MACRONUTRIENT ACCUMULATION AND RELATIONSHIPS IN A SCOTS PINE (*PINUS SYLVESTRIS* L.) ECOSYSTEM ON RECLAIMED OPENCAST LIGNITE MINE SPOIL HEAPS IN CENTRAL POLAND[1]

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Abstract: The aim of this study was to determine the sources, accumulation rate and relationships between macronutrients in reclaimed mine soils (RMS) and aboveground plant biomass on external slopes of lignite mines in central Poland. The study was conducted on two different types of sites with 10-year-old Scots (*Pinus sylvestris L.*) pine stands located on Quaternary loamy sands (QLS) and on Tertiary acidic carboniferous sands following neutralisation (TCS). The control plot was located in the same vicinity on an external slope in a natural pine ecosystem on a Haplic Podzol in a young mixed coniferous forest habitat (NPE). The nutrient resources, apart from N, were higher in RMS than in comparable Haplic Podzols, however, N primarily accumulated in the mineral horizons. In forest soils, the main macronutrient resources were accumulated in organic horizons, which in natural soils of coniferous forest habitats constitute the main source of nutrients. The proportion of individual macronutrients accumulated in the biomass vs. pools in soil was much lower on the external slope RMS than in the natural site, which in view of the potential richness of RMS, indicated poorer sorption and utilization of macronutrients in aboveground plant biomass than in natural habitats. Other important linear correlations (p=.05) were found between the sources of nutrients in RMS and elements accumulated in biomass (most clearly in case of K, Ca and Mg), which indicates important relationships between soil and vegetation in the first stages of ecosystem development as stimulated by reclamation.

Additional Key Words: reclamation, Scots pine, ecosystem, macronutrients.

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Introduction

As is true in many contemporary environmental problems, the rehabilitation of a drastically disturbed terrestrial system, such as lands mined for recovery of coal and minerals, requires site-specific knowledge to ensure the reclamation strategies chosen will be sustainable (Wali and Freeman, 1973; Krzaklewski, 1982; Daniels et al., 1992; 1996, 1999; 2001; 2002; Wali, 1999; West and Wali, 2002; Bradshaw and Chadwick, 1980, Bradshaw and Hüttl, 2001; Urbanska et al., 1997; Wali, 1999; Hüttl and Weber, 2001, Pietrzykowski, 2006; Pietrzykowski and Krzaklewski, 2007 a, b). In central Europe, a large proportion of post-mining landscapes are reclaimed to forest.

From an ecological point of view, reclamation is a process of restoring the whole ecosystem (Bradshaw and Hüttl, 2001). The ecosystem, according to the traditional definition (Golley, 1993 after Tensley A. G., 1935), should consist of an integrated system of biotic and abiotic elements where all the trophy layers contain a complete set of species ensuring the circulation of matter and energy flow. A complete assessment of the reclamation processes should take into consideration many ecological factors (Rodrigue et al., 2002). It is therefore important to determine the soil development rate including the depth of organic horizons, nutrient accumulation rates, balance of elements (Bradshaw, 1983; Daniels et al., 1992; Li and Daniels, 1994; Bendtfeldt et al., 2001; Schaff, 2001) and plant community development. Plant community parameters should include the number of species, biodiversity of communities, and the proportion of species characteristic of forest and non-forest communities (Jochimsen, 1996; Pietch, 1996; Wiegleb and Felinks, 2001).

Chemical compound pools (mineral and organic substrates) are the inanimate elements of the ecosystem (the biotope), whereas plant and animal communities are considered the animate elements of the ecosystem (biocenosis) (Odum, 1971). In the course of reclamation treatment, all the factors which affect the functionality of the ecosystem are developed from essentially zero such as in primary succession (Wali and Freeman, 1973; Wali 1999). Creation of conditions for efficient circulation of matter and energy flow between the biotope and the biocenosis determines the success of the reclamation treatment which stimulates the process of ecosystem restoration (Bradshaw and Hüttl, 2001). However, the key question is when the restored biological systems cycle nutrients at rates that meet their demand without compromising their productivity (Bell, 2001; Bradshaw and Hüttl, 2001; Bendtfeldt et al., 2001; Knoche et al., 2002, Pietrzykowski and Krzaklewski 2007 a).

The stand of trees is an element within animate forest ecosystems which most distinctly modifies their microclimate, light and biochemical conditions for other organisms undergoing succession. The condition and growth of stands of trees introduced to reclaimed areas directly depend on the capacity of substrates (parent rock) and the developing soil to meet the nutrient requirements which gradually increase along with the growth of biomass. There are differences between ecosystems restored on post-mining sites and natural forest ecosystems (Bell, 2001; Daniels et al., 1992; Schaff, 2001) and they include a disturbed element circulation cycle, and low percentage of organic matter developed *in situ*. These conditions can significantly limit the pool of available elements for nutrient cycling in tree stands (Baule and Fricker, 1970), and these cycles are also occasionally limited by direct acid-metal phytotoxicity in reclaimed mine soils (RMS).

The aim of this work was to (1) determine the sources of soil macronutrient elements: C; N; S; P; K; Ca; Mg; Na, and (2) to determine relationships between total and available forms in RMS and (3) their accumulation in the biomass of approximately 12-year-old pine stands growing in the KWB 'Bełchatów' (in central Poland) reclaimed opencast lignite mine spoil heap. The study was conducted on stands of pine trees since the Scots pine (*Pinus sylvestris* L.) is one of the main species introduced when reforesting post-mining sites in central Europe (Baumann et al., 2006) due to its low habitat requirements and pioneering character (Fober, 1993).

Materials and methods

Study site

The study was conducted in the top portion of an opencast lignite mine spoil heap, 'Bełchatów', in central Poland (N 51 13.196; E 19 25.569). The spoil heap ranged in height from 120 to 180 m and covers an area of 1480 ha; including slopes (embankments and shelves) of 1165 ha, and a summit portion of 318 ha. Climate in the area is transitional and changeable due to clashes between polar maritime air masses and polar continental air masses. The average annual temperature is 7.6^{o}C; the annual amplitude is 21^{o}C; the growing period lasts 200 − 210 days, and total precipitation is 580 – 600 mm (Woś, 1999). The site is located mostly on a mixture of Quaternary loamy sands, and sand with gravel, which occasionally consists of loam, bouldery clay and clay. There are also areas of Tertiary sandy strata with loam and clay, frequently carbonated and sulphurised, which are very acidic, displaying phytotoxic properties (Katzur and Haubold-Rosar, 1996; Krzaklewski et al., 1997). The reclamation treatment on the top portion of the spoil heap consisted of NPK mineral fertilisation (N − 60, P − 70 and K – 60 kg·ha^{-1}), and sowing a mixture of grass and leguminous plants (50 − 60 kg·ha^{-1}). The tertiary pyritic strata was earlier neutralised with bog lime incorporated into the surface horizon to a depth of 40 cm (Krzaklewski et al., 1997). The area was later reforested mainly with 50% Scots pine (*Pinus sylvestris* L.) and 30% common birch (*Betula verrucosa* Ehrh.). The predominantly 1-year-old seedlings were planted on a 0.7 m length × 1.5 m width spacing (Krzaklewski et al., 1997).

Field studies and laboratory analyses

The study plots (10×10 m) were located in approximately 12 to 17-year-old stands of pines on the top portion of the spoil heap (4 replications for each variant): one on the potentially fertile Quaternary loamy sand (QLS) and two on Tertiary carboniferous and pyritic sand following neutralisation (TCS). The control plot (NPE) was located in a forest in the vicinity of the spoil heap in a 17-year-old stand of pine trees, in a mixed coniferous forest habitat, ideal for this species.

Dendrometric measurements of the tree stands were made including diameter of trees at the root collar, diameter at a height of 1.3 m (i.e. DBH) and their overall height (h). Later, 35 study trees were selected proportionally to their diameter, and were cut down and weighed (the branches were weighed separately) and their foliage was tested. Foliage samples were taken to determine water content and elemental composition in the laboratory. Next, 22 tree root systems were excavated, the diameter at the root collar was measured, as were the maximum horizontal and vertical range of the roots. Roots were weighed leter. Woody tissue was sampled to determine water content and elemental composition. The measurements and the obtained data were used to develop empirical equations to determine the aboveground tree biomass and root systems on the spoil heap [Mg·ha^{-1}] (Socha, 2006; unpublished data). Fine roots less than 2 mm in diameter were assessed using cylinders (250 cm^3) for sampling in 3 replications at three depths (0 – 8, 8 – 50 and 50 – 110 cm) from one plot per each variant on the spoil heap. In the lab, the samples were rinsed, dried and the roots were weighed. The aboveground biomass of the herbaceous vegetation was determined using the harvest method at the peak of the vegetation period, from 1×1 m squares in 3 replications located diagonally on each study plot. Next, herbaceous vegetation was sampled to determine water content and elemental composition in the lab.

In the course of the soils study, a 110-cm soil pit was dug in the spoil heap and another 150 cm pit in the control plot was dug, and soil morphology was described. To determine volumetric density, samples of intact structure were collected into 250 cm^3 cylinders in 3 replications for each horizon. Apart from soil pits, 3 bore holes were made in each plot with soil drills (from Eijkelkamp) and mixed samples were collected to determine the content of elements and other physical and chemical soil properties from depths of: 0 - 8 cm (organic mineral horizons displaying some features of parent rock AiC); from 8 – 50 cm, and from 50 -110 cm (parent rock horizons C). Samples of the organic horizon (raw humus – L/Of) were collected in autumn after the vegetation period from 1×1 m plots in 3 replications from each plot; the mass was assayed on the spot and mixed samples were collected for lab tests.

In the laboratory, soil samples were dried and screened with a 2 mm screen, and samples from the L/Of horizon were ground after drying. The following factors were determined in the soil samples: particle size distribution using areometrical method, pH potentiometrically in H_20 and in 1M KCl (1:2.5 ratio); organic carbon (C_{org}) and total sulphur (S_t) content using the infra-red absorption method, and total nitrogen (N_t) using the thermal conductivity method with the 'Leco CNS 2000' analyser; basic exchangeable cations Na^+, K^+, Ca^{2+}, Mg^{2+} in 1 M NH_4Ac by AAS detection; the content of total elements: Na, Mg, Ca, K after digestion in the mixture of HNO_3, (d=1.40) and 60% $HClO_4$ acid in 4:1 ratio using the AAS method. Phosphorus (P) in a form assimilated by plants was assayed using the Egner-Riehm method in calcium lactate extract ($(CH_3CHOHCOO)_2Ca$) acidified with hydrochloric acid to pH 3.6 and in total form using the molybdate blue colorimetry method from extracts in $HClO_4$ (Ostrowska et al., 1991; Van Reeuwijk, 1995). Soil subtypes were defined according to FAO (1988) taxonomy.

In mixed samples of Scots pine needles and herbaceous vegetation from the undergrowth (one sample for each study plot) the C, N, S content was assayed on the 'Leco CNS 2000' analyser; Na, K, Ca, Mg after digestion in the mixture of HNO_3, (d=1.40) and 60% $HClO_4$ acid in a ratio of 4:1 using the AAS method and P using molybdate blue colorimetry from an extract in 60% $HClO_4$ (Ostrowska et al., 1991).

The results, i.e., the total pools of elements in soil, were statistically analyzed using the *Statistica 6.1* programme. Differences between mean values of features from two independent groups (QLS and TCS) were tested. Distributions were compared to normality using the Shapiro-Wilks test. Next, to compare mean values of features in two variants, a t-student test was applied for independent variables (p=0.05). Correlations between sources of elements in available and exchangeable forms in soil versus accumulation in aboveground community biomass (p=0.05) were also tested.

Results and Discussion

Soil characteristic on the spoil heap

In the top portion of the spoil heap the soils were classified as Urbic Anthrosols with initial development of organic OL/f horizons which produced semi-mor-type humus at the development stage with raw humus and a thin layer of initial transitional organic-mineral horizons reflecting the features of the parent rock (AiC). In both soil types (QLS and TCS), rock type was mixed due to non-selective dumping of the rock cap. In QLS, soils developing from these strata exhibited predominantly sandy clay textures with an average of 28 % silt and 4 % clay. They were also sometimes interbedded with clay (43 % silt fraction and 9 % clay fraction) or sand. The soil bulk density averaged 1.67 g/cm^3. In the TCS soil profile, there were remains of bog lime which had been used as a neutraliser. Soils developing on these strata exhibited lighter and more varied sandy textures, sometimes grading to loamy sand. The bulk density of the strata averaged 1.68 g/cm^3. In the control plot in the neighboring forest ecosystem, the soil was a Haplic Podzol formed on fluvioglacial sandy strata with only up to 1 % silt and up to 5 % clay.

In the reclaimed areas features such as texture, soil cohesion and the neutralisation depth of toxically acidic strata determined the depth to which root systems occurred (Fabijanowski and Zarzycki 1969; Anderson, 1977; Daniels et al., 1992). The depth to which root systems occur controls the zone of influence of living organisms and organic compounds (Bednarek and Prusinkiewicz, 1997). In QLS, roots ranged to 70 cm in depth and in TCS roots penetrated to 50 cm. In those habitats, a marked flattening and deformation of pine root systems was observed. In natural conditions pines develop a typical taproot system. In the natural Haplic Podzol, the roots reached a depth of 90 cm, and has been reported that roots of pine trees in natural conditions often reach a depth of several metres (Obmiński, 1970).

The spoil heap pH in quaternary strata was neutral or alkaline and pH_{KCl} averaged 7.3 and pH_{H2O} was 7.6. In organic OL/f horizons, the pH was clearly acidic (4.1 pH_{KCl} and pH_{H2O} 4.4) which was due to the acidifying impact of organic litterfall under pine trees (Obmiński, 1970).

Soils on tertiary strata following neutralisation displayed a different pH stratification in the soil profile. The highest pH occurred in the 0 − 8 cm layer of AiC horizon and averaged 5.7 pH_{H2O} and 4.9 pH_{KCl}. Deeper, there was a decrease in pH to as low as 3.0 pH_{H2O} and 2.7 pH_{KCl}. Sometimes higher content of bog lime resulted in pH_{H2O} of up to 7.8 and pH_{KCl} up to 7.4. It indicated considerable micro-habitat variability in this type of plot. In natural soil, the lowest pH (4.3 pH_{H2O} and 3.5 pH_{KCl}) occurred in organic-mineral horizons with podzol features (AEes).

In the spoil heap, soil TEB (Total Exchangeable Bases) in QLS averaged from 26.5 to 27.6 $cmol(+)·kg^{-1}$, and CEC (Cation Exchange Capacity) from 27.0 to 28.0 $cmol(+)·kg^{-1}$ (only in organic OL/f horizon did it increase to 55.2 $cmol(+)·kg^{-1}$). The highest TEB in mineral horizons (up to 35 $cmol(+)·kg^{-1}$) was related to higher ratios of sandy clays with up to 9 % clay. In TCS, TEB was much lower and ranged from 2.3 to 4.7 $cmol(+)·kg^{-1}$, whereas CEC ranged from 5.0 to 5.8 $cmol(+)·kg^{-1}$. Also in this variant, organic OL/f horizons exhibited the best exchange potential which is connected with excellent soil organic matter (SOM) exchange properties (Ellerbrock et al., 1999).

Community biomass

Terrestrial ecosystems consist of above- and belowground components and their impact on one another is crucial for circulation of matter and energy flow (Odum and Odum, 2003; Wardle et al., 2004). Accumulation of elements in soil in the course of soil development processes, and especially the SOC sequestration potential in RMS, depends on the amount of biomass production and return to soil, and mechanisms of C protection (Shrestha and Rattan, 2006).

The aboveground plant community biomass in QLS averaged 51.9 $Mg·ha^{-1}$, and in TCS it averaged 11.3 $Mg·ha^{-1}$. These differences mainly resulted from the age and stage of development of the pine trees and not from habitat conditions. However, a 19-year-old pine tree on loamy quaternary sand in QLS had a 1.5 X larger biomass than a 17-year-old pine tree in the control plot (Table 1).

Table 1. Biomass of individual components of the pine ecosystem on the top portion of 'Bełchatów' lignite mine spoil heap and in fresh mixed coniferous forest habitat.

Variant of site	Biomass (dry biomass [Mg · ha $^{-1}$])					
	Total aboveground biomass	Roots[1]	Herbaceous and shrubs	Trees	Wood[2]	Foliage
QLS	51.876 (12.436)	6.570 (1.057)	0.134 (0.085)	51.741 (12.454)	43.535 (10.693)	8.206 (1.770)
TCS	11.275 (2.998)	2.790 (0.298)	0.033 (0.008)	11.242 (3.005)	9.072 (2.540)	2.170 (0.465)
Control NPE	35.813	7.132	0.152	35.661	31.863	3.798

Explanations: 394 (156) - mean (SD); [1] in natural stand (NPE) community root biomass assumed to be 0.2 of wood biomass (according to Lieth and Whittaker, 1975; Miller et al., 2006); [2] - wood: large timber and branches of trees with DBH > 7cm.

In the forest site and in the investigated spoil heap communities, stands of trees constituted the main component of aboveground biomass while the percentage of herbaceous vegetation did not exceed 0.3 - 0.4 %. Compared to the total aboveground tree stands biomass, the root biomass amounted to 13% in QLS, and 25% in TCS, whereas the foliage biomass was 15 and 19 % respectively. Although the foliage comprised a small share of standing tree biomass, it made up a considerable part of annual icremental biomass production, frequently equal to that of woody tissue (Assmann, 1970). The typical aboveground tree biomass in forests of the temperate zone has been estimated at 21 Mg·ha^{-1} (approx. 30-year-old stands of trees) and 170 Mg·ha^{-1} (50-year-old stands of trees) (Krebs, 2001). In natural conditions on the Polish lowlands, the reported biomass of age group 1 (up to 20 year-old) stands of pine trees on average amounted to 50 Mg·ha^{-1}, but in the next age group it increased by nearly two-fold (Orzeł et al., 2005). For four 17-year-old stands of pine trees on a reclaimed sand pit (in southern Poland) the biomass amounted to 25 Mg·ha^{-1} (Pietrzykowski, 2005). So far, the tree biomass on the spoil heap has reached values which were close to natural conditions, and in the case of QLS, the biomass of 19-year-old stands of pine trees was higher than the control plot biomass. Very dynamic growth of the aboveground pine tree biomass on reclaimed soil was also reported in the Lusatian Mining District (Hüttl and Weber, 2001). However, their data set refers to the first generation of stands of trees in age group 2 (i.e. not exceeding 40 years of age). It is currently difficult to predict whether the cycling of nutrient elements will be intensive enough and whether a self-sustainable ecosystem will develop with such growth of aboveground tree biomass in post-mining sites (Knoche et al., 2002).

Macronutrient accumulation in soil

Low content of organic matter and related low total nitrogen and organic carbon accumulation are the common limiting features of reclaimed mine soils (RMS) (Bendtfeld, et al., 2001). Soil organic matter is especially important in determining other qualities of mine soils (Anderson, 1977; Roberts et al., 1988; Li and Daniels, 1994; Ellerbrock et al., 1999; West and Wali, 2002). Total accumulation of organic carbon (C_{org}) in both types of soils was similar and averaged over 54.0 Mg·ha^{-1} (Table 2). The values were nearly 1.5-fold lower than the natural soil in the control plot where C_{org} accumulation in the entire profile (up to 150 cm) exceeded 75.5 Mg·ha^{-1}. In organic (O) and organic-mineral (AE) horizons of the podzol developed on fluvioglacial sands under forest, C_{org} accumulation ranged from 76.0 to 122.0 Mg·ha-1. Carbon translocated to the enrichment horizon (B) should be added to this amount (the calculations have been made for Polish lowland habitat conditions on the basis of the Atlas of Polish forest soils; Brożek and Zwydak, 2003).

Nitrogen (and phosphorus) is one of the most deficient elements in reclaimed sites (Marrs and Bradshaw, 1993; Daniels et al., 1999). In the spoil heap soils of former lignite mines developing on tertiary carboniferous sands, geological carbon in the form of lignites often occurs and complicates soil C analysis. Therefore, the C and N accumulation rate in the deeper horizons of the spoil heap soils, especially in case of TCS, may actually be overestimated. Although total N accumulation increases in the course of soil development in mine soils, both in those undergoing reclamation treatment and those where natural succession is taking place (Anderson, 1977, Wali, 1999; Daniels et al. 1999; Pietrzykowski and Krzaklewski, 2007 b), it has been found that the average annual accumulation of N fluctuates and may change with the age of soil and vary by community type introduced in reclamation seedings (Anderson, 1977). Moreover, N accumulation is much less dynamic than carbon accumulation (Wali, 1999). Also, in soils where primary succession takes place, N is gradually mineralised (Marrs and Bradshaw, 1993) which may be deficient for rapidly growing young trees in reclaimed areas which require a lot of N over time (Hüttl and Weber, 2001). Total accumulation of N_t in QLS soils was on average 5.0 Mg·ha^{-1}, and therefore 1.5-fold higher than in TCS soils where it amounted to 3.0 Mg·ha^{-1}. In comparable natural soils, N accumulation was much higher at 11.0 Mg·ha^{-1}.

Table 2. Pool in the soil and accumulation of elements in the biomass in pine ecosystems on the top portion of 'Bełchatów' lignite mine spoil heap.

Element [Kg·ha^{-1}]	In soil		In biomass (aboveground dry biomass)			
	Organic horizon (OL/f)	Organic-mineral and mineral horizons (AiC and C)	Herbaceous and shrubs	Wood[1]	Needles	Total [2]
	Variant: QLS					
C	1592.9 (745.0)	52709.2 (42213.2)	52.60 (34.88)	23700.7 (4803.3)	4492.0 (710.2)	28245.3 (5497.3)
N	19.1 (8.5)	5021.2 (1247.2)	2.61 (2.19)	26.6 (5.4)	87.5 (17.1)	116.7 (21.4)
P	1.8 (1.0)	27.4 (17.6)	0.24 (0.16)	6.2 (1.3)	9.5 (1.6)	15.9 (2.8)
K	3.9 (2.2)	883.6* (269.6)	3.76 (1.83)	29.8 (6.0)	49.6 (11.1)	83.2 (16.7)
Mg	2.5 (1.4)	1288.9* (215.0)	0.33 (0.19)	11.0 (2.2)	9.0 (1.2)	20.3 (3.05)
Ca	27.3 (14.2)	94899.9* (12721.1)	2.99 (2.23)	42.2 (8.5)	19.4 (2.7)	64.6 (10.3)
Na	0.1 (0.1)	135.0* (24.0)	< 0.00	0.82 (0.17)	0.25 (0.28)	1.1 (0.42)
S	1.5 (0.9)	4890.2 (3069.5)	0.74 (0.72)	1.6 (0.4)	35.3 (7.7)	37.6 (8.5)
	Variant: TCS					
C	1263.9 (344.6)	53479.6 (27301.3)	13.56 (3.11)	5925.3 (2283.3)	1411.2 (438.3)	7350.1 (2717.7)
N	15.0 (3.2)	3042.5 (1226.0)	0.29 (0.05)	6.7 (2.6)	31.9 (10.3)	38.9 (12.5)
P	1.8 (0.1)	27.6 (4.7)	0.02 (0.00)	1.6 (0.6)	3.2 (1.1)	4.8 (1.7)
K	2.7 (0.6)	329.1* (45.6)	0.44 (0.06)	7.4 (2.9)	20.1 (6.8)	27.9 (9.6)
Mg	2.5 (0.3)	308.2* (140.9)	0.03 (0.01)	2.8 (1.1)	2.4 (0.8)	5.2 (1.9)
Ca	29.6 (7.4)	9778.1* (3215.4)	0.16 (0.08)	10.5 (4.1)	9.4 (3.5)	20.1 (7.5)
Na	0.12 (0.03)	95.04* (8.90)	< 0.00	0.2 (0.1)	0.04 (0.03)	0.24 (0.10)
S	1.3 (0.2)	4914.0 (2376.6)	0.02 (0.01)	0.3 (0.1)	10.8 (5.0)	11.1 (5.1)

Explanations: 19.1 (8.5) - mean (SD); n = 4 (number of plots in variant); [1] - wood biomass of trees with DBH > 7cm; [2] – total element's accumulation in aboveground biomass (trees, herbaceous and shrubs biomass), *differences for soil element's resource are significant at $p = 0.05$ level (T-student test).

The highest accumulation of exchangeable Ca^{2+}, Mg^{2+}, K^+, Na^+, and available P in mineral horizons took place in QLS on Quaternary strata, and in all cases (except for sulphur) it was considerably higher (p=0.05) than in TCS (Table 2). High S accumulation (S_t), reaching 4.9 $Mg \cdot ha^{-1}$, was related to the properties and origin of spoil heap strata. Soils developing on Tertiary carboniferous and pyritic strata may contain more than 1 % S and are referred to as 'sulphurous mine soils' (Katzur and Haubold-Rosar, 1996). The nutrient resources accumulated in mineral horizons of a comparable natural podzol were much lower than in QLS with Ca^{2+} = 132; Mg^{2+} = 42; K^+ = 16; P = 1.4; and Na^+ = 2.5-fold lower, respectively, than in TCS with 13; 10; 6; 1.3; and 1.7-fold, respectively. According to a habitat classification based on the Soil Quality Index used in forestry in Poland (Brożek and Zwydak, 2003), QLS soils could be even classified higher than natural deciduous forest sites (eutrophic). The accumulation ratio of individual elements in mineral horizons (up to 110 cm depth) and in organic horizons - raw humus layer OL/f in RMS and Ol + Olf in Haplic Podzol) (MH_{BA} : OH_{BA}) (Table 3) constituted a major difference in the distribution of elements accumulated in RMS on the spoil heap and in the comparable Haplic Podzol. In initial mine soils, the OL/f horizons were still insufficiently developed and did not have a sufficient pool of macronutrients. Furthermore, SOM accumulation, decomposition, and mineralization were probably not well established enough to meet the nutrient supply needs for vegetation as in natural forest habitats (Puchalski and Prusinkiewicz, 1975; Baule and Fricker, 1970). In the oligotrophic Haplic Podzol, the resources of elements in mineral horizons were the same (in case of C and Na), and nearly the same (Ca, Mg and K) or even lower (P), and only in exceptional cases such as nitrogen (MH_{NA} : OH_{NA} accumulation was 4.6) and S (MH_{SA}: OH_{SA} was 558) was it many times higher in comparison to resources in the organic horizons (Table 3).

<u>Relationships between elements in soil</u>

The (C:N ratio) may be regarded as an indicator of changes in soils including intensification of organic matter mineralisation processes and related N-availability to plants during the decomposition of organic matter in soil (Baule and Fricker, 1973). In the investigated spoil heap, the soil C:N ratio in the OL/f horizon exceeded 80, whereas in QLS variant in the AiC horizon was 11 and in TCS variant it was 16. In the control podzol the C:N ratio in organic horizons was lower and was 51, and in the organic-mineral horizon (AEes) it was 17. For mor type humus characteristic of podzols in temperate climatic zones, the C:N ratio in organic and organic-mineral horizons oscillates between 30 and 40 and sometimes reached higher values (Baule and Fricker, 1970). Scots pine as a species characteristic of coniferous forests produces organic litterfall which decomposes with difficulty and the C:N ratio usually exceeded 70 (Obmiński, 1970). It was assumed that for initial soils on post-mining sites, the C:N ratio in organic-mineral horizons below 25 would indicate regular mineralization processing of organic matter (Harmsen and Kolenbrander, 1965).

Table 3. The ratio of the accumulation of macronutrient resources in soil mineral horizons to accumulation in organic soil horizon (MH_{BA} : OH_{BA}) and of biomass to soils (B_{BA} : S_{BA}) on the spoil heap of KWB 'Bełchatów' in Quaternary loamy sand strata (QLS variant) and in Tertiary carboniferous and pyritic sands following neutralisation (TCS variant) and in a natural pine ecosystem on Haplic Podzol in fresh mixed coniferous forest habitat (NPE).

Variant of site/element	MH_{BA} : OH_{BA}							
	C	Ca	Mg	K	P	S	Na	N
QLS	33.09	3471.73	515.56	226.60	15.54	3343.72	964.04	263.03
TCS	42.34	330.26	192.30	120.88	19.33	3780.00	826.40	203.14
NPE	0.99	1.24	0.64	0.62	0.34	558.20	0.96	4.64
	B_{BA} : S_{BA}							
QLS	0.54	0.001	0.02	0.09	0.58	0.008	0.008	0.023
TCS	0.14	0.002	0.02	0.08	0.19	0.002	0.003	0.013
NPE	0.63	0.45	15.42	4.70	4.05	0.023	0.072	0.266

Explanation: values calculated based on mean for variants; MH – soil mineral horizons up to 110 cm depth; BA - element accumulation or source in [$Mg \cdot ha^{-1}$]; OH - organic horizons (row humus layer OL/f in reclaimed soil and Ol + Olf in Haplic Podzol); B – aboveground biomass; S – soil; variant's abbreviation and element's form in soil - see methodology chapter;

The potential of the developing mine soils to meet plant nutrient requirements depended on the percentage of elements in forms available for plants (for this study: Na^+, K^+, Ca^{2+}, Mg^{2+} in exchangeable form and available P). In the organic horizons, these forms depended directly on the decomposition rate and mineralization of organic matter developed *in situ*. In mineral horizons, they largely depended on the weathering rate of minerals in the substrate. In natural habitats and especially in oligotrophic podzols, nutrients were mainly stored in the organic horizons and they were gradually released via mineralization processes (Baule and Fricker, 1970). This was of key importance in providing nutrients to trees as a limited amount of nutrients in soil could be compensated for by quick biological cycling of elements (Puchalski and Prusinkiewicz, 1975). Soil organic matter (SOM), even though in its initial phase of accumulation, plays an important role in the tree nutrition balance in reclaimed areas (Roberts et al., 1988; Rumpel et al., 1999; Ellerbrock et al., 1999). In the investigated podzol, the highest percentage of exchangeable Ca^{2+}, Mg^{2+}, Na^{+} and P (in available form) compared to total forms occurred in organic horizons (Ol and Ofh; 0 − 9 cm) and amounted to 43, 49, 35 and 18 %, respectively of the total elemental pool. In the case of K^{+}, the highest percentage of exchangeable forms in the total pool of elements occurred in the enrichment horizon (Bfe, 50-94 cm) and amounted to 6% (Fig. 1). In RMS (QLS), the most favourable relationship in this respect also occurred in organic horizons OL/f (0-2 cm), where Mg^{2+} amounted to 41 % (of total Mg) whereas Ca^{2+} was 24%; K^{+} = 43%; Na^{+} = 24% and P was = 19 % of the total elemental pool (Fig. 1).

In mineral horizons, the percentage of exchangeable and available forms decreased. However, in comparison to natural soils, the percentage of exchangeable forms in the entire pool of macronutrient elements was considerably higher. In the deeper mineral horizons, nutrients were mainly supplied due to weathering of minerals. In the more shallow horizons, what was also important was the enrichment process occurring via soil development where organic matter, colloidal fractions and sesquioxides were being supplied from the organic layers (Dobrzański and Zawadzki, 1995). In QLS soils in the OL/f horizon (0 − 2 cm), similar relationships were noted for Mg^{2+}, K^{+}, and Na^{+}. Exchangeable forms of these elements constituted approximately 40 % of the total elemental pool in total form. However in the case of Ca^{2+} and P, the largest percentage of forms available to plants occurred in mineral layers: P at 17 % from 10 to 50 cm, and Ca^{2+} at 46 % from 50 to 110 (Fig. 1). This was clearly connected with the bog lime neutralization treatment which was incorporated to a depth of at least 30 cm.

Relationships between element accumulation in soils and aboveground biomass

Relations between soils and vegetation under natural conditions have long been studied and soil development and ecological succession of communities are closely linked (Braun-Blanquet, 1964; Odum, 1971; Krebs, 2001). In reclaimed post-mining sites these relationships are not yet stable and may be frequently disturbed. Clear links between the trophism of mine soils (as expressed by Soil Trophy Index, according to Brożek and Zwydak, 2003), and ecological indicators based on Ecological Indicator Values of Vascular Plants (according to Ellenberg, 1979) have been documented in sand pits where natural succession was allowed to occur ('Szczakowa' sand mine pit in southern w Poland; Pietrzykowski and Krzaklewski, 2006).

Relationships between community features and abundance of soils developing on former mining sites under succession were also described by Wali (1999) on the bases of studies of abandoned coal-mine spoil materials in a mixed grass prairie region (in western North Dakota, USA).

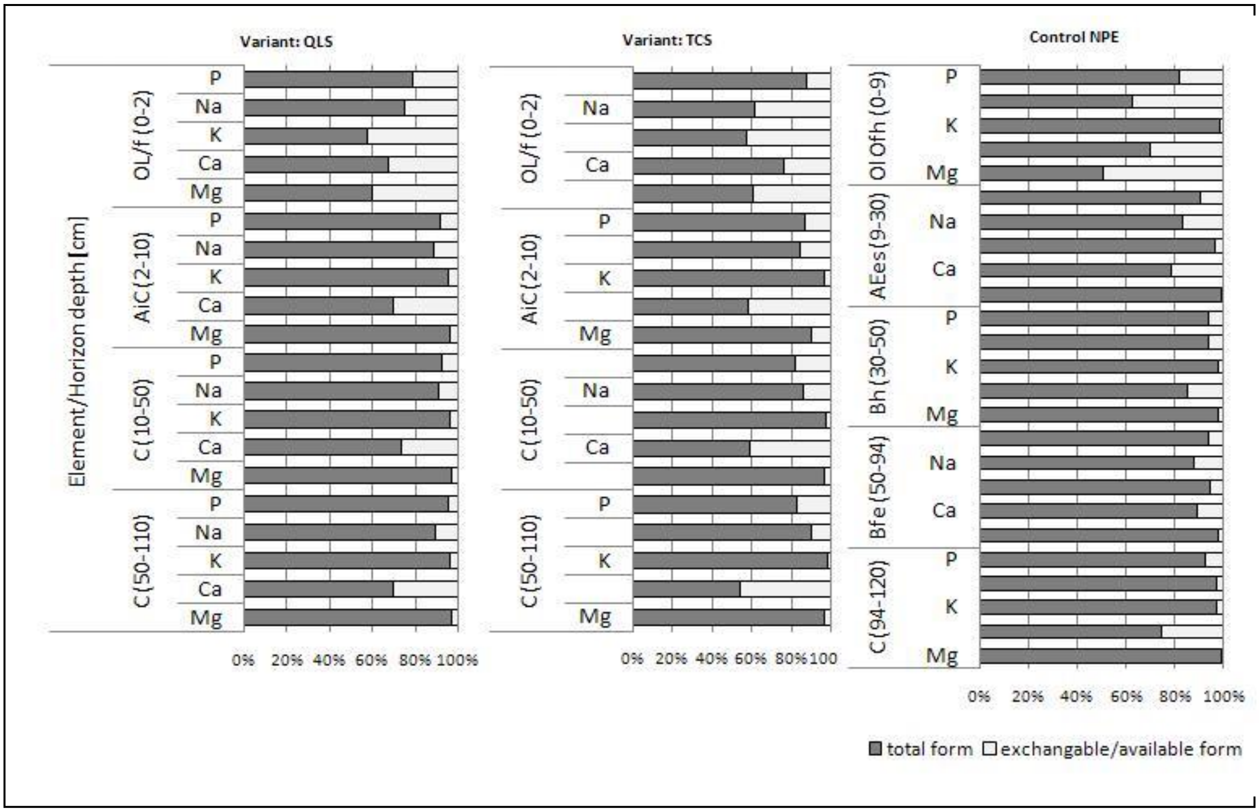

Figure 1. The share of exchangeable and available forms of the total macronutrient elemental pool in spoil heap soils of KWB ‘Bełchatów’ in Quaternary loamy sand strata (QLS variant) and in Tertiary carboniferous and pyritic sands following neutralisation (TCS variant) and in a natural pine ecosystem on Haplic Podzol in fresh mixed coniferous forest habitat (NPE).

For this spoil heap, the ratio of elements accumulated in the aboveground biomass to the resources in soil mineral horizons (B_{BA}:S_{BA}) differed largely from the control plot in the mixed coniferous forest, especially for Ca, Mg, K and P. Communities in reclaimed areas accumulated considerably less of those elements in relation to the potential resources (Table 3). For biomass in the forest habitat, the B_{BA}:S_{BA} ratio was much higher, which indicates that the elements available in soil were much better utilized by those communities. On this basis, it may also be claimed that the element exchange mechanism by pine communities on the spoil heap has different dynamics than in natural habitats. A dependence analysis between the accumulation of nutrients (in exchangeable and available forms expressed in [Mg·ha^{-1}] to a depth of 110 cm) and elements accumulated in community biomass showed a significant linear correlation (p=.05) for K, Ca and Mg (Table 4). This indicates the existence of marked relationships between the abundance of soil nutrients available to plants and the level of elements accumulated in community biomass developing on the spoil heap. Under natural conditions, such obvious dependence occurs in the first stages of primary succession where plant communities depend directly upon elements from the parent rock transformed into soil (Odum, 1971; Krebs, 2001). In the more complex conditions of natural forest ecosystems there are many other variables which modify these factors, including organic matter decomposition rate, individual biochemical cycles of elements, and the soil volume used by tree root systems which was difficult to determine in this study.

Table 4. A table of correlations between resources of macronutrient elements [Mg · ha $^{-1}$] in mineral soil horizons to 110 cm depth versus those in aboveground pine tree stand biomass on the upper portion of "Bełchatów" lignite mine spoil heap.

	Elemnt's accumulation [Mg·ha^{-1}]	In biomass (aboveground biomass: trees and herbaceous vegetation)							
		C-biom	N-biom	S-biom	P-biom	K-biom	Ca-biom	Mg-biom	Na-biom
In Soil (mineral horizon up to 110 cm depth)	C-soil	0.18	0.11	0.30	0.17	0.31	0.22	0.11	0.09
	N_t-soil	0.55	0.59	0.55	0.57	0.52	0.58	0.61	0.44
	S_t-soil	0.03	-0.01	-0.10	0.05	0.02	0.01	0.02	-0.06
	P-soil	-0.05	0.04	-0.17	-0.03	-0.18	-0.07	0.03	0.06
	K^+-soil	**0.80***	**0.74**	**0.84**	**0.78**	**0.85**	0.82	0.78	0.61
	Ca^{2+}-soil	**0.92**	**0.90**	**0.91**	**0.92**	0.92	**0.93**	0.93	**0.79**
	Mg^{2+}-soil	**0.82**	**0.80**	**0.81**	**0.82**	0.82	0.83	**0.85**	0.67
	Na^+-soil	0.62	0.56	0.59	0.61	0.64	0.62	0.62	0.37

* -* **marked** differences are significant at p= 0.05; n=8; N_t - total nitrogen; S_t - total sulphar; K+ - exchangeable cation forms – see methodology chapter.

Conclusions

The highest aboveground pine stand biomass occurred in QLS on quaternary strata, However when compared to TCS on less abundant tertiary sands following neutralization, lower biomass resulted from age differences (19 and 12 years), and not just from differences in habitat conditions between the plots. The higher community biomass in QLS (1.5-fold) on the spoil heap compared to pine tree stand biomass in the control plot in natural habitat indicated that quaternary loamy sand strata was potentially a good soil substrate for this species. Total accumulation of organic carbon (C_{org}) in both soil variants was 1.5-fold lower, and in case of total N_t , more than 3 -fold lower when compared to natural soil in the control plot. Nitrogen was the most deficient element in those conditions. The accumulation and the biogeochemical cycling of carbon and nitrogen were closely linked with the processes of soil development and community development on the spoil heap. The accumulation of these elements was a good indicator of the rate of these processes. In case of the exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) in the mineral RMS horizons, their accumulation was mostly connected with the potential abundance of rock strata and weathering processes during the development of soil. This was why the resources of these elements were considerably higher in the spoil heap soil than in the Haplic Podzol which formed on oligotrophic fluvioglacial sands. The higher (statistically significant) resources of macronutrients in QLS soils on quaternary strata compared to TCS soils on tertiary sands were also related to the origin and properties of parent rocks of the developing soil. Since this feature clearly differentiated the degrees of soil nutrient abundance on the spoil heap, it may be used to develop a habitat condition indicator for these materials.

A significant difference between RMS soils and natural Haplic Podzols were the accumulation ratios of individual elements in mineral and organic horizons (MH_{BA}:OH_{BA}). In the case of mine soils, the initial organic horizons did not yet constitute a significant source of nutrients and SOM accumulation and decomposition were not the basic mechanism for supplying plants with nutrients as is the case in natural forest habitats. There were also differences in the ratio of elements accumulated in aboveground biomass to the potential sources in soil (B_{BA}:S_{BA}) on the spoil heap and in the control plot, particularly for Ca, Mg, K and P. Plant communities in reclaimed area accumulated much fewer elements compared to potential sources in soil. However, for plant biomass in forest habitats of the oligotrophic Haplic Podzol, the ratio was much higher and indicated that macronutrient resources in soil were optimally utilized by the plant community. On this basis it may be assumed that the exchange mechanism of elements by plant communities dominated with pine on the spoil heap had different dynamics than in natural habitats. Moreover, the reported correlations between the accumulation of nutrients in soil and elements accumulated in plant community biomass (most clearly in the case of K, Ca and Mg), indicates the existence of marked links between soil and vegetation in the process of ecosystem development on a former mining spoil heap as stimulated by reclamation treatments.

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