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*Soil Chemistry*

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# POOLS OF AVAILABLE NUTRIENTS IN SOILS FROM DIFFERENT ALTITUDINAL FOREST ZONES LOCATED IN A MONITORING SYSTEM OF THE KARKONOSZE MOUNTAINS NATIONAL PARK, POLAND**

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*Abstract.* The aim of the paper was to assess the role of forest litter and mineral soil layers (0-10 and 10-20 cm) as stocks of plant-available macronutrients in the forested zone of the Karkonosze Mountains National Park, an area of forest decline at the end of 20th century. Soil samples were collected in 529 monitoring sites arranged in a 200x300 m grid. Concentrations of plant-available nutrients were much higher in the organic layer (forest litter) than in mineral soil layers, but calculated pools of available nutrients in the organic layer contributed to a lesser extent to their total pools. Those pools of nutrients stored up in the upper forest zone (1 000-1 250 m a.s.l.) proved to be significantly larger than those in the lower forest zone (500-750 m a.s.l.).

Forest decline, which in the 1970s affected spruce forests in the western and central European mountains, including the Sudetes and Karkonosze Mountains National Park, was one of the most serious ecological problems of that time [6, 23, 35]. Many theories were used to explain the phenomenon, and it became clear that there were several synergic factors acting simultaneously that made the trees less resistant to the combined effects of severe environmental conditions, anthropogenic pollution and pathogenic organisms, and which finally led to detrimental effects [23, 30, 31].

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**This study was carried out in the frame of monitoring system in the Karkonosze National Park.

For many years, the crucial role in forest decline was attributed to environmental pollution caused by industrial sources, in particular to acid precipitations and air-borne soil pollution with heavy metals. Therefore, many research projects were carried out to examine soil acidification, aluminum toxicity, and accumulation of trace elements in mountainous soils in various regions of Europe [16, 22], including the Sudetes [3, 8, 9, 15, 32]. It turned out, however, that neither soil acidification nor pollution with metals were fully responsible as the only factors responsible for tree decline. Another important soil feature that might have negatively affected tree health conditions was the insufficient supply of nutrients. Although nutritional requirements of protected, non-productive, forest stands are relatively low, it has been shown that nutrient deficiency may be a crucial stress factor, especially in sensitive mountain forest ecosystems [2, 13, 34, 35]. Deficiencies of phosphorus and potassium are likely to develop in later stages of forest growth [12].

The need to examine and monitor biotic and abiotic conditions of the area of Karkonosze Mountains National Park and to indicate their possible future changes, encouraged the Park authorities establish a comprehensive system of environmental monitoring [17]. The system consists of over 850 sites, situated both in a forested zone, and in subalpine zone, arranged in a 200x300 m grid, as shown in the Fig. 1. Soil monitoring is included as an integral part of environmental research. Basic soil properties: pH, organic matter, total nitrogen, bioavailable nutrients P, Mg and K, exchangeable Al, and selected heavy metals were selected as the main indicators of soil quality [17]. The budget of organic matter, total and mineral nitrogen, and sulphur were examined in selected locations and will be described separately.

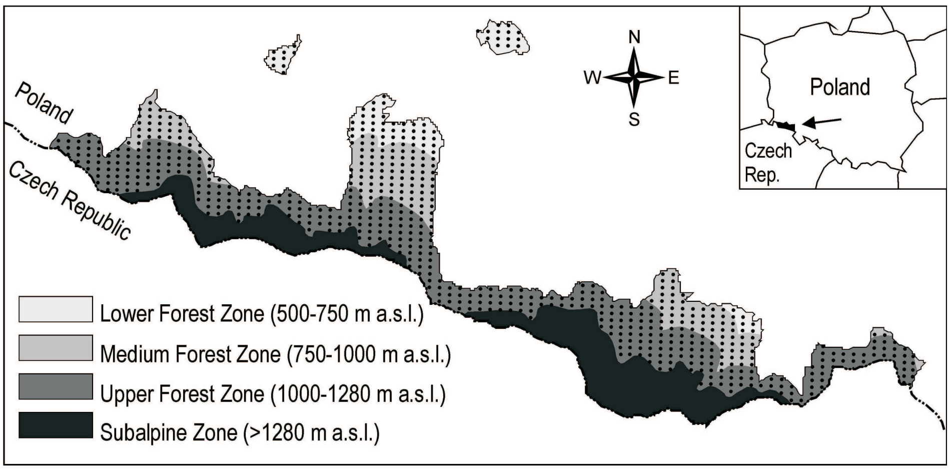


Fig. 1. Arrangement of monitoring sites and the ranges of altitudinal forest zones in the map of the Karkonosze National Park.

In this paper, we present the data on soil nutrient status, regarding plant-available forms of P, Mg and K. Special attention will be given to the role of organic layers in soil fertility, in distinguished 3 zones of forested area, with different ecological features and weather conditions [5], i.e.:

I. Upper forest zone UFZ (1 000-1 250 m a.s.l),

II. Medium forest zone MFZ (750-100 m a.s.l.),

III. Lower forest zone LFZ (500-750 m a.s.l.).

While the concentrations of bioavailable nutrients in soils are the parameters of essential ecological relevance for plants, the pools of nutrients are crucial from the standpoint of forest sustainability; therefore, both concentrations and pools of available nutrients were discussed.

## EXPERIMENTAL PROCEDURES

### *Soil sampling*

Soil samples were collected at 529 sites situated in the forested zone of the Park, together forming a monitoring system. The arrangement of the monitoring sites and the ranges of forest zones are shown in the map (Fig. 1). All sampling sites were divided between three groups, according to their altitudinal forest zones: UFZ, MFZ and LFZ (Table 1). Natural spruce (*Picea abies*) stands are typical of the upper mountain forest zone, whereas man-introduced spruce forests and mixed spruce and beech (*Fagus sylvatica*) are, respectively, the most abundant forest

TABLE 1. SITUATION AND BASIC FEATURES OF SAMPLING SITES

| Sampling sites | Forest zone and corresponding altitude | | |
|---|---|---|---|
| | LFZ 500-750 m a.s.l. | MFZ 750-1 000 m a.s.l. | UFZ 1 000-1 250 m a.s.l. |
| Number of sites | 77 | 194 | 258 |
| Surface coverage with rocks (%) | | | |
| - minimum - maximum | 5-70 | 5-95 | 10-98 |
| - mean | 26 | 31 | 51 |
| - geometric mean | 20 | 22 | 44 |
| - factor p | 0.26 | 0.31 | 0.51 |
| Thickness of forest litter (cm) | | | |
| - minimum - maximum | 1-11 | 2-12 | 2-15 |
| - mean | 5.0 | 5.2 | 6.5 |
| - geometric mean | 4.5 | 4.6 | 5.9 |

LFZ – lower, MFZ – medium, and UFZ – upper forest zones.

types in the medium and lower forest zones. In all sampling sites, the most important features of micro-relief were described, and the percentage of surface coverage by rock outcrops and stones was determined by simple visual estimation.

The samples were collected with split-tube samplers in order to minimize damage to the soil surface within the monitoring area. Sampling depth was based on the assumption that the most important pool of available nutrients would be concentrated in the surface soil layer, down to 20 cm. Therefore, mineral soil samples were taken from the depths 0-10 and 10-20 cm. In most cases, it turned out impossible to collect the samples from deeper layers because of shallow occurrence of large stones and unweathered rock.

The samples of organic layer (a forest litter) were collected if only the litter was present. The mean thickness of organic layer was assessed for each site.

*Laboratory analyses*

Soil samples were dried and homogenised prior to analyses. Basic soil properties: grain size distribution, organic matter content, and soil reaction $pH_{KCl}$ (in 1mol $dm^{-3}$ KCl, 1:2.5 m/v) were measured electrometrically. Particle-size distribution was determined by the sieve method (sand fraction) and by hydrometer method (silt and clay fractions). 'Plant-available' phosphorus and potassium (referred to in this text as 'available' forms of elements) were extracted with ammonium-lactate solution (Egner-Riehm method), and 'plant-available' magnesium was determined in $CaCl_2$ extraction (Schachtschabel method), as described by Ostrowska *et al*. [26] and Page [27]. The nutrient status of the soils was assessed according to the classification given by Kocjan [20], worked out for the Polish national forestry management.

*Further calculations and assessment*

The mean concentrations of nutrients in the 0-20 cm layer were calculated, on the basis of the thickness of particular layers (organic and mineral) and their assessed bulk densities. For this estimation, soil bulk density was reckoned as 0.15 g $cm^{-3}$ for surface organic horizons, 1.2 g $cm^{-3}$ for humus horizons (a 0-10 cm layer) and 1.3 g $cm^{-3}$ for deeper mineral horizons. Bulk density of deeper layers of organic soils, containing usually certain amounts of mineral components, was established as 0.3 g $cm^{-3}$.

Cumulative pools of nutrients M (g) accumulated in soil within each of soil layer, on the surface S (S = 1 $m^2$), were calculated as:

$$M\ (g\ m^{-2}) = C\ (g\ kg^{-1})\ S\ (m^2)\ d\ (cm)\ \sigma\ (g\ cm^{-3})\ (1-p)\ (1-r)\ /\ 100, \quad (1)$$

where: C stands for nutrient concentration (mg $kg^{-1}$), *d* - for the depth of soil layer, $\sigma$ – for soil bulk density, *p* – for the factor of soil surface coverage with rocks and stones, and *r* – for the contribution of skeleton in particular soil layer.

Additionally, for rough assessment of soil nutritional status, the mean concentrations of nutrients in the 40 cm surface layer were calculated and compared with the threshold values given by Kocjan [20]. For this purpose, basing on the study made in selected representative sites, the mean concentrations of nutrients in the 20-40 cm layer were taken on as 25% of those measured in the 10-20 cm layer, and the mean concentrations in soil, down to the depth of 40 cm (including forest litter) were calculated as weighted mean values.

For each of the three altitudinal forest zones distinguished in this study, the means and standard deviations SD of available nutrient concentrations (mg $kg^{-1}$ of soil) and nutrient cumulative pools (g $m^{-2}$) were calculated and discussed. Statistically significant differences between the distinguished groups of monitoring sites were determined at the significance level of 0.95%, using basic statistical analyses of variance and the Duncan test. Further analysis of relationships between the parameters characterizing soil nutritional status was performed with the PCA method (Principal Component Analysis). All statistical analyses were made with the Stat-Soft Statistica software, version 8.

## RESULTS AND DISCUSSION

### *General soil characteristics*

Soils in the Karkonosze Mountains developed from granite regoliths and therefore their texture is typical for weathered material of granite origin, and corresponds to loamy sands and sandy loams. Field observations confirmed that Dystric Cambisols (according to WRB classification [10]), not rarely with the features of podzolization, and locally also Podzols, were the most typical soil types for the LFZ (500-1 000 m a.s.l.). Stagnic Podzols occurred also in two upper zones, but there – in large areas – they were accompanied by shallow mineral soils classified as Leptosols or Regosols. Abundant were also soils with relatively deep organic layers, classified as Histic Leptosols, Histic Regosols or Histosols.

A characteristic feature of almost all sites was the occurrence of rocks or stones on the soil surface. The percentage of soil coverage with rocks and stone fragments ranged from 0 up to 98%, and generally tended to increase with the altitude. The mean value of surface coverage with rocks was estimated at 26% in the lower forest zone (LFZ), whereas the coverage of mineral soils in the UFZ was higher, in the range: 10-98%, with a mean value of 51% (Table 1).

Mineral soils contained an additionally high contribution of skeleton, particularly in their deeper mineral layers. A mean factor of skeleton contribution ($r$) tended to increase with the altitude and was estimated at the level: 0.1-0.2 for soil 0-10 cm layer, and 0.3-0.5 for the 10-20 cm layer of mineral soils (Table 1).

All soils examined in this study were strongly acidic, and their $pH_{KCl}$ ranged from 2.2 to 4.4. Soil pH tended to slightly increase down the soil profiles, and the lowest pH values were found in the forest litter, in particular at the sites situated in the UFZ. Strongly acidic soil reactions resulted undoubtedly both from natural factors (parent rock poor in basic components, climatic conditions, processes of organic matter transformation) and anthropogenic acidification caused mainly by long-lasting input of acidic precipitation. Such strongly acidic reaction may negatively affect soil nutrient management, by immobilization of soil phosphorus and accelerated leaching of magnesium and potassium [1, 24].

The mean content of soil organic matter (SOM) decreased, obviously, with increasing sampling depth (Table 2) and so did the concentrations of total nitrogen. The 0-10 cm layer was significantly richer in SOM and total nitrogen in the upper forest zone (UFZ) than in the medium and lower forest zones (MFZ and LFZ), which is a typical feature of mountain soils in Karkonosze [8, 17]. The mean values of the ratio C:N in the forest litter remained below 25, and ranged from 20.8 in UFZ to 24.8 in LFZ (Table 2). According to some authors [7, 11], these values indicate that the potential risk of nitrate leaching from soils should be considered, particularly in the upper forest zone. At the same time, however, the mean values of C:N ratio in the 0-10 cm and 10-20 cm soil layers remained in the range 11.0-16.1, typical for stable conditions of SOM transformation [8].

*Concentrations and pools of available P, K and Mg*

*Phosphorus*. Concentrations of plant-available phosphorus in soils varied in broad ranges: 10.6-143 mg $kg^{-1}$ in the forest litter, 1.8-73.0 mg $kg^{-1}$ in the 0-10 cm layer and 0.88-37.8 mg $kg^{-1}$ in the 10-20 cm layer (Table 3). The results obtained for all soils and soil depth groups, showed very high variability, confirmed by high values of standard deviations SD, in most cases above 30%, and often above 50% of the mean values (Table 3). Organic horizons contained significantly higher concentrations of available phosphorus, (as related to soil dry mass), than did mineral soil layers (Fig. 2a). The assessed mean concentrations of plant-available phosphorus in the 40 cm deep soil layer (Table 4) were in the range of moderate values, according to the guidance by Kocjan [20]; however, the mean data obtained for lower altitudinal forest zones (LFZ and MFZ) came quite close to the level of insufficient P availability (i.e. close to 12 mg $kg^{-1}$). This means that in some locations, the problem of phosphorus deficiency may really occur. Such a problem was described by many authors who examined mountain soils developed of granites and additionally affected by acidic precipitations [21, 25, 35]. There were no significant differences between phosphorus concentrations in the forest litter samples collected from various altitudinal zones, but the concentrations of available phosphorus in the 0-10 cm and 10-20 cm layers were significantly higher in the soils of upper zone (UFZ) than in lower zone (LFZ), as shown in the Fig. 2a.

TABLE 2. ORGANIC MATTER AND TOTAL NITROGEN CONTENT IN SOILS

| Values | Forest zone and corresponding altitude | | |
|---|---|---|---|
| | LFZ<br>500-750 m a.s.l. | MFZ<br>750-1 000 m a.s.l. | UFZ<br>1 000-1 250 m a.s.l. |
| Organic matter content in forest litter (g $kg^{-1}$ d.m.) | | | |
| - minimum - maximum | 496-911 | 484-929 | 347-966 |
| - mean | 788 | 771 | 785 |
| - geometric mean | 777 | 764 | 769 |
| Organic matter content in soil 0-10 cm layer (g $kg^{-1}$) | | | |
| - minimum - maximum | 63.5-387 | 71.5-298 | 67.1-790 |
| - mean | 131 | 157 | 304 |
| - geometric mean | 120 | 147 | 246 |
| Organic matter content in soil 10-20 cm layer (g $kg^{-1}$) | | | |
| - minimum - maximum | 36.7-248 | 33.3-178 | 28.9-261 |
| - mean | 77.5 | 76.9 | 112 |
| - geometric mean | 68.5 | 71.8 | 97.3 |
| Total content of nitrogen in forest litter (g $kg^{-1}$ d.m.) | | | |
| - minimum - maximum | 13.2-18.4 | 9.86-21.2 | 8.57-24.5 |
| - mean | 15.9 | 17.7 | 18.9 |
| - geometric mean | 15.8 | 17.4 | 18.7 |
| Total content of nitrogen in soil 0-10 cm layer (g $kg^{-1}$) | | | |
| - minimum - maximum | 3.74-9.00 | 3.17-13.6 | 1.28-19.9 |
| - mean | 5.74 | 6.79 | 9.46 |
| - geometric mean | 5.47 | 6.25 | 8.22 |
| Total content of nitrogen in soil 10-20 cm layer (g $kg^{-1}$ ) | | | |
| - minimum - maximum | 1.65-3.03 | 1.52-8.28 | 0.47-17.2 |
| - mean | 2.45 | 3.49 | 4.30 |
| - geometric mean | 2.40 | 3.24 | 3.39 |
| Calculated value of C:N (mean values) | | | |
| - forest litter | 24.8 | 21.8 | 20.8 |
| - soil 0-10 cm layer | 11.4 | 11.6 | 16.1 |
| - soil 10-20 cm layer | 15.8 | 11.0 | 13.0 |

Explanations as in Table 1.

TABLE 3. CONCENTRATIONS OF PLANT-AVAILABLE PHOSPHORUS, POTASSIUM AND MAGNESIUM IN SOILS

| Forest zone and altitude | Sampling depth (cm) | P | | | | K | | | | Mg | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | range | mean | SD* | CV** | range | mean | SD | CV | range | mean | SD | CV |
| | | (mg $kg^{-1}$) | | (%) | | (mg $kg^{-1}$) | | (%) | | (mg $kg^{-1}$) | | (%) | |
| LFZ 500-750 m a.s.l. | forest litter | 28.2-116 | 65.0 | 24.9 | 38 | 233-1134 | 494 | 267 | 54 | 78.0-171 | 127 | 26.1 | 21 |
| | 0-10 | 2.6-22.4 | 8.5 | 6.3 | 74 | 37.4-302 | 83.0 | 64.0 | 77 | 21.0-129 | 41.7 | 24.2 | 58 |
| | 10-20 | 1.76-14.9 | 4.5 | 3.4 | 76 | 8.3-105 | 34.0 | 22.2 | 65 | 7.0-36.0 | 21.1 | 7.1 | 33 |
| MTZ 750-1 000 m a.s.l. | forest litter | 10.6-143 | 54.6 | 26.1 | 47 | 67.2-905 | 389 | 353 | 39 | 27.0-1040 | 151 | 133 | 88 |
| | 0-10 | 2.6-42.7 | 12.9 | 12.6 | 98 | 7.5-429 | 108 | 86.3 | 80 | 7.0-171 | 47.6 | 28.3 | 53 |
| | 10-20 | 0.88-37.8 | 7.1 | 8.5 | 122 | 1.66-178 | 43.2 | 29.3 | 68 | 5.0-83.0 | 24.5 | 13.9 | 56 |
| UFZ 1 000-1 250 m a.s.l. | forest litter | 21.6-132 | 65.9 | 24.9 | 38 | 165-973 | 459 | 182 | 40 | 87.0-229 | 136 | 35.6 | 26 |
| | 0-10 | 1.8-73.0 | 22.7 | 13.0 | 56 | 29.9-463 | 209 | 136 | 65 | 23.0-195 | 83.6 | 52.3 | 62 |
| | 10-20 | 1.3-37.8 | 12.2 | 8.9 | 74 | 8.3-180 | 76.6 | 43.4 | 56 | 5.0-63.0 | 32.6 | 14.0 | 42 |

*SD – standard deviation, **CV – coeffficient of variation. Other explanations as in Table 1.

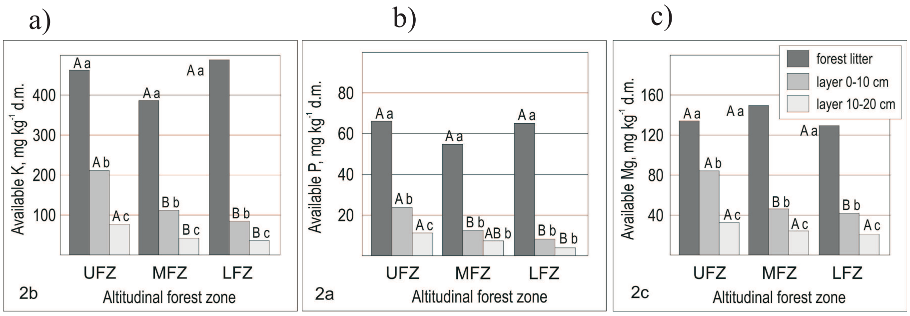


Fig. 2. Concentrations of available nutrients in the forest litter and in the 0-10 and 10-20 cm layers (mg kg$^{-1}$), as related to altitudinal forest zones: UFZ, MFZ and LFZ. Symbols A, B, C/a, b, c – homogeneous groups of Duncan's multiple range test at P<0.05 (A, B, C – comparison of mean values in particular soil layer between altitude forest zones; a, b, c - comparison of mean values between soil layers in one altitude forest zone): a) phosphorus, b) potassium, c) magnesium.

TABLE 4. ASSESSED AVERAGE CONCENTRATIONS OF PLANT-AVAILABLE PHOSPHORUS, POTASSIUM AND MAGNESIUM IN THE 40 cm LAYER FOREST SOILS, REFERRING TO THE THRESHOLD VALUES ACCORDING TO KOCJAN [20]

| Category of soil fertility | Reference concentrations of available macronutrient forms (threshold values) (mg kg$^{-1}$) | | |
|---|---|---|---|
| | P | K | Mg |
| Sufficient | >33 | >90 | >18 |
| Moderate | 12-33 | 50-90 | 6-18 |
| Insufficient | <12 | <50 | <6 |
| Forest zone and altitude | Average concentrations calculated for the 0-40 cm layer, mg kg$^{-1}$ | | |
| LFZ, 500-750 m a.s.l. | 12.,1 | 96 | 35 |
| MFZ, 750-1 000 m a.s.l. | 13.2 | 95 | 42 |
| UFZ, 1 000-1 250 m a.s.l. | 20.8 | 154 | 55 |

The pools of nutrients in upper soil layers, expressed in relation to the surface unit (1 m$^2$ or 1 ha), are important parameters that characterize system sustainability [18]. The data on the pools of available phosphorus accumulated in soil on the surface unit are presented in Fig. 3a. From the graph, we can obtain quite different picture illustrating the relative importance of forest litter and mineral soil layers (or deeper layers of organic soils) in building the pool of available phosphorus in soils. In spite of the fact that phosphorus concentrations (expressed in mg kg$^{-1}$) in the forest litter were much higher than those in mineral horizons, the pools of this element present in the litter remained either comparable or lower than the pools present in the underlying soil layers (Table 5, Fig. 3a). The highest pools of plant-available phosphorus, with the mean value of 1.79 g m$^{-2}$, were present in the

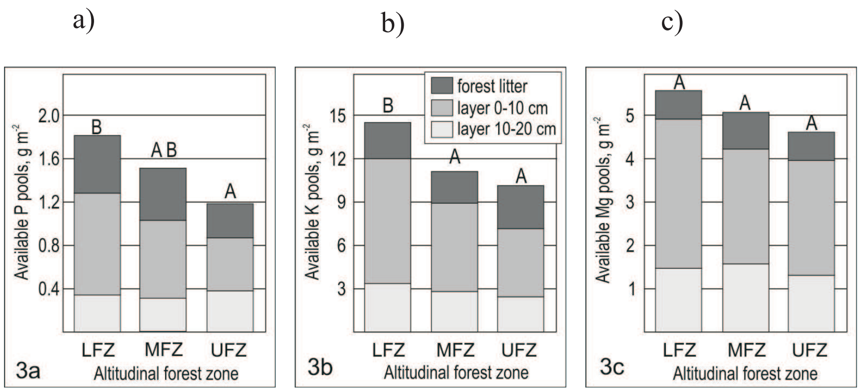


Fig. 3. Cumulative pools of available nutrients in soils, including forest litter and in the layers 0-10 and 10-20 cm (g $m^{-2}$), as related to altitudinal forest zones: UFZ, MFZ and LFZ. . Symbols A, B, C/ a, b, c – homogeneous groups of Duncan's multiple range test at $P<0.05$ (A, B, C – comparison of mean values in particular soil layer between altitude forest zones; a, b, c - comparison of mean values between soil layers in one altitude forest zone): a) phosphorus, b) potassium, c) magnesium.

soils of upper forest zone, despite the fact that soils in that zone have the lowest pH values and are exposed to the most intensive rainfalls likely to cause soil erosion. The 0-10 layers of soils in the UFZ are, however, rich in organic matter (Table 2), and relatively high pools of available phosphorus may be attributed to the presence of high amounts of humus. It should be stressed here that quite low mean pools of available phosphorus in medium and lower forest zones, calculated as 1.16 and 1.48 g $m^{-2}$ (corresponding to 11.6 and 14.8 kg $ha^{-1}$) may not be sufficient for optimal growth of trees, particularly in the spots of forest decline, where forest stands were restored in the 1980s and 1990s, and trees grow relatively fast.

*Potassium and magnesium*. The soils contained highly differentiated concentrations of available potassium, in the ranges: 67-1134, 7.5-463, and 1.7-180 mg $kg^{-1}$ in forest litter and in the 0-10, and 10-20 cm layers, respectively (Table 3). The concentrations of available K in forest litter were far much higher than those in the 0-10 cm, and 10-20 cm layers, and did not depend on altitudinal zone, as shown in the Fig. 2b. The concentrations of available K in the 0-10 cm, and 10-20 cm layers, compared between altitudinal zones, clearly showed the tendency to decrease with decreasing altitude, and were significantly higher in the upper zone (UFZ) than in medium and lower forest zones (MFZ and LFZ). All the relationships between the concentrations of available potassium in forest litter and mineral soil layers, in various altitudinal zones, were similar to those found for available phosphorus.

The pools of plant-available potassium accumulated in the upper soil layers on the surface unit also showed the same patterns as the pools of available phosphorus (Fig. 3b). The 0-10 cm soil layer appeared to be the largest reservoir of available

TABLE 5. POOLS OF PLANT-AVAILABLE PHOSPHORUS, POTASSIUM AND MAGNESIUM IN SOILS, DOWN TO 20 cm

| Forest zone and altitude | Sampling depth (cm) | P | | | | K | | | | Mg | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | range | mean | GM* | CV** | range | mean | GM | CV | range | mean | GM | CV |
| | | (mg $kg^{-1}$) | | (%) | | (mg $kg^{-1}$) | | (%) | | (mg $kg^{-1}$) | | (%) | |
| LFZ 500-750 m a.s.l. | forest litter | 0.16-0.64 | 0.36 | 0.33 | 38 | 1.28-6.24 | 2.72 | 2.43 | 54 | 0.43-0.94 | 0.70 | 0.69 | 20 |
| | 0-10 | 0.16-1.36 | 0.51 | 0.40 | 75 | 2.26-18.3 | 5.02 | 4.22 | 77 | 1.27-7.80 | 2.52 | 2.29 | 58 |
| | 10-20 | 0.12-0.98 | 0.29 | 0.24 | 76 | 0.54-6.85 | 2.23 | 1.88 | 65 | 0.46-2.36 | 1.38 | 1.30 | 33 |
| MTZ 750-1 000 m a.s.l. | forest litter | 0.06-0.76 | 0.29 | 0.26 | 48 | 3.35-4.78 | 2.05 | 1.86 | 39 | 0.14-5.49 | 0.79 | 0.68 | 88 |
| | 0-10 | 0.15-2.47 | 0.75 | 0.49 | 98 | 0.43-24.9 | 6.28 | 4.81 | 80 | 0.41-9.91 | 2.78 | 2.40 | 59 |
| | 10-20 | 0.06-2.38 | 0.44 | 0.27 | 121 | 0.10-11.2 | 2.71 | 2.13 | 68 | 0.31-5.21 | 1.54 | 1.33 | 57 |
| UFZ 1 000-1 250 m a.s.l. | forest litter | 0.10-0.63 | 0.32 | 0.29 | 38 | 0.79-4.65 | 2.19 | 2.03 | 40 | 0.42-1.09 | 0.65 | 0.63 | 26 |
| | 0-10 | 0.07-3.01 | 0.93 | 0.72 | 57 | 1.23-19.1 | 8.61 | 6.62 | 65 | 0.95-8.03 | 3.44 | 2.83 | 63 |
| | 10-20 | 0.06-1.69 | 0.54 | 0.39 | 74 | 0.37-8.03 | 3.42 | 2.82 | 57 | 0.22-2.81 | 1.45 | 1.31 | 43 |

*GM – geometric mean, **CV – coefficient of variation.

potassium, although its concentrations in this layer were much lower than those present in the forest litter. Soils in UFZ contained significantly larger pools of plant-available potassium, than did the soils in MFZ and LFZ. The mean pools of potassium calculated for distinguished altitudinal forest zones were in the range: 10.0-14.2 g $m^{-2}$ (corresponding to 100-142 kg $ha^{-1}$), and should be assessed as high or even very high. The mean concentrations of available potassium, assessed for a 40 cm layer of soil, were at the level of 154 mg $kg^{-1}$ in UFZ and 95-96 mg $kg^{-1}$ in two lower altitudinal zones, and therefore, fell in the range of sufficient soil fertility (Table 4). The soils developed from granite-type rocks are usually rich in potassium, although some authors [28] reported low values of available potassium in subalpine soils in the Karkonosze Mts. and explained this effect by relatively low weathering rate of granitic rocks combined with high intensity of base cations leaching from soils at low pH and high annual precipitation.

The trends, similar to those for potassium, were confirmed also for magnesium. The concentrations of available Mg in the forest litter varied in the range: 27-1040 mg $kg^{-1}$ and were statistically independent on altitudinal zone. The respective ranges of available Mg concentrations in the 0-10 cm and 10-20 cm soil layers were: 7-195 and 5-83 mg $kg^{-1}$ (Table 3). Clearly visible differentiation between all those three soil layers, was statistically confirmed (Fig. 2a). Comparison of available Mg concentrations in 0-10 cm soil layer of various altitudinal zones indicated significant difference between the upper forest zone (UFZ) and both lower zones (and did not differ from one another). It should be added, however, that similarly to the data obtained for phosphorus, also potassium and magnesium concentrations in all altitudinal forest groups and all layers, indicated high variability, and standard deviation values SD within those groups were usually higher than 30% of the mean (Table 3).

Mean concentrations of available Mg in the 0-40 cm layer were assessed as 55, 42, and 35 mg $kg^{-1}$ in UFZ, MFZ, and LFZ, respectively (Table 4); and were twice, or more than twice, as high as the threshold value for soil nutritional status referred to as sufficient. This observation does not correspond with conclusions drawn by several authors who indicated Mg deficiency as an important factor for poor forest conditions in recent decades, not only in the Karkonosze Mts. [28, 33], but also in other ranges of the Sudetes [14], and other European mountains [4, 19, 29]. Relatively high concentrations of available Mg in the 0-40 cm layer, presented in this paper, cannot be attributed to the fact that forest litter was considered a component of this layer, because its contribution to the total pools of available Mg was rather low, below 15%. The largest reservoir of Mg was, in fact, the 0-10 cm layer (Fig. 3c).

The mean pools of available magnesium, calculated separately for each altitudinal zone, were in the range 4.6-5.5 g $m^{-2}$ and did not significantly depend on the zone (Fig. 3c).

## DISCUSSION

Altitudinal and profile variability of available P and K in the forest soils of the Karkonosze Mts. appeared to follow similar patterns, and their concentrations strongly correlated (at $P<0.05$) with each other both in the forest litter and in the underlying soil layers (Table 6). Available Mg correlated positively with P and K in the 0-10 and 10-20 cm layers, but not in the forest litter. In lieu of this, the concentrations of available Mg in the forest litter correlated with pH, and tended to increase with increasing pH values. For available forms of all nutrients, significant correlations were found between their concentrations in the 0-10 cm layer and the content of the SOM in that layer (Table 6).

TABLE 6. CORRELATION COEFFICIENTS BETWEEN THE CONCENTRATIONS (mg kg$^{-1}$), OF AVAILABLE NUTRIENTS IN SOILS AND CRUCIAL SOIL PARAMETERS, CALCULATED SEPARATELY FOR FOREST LITTER AND 0-10 AND 10-20 cm SOIL LAYERS

| Para-meter | Concentrations in forest litter (mg kg$^{-1}$) | | | Para-meter | Concentrations in 0-10 cm soil layer (mg kg$^{-1}$) | | | Para-meter | Concentrations in 0-10 cm soil layer (mg kg$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | P_0 | K_0 | Mg_0 | | P_10 | K_10 | Mg_10 | | P_20 | K_20 | Mg_20 |
| K_0 | 0.61* | x | x | K_10 | 0.63* | x | x | K_20 | 0.51* | x | x |
| Mg_0 | 0.11 | 0.13 | x | Mg_10 | 0.49* | 0.86* | x | Mg_20 | 0.50* | 0.66* | x |
| OM_0 | -0.19 | -0.12 | 0.03 | OM_10 | 0.19* | 0.31* | 0.29* | OM_20 | 0.04 | 0.15* | 0.07 |
| pH_0 | 0.04 | 0.03 | 0.46* | pH_10 | -0.07 | -0.11 | -0.07 | pH_20 | -0.18* | -0.13 | -0.07 |

Correlations significant at $P<0.05$ are printed bold and marked with asterisks.

Principal component analysis (PCA) confirmed that 79.7% of variability was caused by a single, common factor (Fig. 4). We can guess that the factor, crucial for governing the amounts of available nutrients and their distribution in soils, should be the SOM content. This judgment has been proved by very high Pearson correlation coefficients between the concentrations of available P, K, and Mg in the soils and the content of organic matter (calculated for the whole database), the values of which were: R = 0.65, 0.68, and 0.55, respectively. This observation seems to be of essential importance for planned reconstruction and management of degraded systems in the Karkonosze Mts., which undoubtedly should consider the need for conservation and restoration of SOM.

Interpretation of the second component, which contributed to almost 15% of the variability in nutrient concentrations, is not similarly clear and cannot be precisely defined. Therefore, further analyses will be required to decide whether this component should be attributed to soil characteristics (such as soil pH), to natural geochemical features of elements, or to anthropogenic impacts.

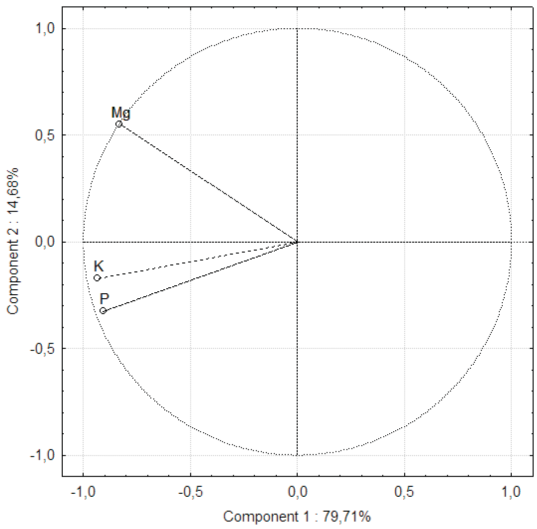


Fig. 4. Biplot of PCA on available phosphorus P, potassium K, and magnesium Mg in all samples examined.

## CONCLUSIONS

1. Comparison of nutritional status of soils in the three distinguished altitudinal zones indicates that the pools of available nutrients: P and K are, in the upper forest zone (over 1 000 m a.s.l.), significantly higher than in the lower forest zone (below 750 m a.s.l.), with the pools in the medium forest zone falling in-between. The pools of available Mg appear not to significantly depend on the altitude.

2. The soils examined in this study contain relatively low amounts of available P, and deficiency of this macronutrient may occur in some forest stands, particularly in the lower and medium altitudinal zones (below 1 000 m a.s.l.).

3. Forest litter in the area of the Karkonosze National Park, has much higher concentrations of plant-available macronutrients than do underlying 0-10 and 10-20 cm soil layers. Nevertheless, the role of forest litter in making up soil nutrient status should not be overestimated, as the pools of nutrients in the forest litter remain much lower than those in the underlying soil. The 0-10 cm soil layer makes up the largest reservoir of nutrients.

4. Nutritional status of soils, particularly in their 0-10 cm layer, showed a dependence on organic matter content and pH. The concentrations of available P and K in this layer strongly correlated with each other and apparently depended on soil OM, whereas the concentrations of available Mg in forest litter were governed mainly by soil pH.

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## ZASOBY PRZYSWAJALNYCH FORM MAKROSKŁADNIKÓW W GLEBACH LEŚNYCH RÓŻNYCH STREF WYSOKOŚCIOWYCH W SYSTEMIE MONITORINGU KARKONOSKIEGO PARKU NARODOWEGO, POLSKA

W pracy przedstawiono znaczenie ektopróchnicy oraz mineralnych warstw gleby: 0-10 i 10-20 cm w tworzeniu zasobów przyswajalnych dla roślin form makroskładników w glebach strefy leśnej Karkonoskiego Parku Narodowego, dotkniętej w końcu XX wieku masowym wymieraniem drzewostanów. Próbki gleb pobrano w 529 punktach monitoringowych rozmieszczonych w siatce 200x300 m. Stężenia przyswajalnych form makroskładników były znacznie wyższe w warstwie organicznej (ektopróchnicy) niż w warstwach mineralnych, ale zasoby przyswajalnych makroskładników zgromadzonych w warstwie organicznej stanowiły znacznie mniejszy udział w całkowitej puli tych składników zgromadzonej na jednostkowej powierzchni. Zasoby te zgromadzone w glebach górnej części regla górnego (1 000-1 250 m n.p.m.) okazały się istotnie większe niż w strefie regla dolnego (500-750 m n.p.m.).