduous forests: beech, alder, riparian, oak and broadleaved forests.

According to the geological map, the heathlands in Tuchola Forest are located on sandy soils, dominated by the types of podzolic and rusty soils [Kistowski 2020]. The heathland under study covered an area of 10,000 m^2 (including 8,000 m^2 of a burnt area, and 2,000 m^2 of a control area). The heathland occupied a flat, narrow area, with an elongated shape (Figure 1, 2), and a large zone of lateral contact with the surrounding pine forests. The heathland showed intermediate features between the moss (*Pohlio-Callunetum)* and the bearberry moorland (*Arctostaphylo-Callunetum*). On the studied area, the dominant species was *Calluna vulgaris,* although a small share of *Vaccinium vitis-idaea* and *Pecuedanum oreoselinum* was also recorded [Kujawa-Pawlaczyk 2004; Matuszkiewicz 2008].

Sampling and physicochemical analyses

Research on the heath in Tuchola began in March (08.03.2023) before the spring burning (21.04.2023) and continued in June (22.06.2023) after the occurrence of young shoots of *C. vulgaris* (Figure 2A–D). Field works began with the delineation of the research and control area, on which 5 soil and heather sampling sites were located (research area: R1–R5 and control area: C1–C5), (Figure 1). Soil samples were taken from three different depths (a: 0–5 cm, b: 5–10 cm, c: 10–15 cm) due to the largest cluster of roots. Heather samples consisted of 1-year old above-ground shoots and live roots with a diameter of 3–6 mm from a soil layer with a thickness of 0–15 cm. Samples weighing about 100 g were taken from each site separately. The soil samples were dried in a forced air dryer at 65 °C, and then ground in a mortar, sieved through a 1 mm mesh sieve, and poured into sealed polyethylene string bags. The samples of 1-year old aboveground shoots were segregated, the roots were rinsed in distilled water to remove soil residues. The plant material prepared in this way was dried in paper bags at a temperature of 65 °C in a forced air dryer. Then, the plant samples were homogenized in a laboratory grinder (IKA A11, basic)

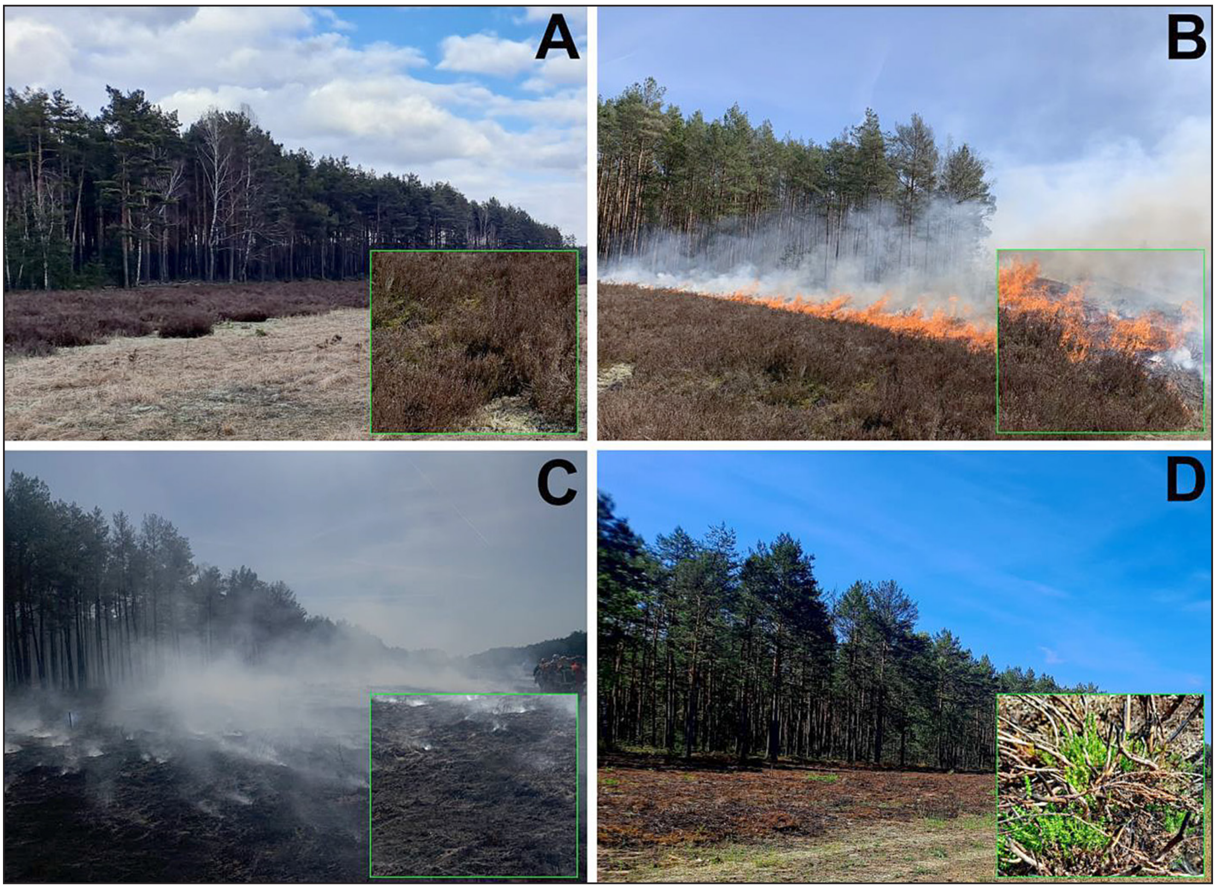

Figure 2. Heath covered by research, (a) before burning (08.03.2023), (b) during burning (21.04.2023), C – immediately after burning (21.04.2023), D – two months after burning (22.06.2023)

and stored in sealed string bags until analysis. In the soil samples, active acidity (pH in H_2O) and exchangeable acidity (pH in 1M KCl) were determined using the potentiometric method (Elmetron, CPI 551). Then, in the soil samples, the content of organic matter (OM) was determined using the incandescent loss method, in a muffle furnace (Czylok, FCF 7SP), at 550 °C according to Karczewska and Kabała [2008] and the nitrogen content with a CHNS analyzer (Flash Smart, Thermo Fisher Scientific, Waltham, MA, USA), using methionine as a standard and reference material (Certificate number analysis – 291468, ThermoScientific).

In order to determine the content of K, Mg, Ca, P, Zn, Cu, Mn and Fe, both the soil samples (0.5 g) and the shoots (0.5 g) and roots (0.5 g) of *C. vulgaris* were digested in a microwave mineralizer (ETHOS EASY, Milestone connect) with the addition of 65% nitric acid solution (V) and 30% H_2O_2 solution in a volume ratio of 5:1, at 200°C. In the obtained solutions, the P content was determined using the spectrophotometric method with ammonium molybdate (UV-VIS, Hitachi U-5100), and the content of the remaining macro- and micronutrients: K, Mg, Ca, Zn, Cu, Mn and Fe was determined with atomic absorption spectrometry (ASA, iCE3500, ThermoScientific) in the flame version, in a mixture of acetylene and oxygen. Fluka standards (1g/1000 ml) were used to calibrate the apparatus. The content of metallic elements was measured at the following wavelengths: K (766.5 nm), Mg (285.2 nm), Ca (422.7 nm), Zn (213.9 nm), Cu (324.8 nm), Mn (279.5 nm) and Fe (248.3 nm). Measurements of calcium content were conducted with the addition of 5% $LaCl_3$ solution to reduce interference.

Data preparation

The distribution of the obtained physicochemical and chemical data was checked using the Shapiro Wilk test. The physicochemical properties of soil and the content of macro- and micronutrients in soil, shoots and roots of *C. vulgaris* on the burnt and the control areas were compared using the non-parametric Kruskal Wallis test ($p<0.05$). The results of the calculations are presented in the tables (Table 1–4).

RESULTS AND DISCUSSION

Physicochemical properties of soil

The soils on the studied heathland showed a strongly acidic reaction, with pH values from 3.90 to 4.75 (pH, H_2O) and from 3.38 to 4.49 (pH, KCl). The acidity decreased slightly with the depth of the soil layers both before and after the burning of the heathland. In the short-term assessment, the process of firing the test area in Tuchola did not significantly affect the change in active acidity (pH, H_2O) or exchangeable acidity (pH, KCl) compared to the control area (Table 1).

Excessive acidity of soils is a factor limiting plant growth, due to a decrease in the bioavailability of nutrients and an increase in the

Table 1. Physicochemical properties of soil (mean ± standard deviation) with Kruskal Wallis (K-W) test results ($p<0.05$)

Parameter		Before burning*	After burning		
		Research area	Research area	Control area	K-W, p
pH (H_2O)	A	3.90 ± 0.3	4.75 ± 0.3	4.68 ± 0.4	-
	B	4.13 ± 0.2	4.44 ± 0.2	4.40 ± 0.2	-
	C	4.55 ± 0.1	4.68 ± 0.2	4.65 ± 0.2	-
pH (KCl)	A	3.46 ± 0.2	3.39 ± 0.3	3.38 ± 0.2	-
	B	3.60 ± 0.2	3.50 ± 0.1	3.52 ± 0.2	-
	C	4.40 ± 0.2	4.23 ± 0.5	4.49 ± 0.1	-
OM, %	A	22.58 ± 10	46.73 ± 6.5	32.76 ± 6.3	<0.05
	B	2.84 ± 0.6	4.29 ± 0.7	2.15 ± 0.4	<0.01
	C	2.03 ± 0.7	1.80 ± 0.4	2.18 ± 0.3	-

Note: pH = -log[H^+], OM – organic matter [%], * – no statistically significant differences were found between the research and control areas, A: (0–5 cm), B: (5–10 cm), C: (10–15 cm).

availability of potentially toxic elements, i.e. aluminium. Considering all nutrients, the soil pH (H_2O) ranging from 5.5 to 7.0 [Ostrowska and Porębska 2002], is assumed to be optimal for the functioning of plants as in an excessively acidic environment most macronutrients are unavailable to plants. The pH values of the surface (A) and near-to-surface (B, C) layers of soil on the research area in Tuchola were typical for forest soils [pH: 3.0–6.0, Bednarek et al., 2005]. Lack of statistically significant differences in the pH values of soil samples, both on the burnt and control area, was also shown by Marcos et al. [2009]. Such a situation may be the result of incomplete incorporation of ash into the soil in too short time and a limited amount of rainfall. Our research results are confirmed by the work of Mohamed et al. [2007]. Organic matter (OM) was accumulated mainly in layers A and B of the tested area. The OM content averaged 22.58% (A), 2.84% (B), and 2.03% (C) before spring burnout. After burning the heathland, an increased OM content was observed in layers A (46.73%) and B (4.29%) compared to the control area, and these differences were statistically significant (Table 1). During the firing of the heath, the surface organic layer was not completely destroyed, and the greatest OM losses were observed in layers A and B, which is obvious due to the highest flame penetration and high content of combustible fractions. Incomplete burning of *C. vulgaris* shrublets was also recorded on moors burned in Spain [Marcos et al., 2009].

Table 2. Chemical properties of soil (mean ± standard deviation) with Kruskal-Wallis (K-W) test results ($p<0.05$)

Parameter [mg/kg]		Before burning*	After burning		
		Research area	Research area	Control area	K-W, p
N	A	3170 ± 230	6900 ± 1100	4900 ± 1200	<0.05
	B	1140 ± 200	600 ± 300	1100 ± 200	<0.05
	C	1430 ± 100	1200 ± 100	1300 ± 100	-
P	A	264.12 ± 73	0.22 ± 0.0	37.27 ± 3	<0.05
	B	127.50 ± 38	5.22 ± 1.8	19.48 ± 1	<0.01
	C	249.10 ± 84	0.02 ± 0.0	45.67 ± 8	<0.01
K	A	540.2 ± 159	706.9 ± 124	523.7 ± 67	<0.01
	B	226.1 ± 95	289.7 ± 53	223.6 ± 37	<0.05
	C	274.8 ± 39	212.1 ± 27	224.2 ± 38	-
Mg	A	307.9 ± 84	469.7 ± 75	300.7 ± 82	<0.05
	B	206.4 ± 41	157.8 ± 33	129.0 ± 31	-
	C	174.8 ± 28	119.0 ± 25	220.3 ± 20	<0.05
Ca	A	7909.4 ± 1322	10609.6 ± 826	7875.7 ± 782	<0.01
	B	5189.7 ± 1224	6476.7 ± 1526	6174.0 ± 789	-
	C	5238.6 ± 616	9356.0 ± 1800	10341.3 ± 2863	-
Zn	A	22.71 ± 5.2	27.21 ± 3.9	26.40 ± 2.2	-
	B	16.31 ± 3.7	8.80 ± 2.1	6.82 ± 1.7	-
	C	13.65 ± 1.1	7.88 ± 1.8	8.46 ± 0.3	-
Cu	A	6.09 ± 1.2	8.23 ± 1.4	7.64 ± 0.6	-
	B	4.15 ± 1.0	2.38 ± 0.2	2.98 ± 0.6	<0.05
	C	3.42 ± 0.3	1.81 ± 0.4	3.10 ± 0.8	<0.01
Mn	A	65.23 ± 20	165.37 ± 66	47.58 ± 26	<0.01
	B	33.53 ± 7.3	32.91 ± 9.8	27.63 ± 4.6	-
	C	55.07 ± 19	81.93 ± 44	61.22 ± 15	-
Fe	A	2196.0 ± 414	2748.7 ± 398	3242.2 ± 456	-
	B	1892.0 ± 504	2068.9 ± 257	1685.8 ± 352	<0.05
	C	2560.0 ± 768	2864.4 ± 721	3732.7 ± 788	<0.05

Note: * – no statistically significant differences were found between the research and control areas, A: (0–5 cm), B: (5–10 cm), C: (10–15 cm).

Macro- and microelements content in the soil

Analyses of soil samples showed that both surface (A) and near-to-surface (B, C) layers were characterized by an exceptionally low content of macronutrients (Table 2). The highest amount of nutrients was found in layer A, which was associated with its higher content of organic matter compared to layers B and C (Table 1). The nitrogen content ranged from 3170 mg/kg (A) to 1140 mg/kg (B) before firing. As a result of the spring burning of the heath, an increase in the content of N in layer A and a loss in layer B compared to the control area were observed. These differences were statistically significant ($p<0.05$). According Forgeard and Frenot [1996], during the burning of moors, the losses of up to 50% nutrients contained in the soil may occur due to the formation of volatile forms, e.g. nitrogen.

The most deficient macronutrient was phosphorus (P), the content of which in soil ranged on average from 127.50 mg/kg to 264.12 mg/kg before the growing season (before burnout), and two months after burnout (22.06.2023), on the tested and control area was at the limit of detection (Tab. 2). Intensive growth of young shoots (Figure 2D) stimulated by firing was the cause of increased demand of *C. vulgaris* for phosphorus. Statistically significant differences ($p<0.01$) in the P content in the A, B and C layers of the burnt and control area were demonstrated. A significant loss of phosphorus in the soil in the first year after the fire, compared to the control area, was observed by Marcos et al. [2009]. Forms of phosphorus bioavailable for plants occur in forest soils usually in low concentrations, especially in the growing season [Parzych 2010; Jonczak et al., 2019].

The heathland soils contained lesser amounts of potassium and magnesium, taking average values from 212.1 to 706.9 mg/kg (K) and from 119.0 to 469.7 mg/kg (Mg) depending on the depth of the tested layer and the sampling time. The highest amounts of K and Mg occurred each time in layers A. After controlled burning of the heathland, a statistically significant increase in the content of potassium in layers A ($p<0.01$) and B ($p<0.05$) and magnesium in layers A and C ($p<0.05$) as compared to the control area was observed (Table 2). Regarding the studied macro- and micronutrients, calcium was the dominant one in the soil, with the values ranging from 5 189.7 to 10 609.6 mg/kg. After controlled burning of the heathland, a statistically significant ($p<0.01$) increase in the Ca content in the surface (A) layer of the tested soil, compared to the control area, was observed. The increase in the content of K, Mg and Ca in the soil after the burning of the heath was associated with the inflow of nutrients along with the resulting ash. However, in the short-term assessment of the impact of heath burning, it did not cause a significant increase in the pH of the tested soil due to the small amount of rainfall in May and June and the resulting limited mobility of nutrients [Bednarek et al., 2005, Marcos et al., 2009]. Nutrient immobilization in the soil immediately after the fire was also noted Forgeard and Frenot [1996].

The results of our research indicate that the content of micronutrients in the soil on the heath was typical for forest soils. Zinc content ranged from 6.82 mg/kg to 22.71 mg/kg, and copper content ranged from 1.81 mg/kg to 8.23 mg/kg, depending on the tested layer and the date of sampling (Table 2). After the spring burning of the heathland, a statistically insignificant increase in the Zn content in layers A and B, compared to the control area, was observed. At the same time, Cu contents found in layer B ($p<0.05$) and C ($p<0.01$) were significantly lower than in the control area. Zinc is one of the most mobile micronutrients in the soil. The forms of its occurrence and the related bioavailability for plants closely depend on the pH and the presence of organic matter. According to literature data, the Zn content in the mineral levels of forest soils is most often up to 40 mg/kg [Kabata-Pendias and Pendias 1999], and in organic levels reaches even 80–200 mg/kg [Ostrowska et al., 1991]. The total copper content in forest soils of Poland ranges from 0.2 to 43 mg/kg in organic layers and from 1.2 to 35.0 mg/kg in mineral layers [Ostrowska et al., 1991].

The content of manganese in the soil ranged from 27.63 mg/kg to 165.37 mg/kg, depending on the soil layer and the date of sampling. As a result of burning the heath, a statistically significant ($p<0.01$) higher Mn content was observed in layer A as compared to the control area. In forest soils, the Mn content usually fluctuates from 100 to 500 mg/kg in organic layers and from 30 to 120 mg/kg in mineral layers [Ostrowska et al., 1991].

The iron content in the studied soils ranged from 1685.8 mg/kg to 3732.7 mg/kg, as in the case of other micronutrients, and showed variability along with the depth of the soil layer and the date of sampling (Table 2). After the spring burning of the heathland, statistically significant differences in the Fe content in layers B and C ($p<0.05$), compared to the control area, were observed. Iron, like zinc, is a very mobile element in the soil, and its degree of mobility is most often associated with periodic changes in conditions. The solubility of iron compounds and the associated bioavailability for plants depend on the acidity of the soil [Kabata-Pendias and Pendias 1999].

In the short-term assessment, the spring burning of the heath caused statistically significant differences in the content of N, P, K, Mg, Ca and Mn in the surface layer (A), N, P, K, Cu and Fe in the B layer and P, Mg, Cu and Fe in the C layer of the soil, compared to the control area (Table 2). Literature data confirm that changes in the content of basic nutrients in the soil after fires most often concern a few centimeters of a surface layer with a significant content of organic matter [Dlapa et al., 2008; Granged et al., 2011], which is confirmed by the results of our research.

Accumulation of macro- and microelements in *C. vulgaris*

The vital condition of *C. vulgaris* on the heathland before burnout was poor. Many dead shoots and roots were found. The content of macronutrients in live shoots and roots of *C. vulgaris* was exceptionally low and simultaneously varied depending on the date of sampling. The nitrogen content in shoots remained on average at the level of 3 566 mg/kg to 18 700 mg/kg (Table 3). Lower N contents were noted in the roots of *C. vulgaris,* ranging from 1080 mg/kg to 2 458 mg/kg. After the spring burning of the heath, the emergence of young shoots of *C. vulgaris*, which in June contained four times more nitrogen compared to shoots on the control area, was observed. These changes were statistically significant ($p<0.01$). At the same time, a slight decrease in the N content associated with the emergence of new shoots was observed in the roots. The nitrogen content in plant shoots can reach up to 31 000 mg/kg depending on the growth conditions [Ostrowska and Porębska 2002]. Long-term deficiencies of this component limit growth and development and accelerate plant aging [Ostrowska et al., 1991, Parzych 2010].

The most deficient macronutrient was phosphorus. The average P content in *C. vulgaris* shoots remained at the level of 590 mg/kg to 1 915 mg/kg, and in roots below 265 mg/kg and

Table 3. Macro- and microelements accumulation (mean ± standard deviation) in *C. vulgaris* with Kruskal-Wallis (K-W) test results ($p<0.05$)

Parameter [mg/kg]		Before burning*	After burning		
		Research area	Research area	Control area	K-W, p
N	shoots	3566 ±1644	18700 ± 762	4410 ± 691	<0.01
	roots	2458 ±1179	1080 ± 801	1520 ± 858	-
P	shoots	963 ± 70	1915 ± 77	590 ± 75	<0.01
	roots	196 ± 44	265 ± 50	222 ± 16	-
K	shoots	4019 ± 59	1075 ± 84	376 ± 58	<0.01
	roots	658 ± 66	793 ± 275	929 ± 132	-
Mg	shoots	1348 ± 150	1954 ± 277	1116 ± 60	<0.01
	roots	85 ± 25	346 ± 36	320 ± 63	-
Ca	shoots	20213 ± 825	37432 ± 9221	26268 ± 3940	-
	roots	8042 ± 570	16389 ± 5356	14293 ± 3224	-
Zn	shoots	25 ± 2	38 ± 3	20 ± 2	<0.01
	roots	11 ± 1	18 ±1	19 ± 4	-
Cu	shoots	8 ± 0.4	12 ± 0.4	10 ± 0.3	<0.01
	roots	5 ± 0.3	5 ± 1	4 ± 0.6	-
Mn	shoots	631 ± 128	1434 ± 138	406 ± 101	<0.01
	roots	242 ± 46	1073 ± 427	595 ± 89	<0.05
Fe	shoots	207 ± 17	184 ± 25	188 ± 23	-
	roots	21 ± 5	111 ± 44	60 ± 3	-

Note: * – no statistically significant differences were found between the research and control areas.

reflected the limited P content in the surface and near-surface soil layers (Table 2). The spring burning of the heathland caused a threefold increase in the P content in the shoots of *C. vulgaris* compared to the shoots on the control area. The content of phosphorus in well-nourished plants can reach up to 10 000 mg/kg [Ostrowska et al., 1991], while in forest plant species there are often deficiencies of this biogenic element [Parzych 2010]. Phosphorus deficiency limits the growth of the root system and determines the ability of plants to absorb water and nutrients from the soil [Gaj and Grzebisz 2003].

The K content in *C. vulgaris* was on average at the level of 4019 mg/kg in shoots and 658 mg/kg in roots before burning of the area (Table 3). The spring burning of the heathland resulted in a statistically significant ($p<0.01$) increase in the K content in the shoots of *C. vulgaris* in comparison to the control area. Potassium is a particularly important macronutrient for plants as it participates, among others, in the transport of ions and regulates transpiration. Its natural content in plants can be up to 12 000 mg/kg [Ostrowska and Porębska 2002], and long-term deficiencies contribute to weakening the condition of plants and inhibiting their growth.

The magnesium content of *C. vulgaris* shoots ranged from 1116 mg/kg to 1954 mg/kg (Table 3). Significantly lower amounts of Mg, from 85 to 346 mg/kg, were found in roots. The spring burning of the heathland contributed to a significant increase in the Mg content in the shoots of *C. vulgaris*. These differences were statistically significant ($p<0.01$) as compared to the control area. The content of Mg in plants is necessary for their proper functioning as it plays a key role in the processes of solar energy conversion. Its content in plants most often ranges from 1 000 to 4 000 mg/kg [Ostrowska and Porębska 2002], and in some cases even up to 10 000 mg/kg [Kabata-Pendias and Pendias 1999].

The content of Ca in the shoots of *C. vulgaris* varied. Before the growing season (08.03.2023), an average of 20 213 mg/kg of Ca in shoots and 8 042 mg/kg in roots were found (Table 3). A statistically insignificant increase in calcium content in shoots (37 432 mg/kg) and roots (16 389 mg/kg) as compared to the control area was observed after burning the heath. The calcium content in *C. vulgaris* is strongly associated with the aging process and increases with plant age. The demonstrated high content of Ca in shoots is characteristic for plants functioning under stress conditions related to nitrogen and phosphorus deficiency in the soil. The average Ca content in plants varies widely, from 200 mg/kg to 30 000 mg/kg, depending on the physicochemical properties of soils [Ostrowska et al., 1991].

The zinc content in *C. vulgaris* remained at the level of 20 to 38 mg/kg in shoots and 11 to 19 mg/kg in roots (Table 3). After the spring burning of the heathland, a twofold increase in the zinc content in the shoots of *C. vulgaris* was observed compared to the control area. These differences were statistically significant ($p<0.05$). Adequate Zn content in plants has a positive effect on biomass growth, disease resistance, the proper course of photosynthesis and increases resistance to drought. To cover the demand of plants for Zn, 15–30 mg/kg is usually sufficient, and the average content in plant shoots not directly affected by contamination is usually in the range of 10 to 70 mg/kg [Kabata-Pendias and Pendias 1999].

The copper content in *C. vulgaris* remained at the level of 8–12 mg/kg in shoots and 4–5 mg/kg in roots (Table 3). The spring burning of the heathland resulted in a statistically significant ($p<0.01$) slight increase in the Cu content in the shoots in comparison to the control area. Copper plays a vital role in the transformation of nitrogen compounds. Adequate Cu content in plants favourably affects the effective use of nitrogen available in the soil by plants. For proper growth and development, most plants need 4 to 5 mg/kg of Cu [Kabata-Pendias and Pendias 1999].

The manganese content ranged from 406 mg/kg to 1434 mg/kg in shoots and from 242 to 1 073 mg/kg in roots of *C. vulgaris* (Table 3). After burning the heath, statistically significant differences were observed. More than three times higher Mn content in shoots ($p<0.01$) and almost twice as much Mn in roots ($p<0.05$) compared to the control area. Manganese performs essential functions in plants, participates in photosynthesis, decarboxylation and takes part in the binding of free nitrogen. For the proper development of plants, 10–25 mg/kg is usually sufficient, and a Mn content higher than 500 mg/kg is usually toxic to some species [Kabata-Pendias and Pendias 1999]. The ash resulting from the fire consists of mineral forms of various elements, which can significantly increase the bioavailability of nutrients for plants in a brief time [Pereira et al., 2015]. The high Mn content in *C. vulgaris* was strongly promoted by the acidic reaction of soils on the heath, pH<5 (Table 1).

Table 4. Ratios between selected macro- and microelements (mean ± standard deviation) in *C. vulgaris* with Kruskal-Wallis (K-W) test results (p<0.05)

Parameter [mg/kg]		Before burning*	After burning		
		Research area	Research area	Control area	K-W, p
N/P	shoots	3.72 ± 1.67	9.77 ± 0.47	7.52 ± 1.06	<0.01
	roots	13.18 ± 4.59	3.98 ± 1.06	6.84 ± 2.80	-
K/Mg	shoots	3.01 ± 0.31	0.56 ± 0.08	0.34 ± 0.04	<0.01
	roots	8.19 ± 2.03	2.27 ± 0.61	2.98 ± 0.60	-
K/Ca	shoots	0.20 ± 0.00	0.03 ± 0.01	0.01 ± 0.00	-
	roots	0.08 ± 0.01	0.05 ±0.02	0.07 ± 0.02	-
Fe/Mn	shoots	0.34 ±0.07	0.13 ± 0.03	0.48 ± 0.06	<0.01
	roots	0.09 ± 0.03	0.12 ± 0.05	0.10 ± 0.01	-

The iron content in *C. vulgaris* shoots was much higher than in the roots and ranged from 184 to 207 mg/kg (Table 3). After the spring burning of the heath, a statistically insignificant increase in the Fe content in the roots of *C. vulgaris* compared to the control area was observed. According to literature data, iron is characterized by low mobility in plant tissues. It participates in the processes of molecular nitrogen assimilation and nitrate reduction [Ostrowska et al., 1991]. The absorption of iron for plants depends mainly on the pH of the soil. Its bioavailability is best in an acidic environment (pH<5), (Table 1). Most species show high sensitivity to iron deficiencies, which is manifested by poor condition of plants. The Fe content in plants at natural sites is most often up to 375 mg/kg [Kabata-Pendias and Pendias 1999].

Among micronutrients, the process of controlled burning of heath caused a statistically significant increase in the content of Zn, Cu and Mn in shoots (p<0.01) and Mn in roots (p<0.05), compared to the control area (Table 3). According to Rustowska [2022], fire is a crucial factor affecting the management of nutrients in plant biomass, even several decades after its occurrence. On the other hand, nutrient uptake by plants is a metabolically regulated process, characteristic of the species [Townsend et al., 2006].

Important element ratios in *C. vulgaris*

The state of mineral nutrition of *C. vulgaris* depends not only on the content of macro- and micronutrients in the shoots and roots, but also on the mutual balance between the elements. The values of the N/P ratio in *C. vulgaris* shoots were low and ranged from 3.72 on the test area before firing to 9.77 after firing (Table 4). Burning the heathland caused a statistically significant (p<0.01) increase in the value of the N/P ratio in shoots compared to the control area. According to Güsewell and Koerselman [2002] and Güsewell [2004], the ratio of N/P in green parts of plants in natural sites most often takes values from 12 to 13. According to Zhiguo et al. [2007], the maximum supply of biogenic elements and maximum plant growth occurs at N/P close to 9.5. In the short-term assessment, the process of controlled burning of the heathland in Tuchola positively influenced the increase in the value of the N/P ratio in the shoots of *C. vulgaris*.

For most plants, the normal K/Mg ratio range is 2.2 to 6.4 [Burg 1990]. The results of our research indicate that before the growing season, the K/Mg ratio in shoots remained on average at 3.01 in shoots and 8.19 in roots (Table 4). In the short-term assessment, the spring burning of the heath adversely (p<0.01) affected the value of the K/Mg ratio in the shoots of *C. vulgaris*, reducing it to 0.56.

According to literature data, the correct K/Ca ratio for plant development ranges from 0.8 to 2.0 [Burg 1990]. The results of our research indicate that in the case of *C. vulgaris*, this ratio was much lower (K/Ca<0.8), regardless of the date of sampling and the process of burning the moor. These data confirm the excessive accumulation of Ca both in shoots and in the roots of *C. vulgaris* (Table 4), which is related to the aging of the heath. According to Burg [1990] excess of accumulated calcium adversely affects potassium uptake.

The range of 1.5–2.5 was assumed to be the correct Fe/Mn ratio for plant development. [Kabata-Pendias and Pendias 1999]. Analysing the results of our research (Table 4) regarding the value of Fe/Mn in shoots (0.13–0.48) and in roots (0.09–0.12) of *C. vulgaris*, the toxic effect of manganese (Fe/Mn<1.5) was found, resulting from excessive accumulation of this micronutrient. The symptoms of Mn toxicity are most often associated with plants growing on highly acidic soils (pH<5, Table 1). In the short-term assessment, the process of burning the heath in Tuchola adversely affected the value of the Fe/Mn ratio in *C. vulgaris*.

CONCLUSIONS

The heathland soils showed a strongly acidic reaction. Burning of the heath did not completely destroy the surface organic layer, and the largest losses of organic matter concerned layers A and B of the studied soil. In the short-term assessment, the fire did not cause statistically significant changes in active acidity and exchangeable acidity compared to the control area. The heathland soils were nutrient-poor, with phosphorus being the most deficient element. The acidic pH of soils (pH<5.0) limited the bioavailability of macronutrients to plants. In the short-term assessment, spring burning of the heath caused statistically significant differences in the content of N, P, K, Mg, Ca and Mn in the surface layer (A), N, P, K, Cu and Fe in the B layer and P, Mg, Cu and Fe in the C layer of the soil compared to the control area. The vital condition of *C. vulgaris* on the studied moor was poor. Many dead shoots and roots were found. The macronutrient content in live shoots and roots of *C. vulgaris* was very low, except for calcium. In the short-term assessment, burning of the heath caused statistically significant differences in the content of N, P, K, Mg, Zn, Cu and Mn in shoots ($p<0.01$) and Mn in roots ($p<0.05$), in comparison to the control area. The fire has changed the relationship between important nutrients in *C. vulgaris*. It caused statistically significant ($p<0.01$) changes in the values of N/P, K/Mg and Fe/Mn ratios in shoots compared to the control area.

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