# Soil and plant communities development and ecological effectiveness of reclamation on a sand mine cast

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**ABSTRACT**: The aim of the study was to assess terrestrial ecosystem development (mainly vegetation and soil characteristics) in the area of a sand mine cast (located in southern Poland) that has been either reclaimed or left for natural succession. A total of 20 sites in a chronosequence of 5, 17, 20 and 25 years were set up in two site categories: reclaimed and non-reclaimed sites. Selected properties of initial soils and features of vegetation were measured and they included carbon accumulation in soil; biomass and diversity of communities were also estimated. Next, based on carbon accumulation, the energy trapped in ecosystem components was estimated. Although the results of plant community investigation did not show the same distinct differences between site categories, the case study suggests that reclamation significantly accelerates ecosystem development. In comparison with spontaneous succession, the complete forest reclamation was found to increase the amount of carbon accumulation, thickness of humus horizon, and energy trapped in soil organic carbon and plant biomass in the developing ecosystem 2–3 times and nitrogen accumulation 5 times.

**Keywords**: sand mining; reclamation; succession; initial soils; organic matter; plant development; biodiversity

Opencast mines as a post-mining landscape are examples of large-scale land destruction. According to the majority of international laws, all surface-mined lands, whether for coal or other minerals, must receive reclamation treatments. From an ecological point of view reclamation is defined as a measure supporting 'the development of soils, vegetation, the wildlife, the water balance and water quality in order to allow future land uses such as agriculture or forestry' (Bradshaw, Hüttl 2001).

Most of the surface-mined areas in Central Europe are reclaimed for forestry. In this case the forest ecosystem restoration processes can be accelerated by management, but simultaneously in some parts of non-reclaimed areas the recovery of an ecosystem occurs spontaneously (Jochimsen 1996; Krzaklewski 1993, 1999; Krzaklewski, Fraczek 1999; Pietrzykowski 2005). The necessity of reclamation strategies is an interesting question (Luken 1990; West, Wali 2002; Pietrzykowski 2005; Sourkova et al. 2005; Pietrzykowski, Krzaklewski 2007). However, when wastes are characterized by a high amount of trace elements or salts (e.g. post-flotation tailings etc.) or materials very low in water-holding capacity, reclamation treatments are economically and environmentally effective (Krzaklewski 1993; Wali 1999). In the case of former sandpits where the toxic features mentioned above do not occur and succession is a spontaneous process, it is legitimate to ask whether reclamation treatments are necessary at all. For this reason comparative studies are useful. Another important question is what criteria should be used to evaluate the efficiency of reclamation and ecosystem development (Bell 2001; Bradshaw, Hüttl 2001; Schaaf 2001; Knoche et al. 2002).

All terrestrial ecosystems consist of aboveground and belowground components that interact to influence the community and ecosystem level process

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and properties (e.g. Golley 1993; Wardle et al. 2004). However, soil is a critical component which is in interaction with vegetation, climate and animals (Bradshaw, Hüttl 2001). The main objective of ecological research at post-mining sites is to identify the dominant processes and temporal trends in ecosystem development and to use indicators of ecosystem functioning, including the rate of organic carbon accumulation (Schaaf 2001; Anderson 1977; Wegorek 2003). Important ecological factors connected with plant community development are biomass and diversity of communities, measured by the number species and Shannon diversity index. What is also important to determine the stage of succession is the number of species characteristic of the particular communities including forest, shrub and grassy communities (Pietrzykowski 2005). An additional proposed criterion of the ecosystem development assessment in this study is energy trapped in an ecosystem and its distribution in soil and vegetation. Energy accumulation in the biomass of various components of plant communities makes it possible to describe and reduce its organization from an individual to a population as a single unit, i.e. joule (J) (Golley 1961; Krebs 2001). The quantity of biomass produced of carbon assimilated corresponds to the level of energy trapped during photosynthesis.

The objective of this study was to compare forest ecosystem development based on vegetation and soil features in two scenarios: reclaimed sites managed by man or non-reclaimed sites with natural succession.

## MATERIALS AND METHODS

### Study area

The study sites were located on the Szczakowa Sand Pit works in the Upper Silesia Region in southern Poland (19°26'E; 50°16'N, Fig. 1) within the Przemsza River basin. In terms of geology, the area belongs to the Bytom Basin. In general, its climate can be characterized by an annual average air temperature of 8°C and annual average precipitation of 700 mm. The deposits are genetically related to the fluvioglacial Quaternary sediments deposited in a pre-Quaternary morphological depression. When they were no longer mined, the surface lowered considerably in the opencast working boundaries (from 5 to 25 m deep). The opencast area (over 2,700 ha) was mostly reclaimed by reforestation. The treatment included forming and levelling the surface off, organic matter enrichment (approximately 300 $m^3$/ha) as forest soil upper layers, liming, NPK mineral fertilization (total in 2 years: 140 kg N/ha, 300 kg $P_2O_5$/ha, 180 kg/$K_2O$/ha), 2-year cycle of cultivation of legume plants (mostly *Lupinus* sp.). Next, the areas were reforested, mostly with 1-year old Scots pine (*Pinus sylvestris* L.) and common birch (*Betula verrucosa* Erhr.) (Pietrzykowski 2005). At the mine development stage in the 1970s and 1980s some parts of the pits were scheduled to be mined again. However, falling demand for filling sand and mining restrictions meant that these parts were neither mined again nor reclaimed. The opencast was simply levelled off and drained with a network of canals. Vegetation appeared on this biotope by way of ecological succession and soil developed under the communities. After approximately a dozen years, mostly Scots pine (*Pinus sylvestris* L.), common birch (*Betula verrucosa* Ehrh.) and trembling poplar (*Populus tremula* L.) (Pietrzykowski 2005) appeared in the non-reclaimed areas. Currently, communities which developed by way of succession take up approximately 10% of the total reclaimed Szczakowa Sand Pit works. The experimental plots were divided into two categories located in reclaimed and non-reclaimed areas.

### Field and laboratory methods

A total of 20 research plots (400 $m^2$) were arranged in a chronosequence of 5, 17, 20 and 25 years. The age of non-reclaimed research plots was calculated starting from the moment when parts of the open-

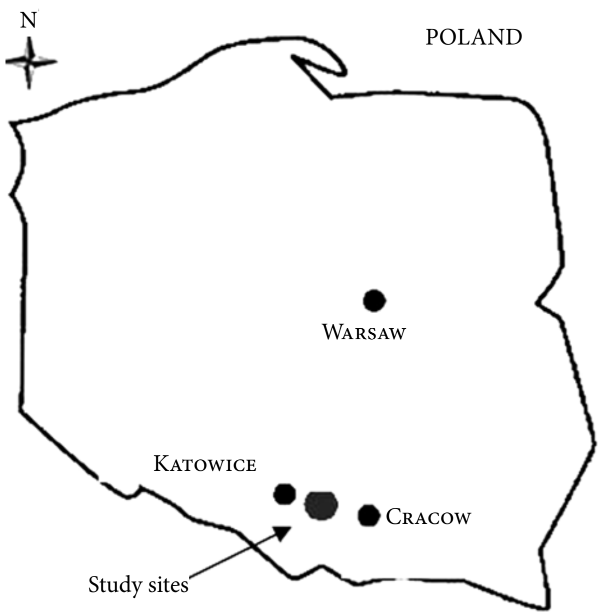


Fig. 1. Location of study sites on a sand mine-cast (South Poland, Upper Silesia Region)

Table 1. Characteristics of the initial topsoil horizons of soil categories in the Szczakowa opencast sand mine

| Age (years) | $n$ | Thickness (cm) | | $pH_{H_2O}$ | | $C_{org}$ (%) | | $N_t$ (%) | | C:N | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\bar{x}$ | SD | $\bar{x}$ | SD | $\bar{x}$ | SD | $\bar{x}$ | SD | $\bar{x}$ | SD |
| **Successional soils** | | | | | | | | | | | |
| L/Of horizon | | | | | | | | | | | |
| 5 | np | np | np | np | np | np | np | np | np | np | np |
| 17 | 12 | 0.8* | 0.6 | 4.51 | 0.37 | 44.96 | 4.58 | 0.83 | 0.36 | 64.1 | 30.3 |
| 20 | 12 | 1.4* | 0.6 | 4.42 | 0.45 | 39.14* | 6.54 | 0.90 | 0.24 | 46.1 | 13.6 |
| 25 | 12 | 1.8 | 0.8 | 5.13* | 0.46 | 39.06 | 10.36 | 1.09 | 0.32 | 36.8* | 7.9 |
| Ai horizon | | | | | | | | | | | |
| 5 | np | np | np | np | np | np | np | np | np | np | np |
| 17 | 22 | 1.2* | 0.4 | 5.05 | 0.28 | 0.55* | 0.19 | 0.037* | 0.012 | 14.3* | 1.7 |
| 20 | 36 | 1.6* | 0.6 | 5.44 | 0.20 | 0.58 | 0.27 | 0.026* | 0.090 | 22.0 | 5.7 |
| 25 | 36 | 1.9 | 0.7 | 5.42 | 0.48 | 0.79 | 0.51 | 0.039* | 0.023 | 20.7 | 5.2 |
| AC horizon | | | | | | | | | | | |
| 5 | 6 | 4.0* | 0.8 | 5.58 | 0.12 | 0.06 | 0.01 | 0.041* | 0.002 | 1.5 | 0.6 |
| 17 | 33 | 5.1* | 3.1 | 5.49* | 0.29 | 0.16 | 0.05 | 0.020* | 0.004 | 7.7* | 1.8 |
| 20 | 35 | 6.1* | 2.7 | 5.40 | 0.20 | 0.13* | 0.05 | 0.013* | 0.004 | 10.6 | 5.0 |
| 25 | 36 | 7.6* | 2.8 | 5.41 | 0.41 | 0.17* | 0.06 | 0.016* | 0.005 | 11.4* | 2.9 |
| **Reclaimed soils** | | | | | | | | | | | |
| L/Of horizon | | | | | | | | | | | |
| 5 | np | np | np | np | np | np | np | np | np | np | np |
| 17 | 12 | 1.7* | 0.5 | 4.43 | 0.65 | 45.03 | 3.67 | 0.87 | 0.37 | 59.7 | 21.6 |
| 20 | 12 | 2.3* | 0.7 | 4.48 | 0.54 | 48.89* | 2.44 | 0.83 | 0.36 | 68.1* | 24.2 |
| 25 | 12 | 2.5* | 0.8 | 4.56* | 0.43 | 45.69 | 8.98 | 0.88 | 0.37 | 58.6* | 21.3 |
| Ai horizon | | | | | | | | | | | |
| 5 | np | np | np | np | np | np | np | np | np | np | np |
| 17 | 22 | 2.5* | 0.8 | 5.21 | 0.34 | 0.67* | 0.25 | 0.065* | 0.062 | 12.0* | 3.8 |
| 20 | 36 | 3.1* | 1.4 | 5.40 | 0.45 | 0.72 | 0.44 | 0.058* | 0.016 | 11.9 | 4.6 |
| 25 | 36 | 3.5* | 1.3 | 5.36 | 0.39 | 0.78 | 0.55 | 0.050* | 0.024 | 19.6 | 18.7 |
| AC horizon | | | | | | | | | | | |
| 5 | 6 | 20.0* | 1.8 | 5.55 | 0.10 | 0.12 | 0.07 | 0.046* | 0.003 | 2.5 | 1.6 |
| 17 | 33 | 12.4* | 4.6 | 5.18* | 0.36 | 0.14 | 0.04 | 0.036* | 0.007 | 4.1* | 1.6 |
| 20 | 35 | 12.6* | 3.5 | 5.42 | 0.35 | 0.16* | 0.06 | 0.038* | 0.008 | 4.4 | 1.9 |
| 25 | 36 | 12.9* | 5.0 | 5.36 | 0.39 | 0.15* | 0.05 | 0.037* | 0.011 | 4.5* | 2.6 |

np – not present; $n$ – number of samples; *significant at the 0.05 probability level

cast mine were abandoned and natural succession was allowed to take place. The age of reclaimed research plots was calculated starting from the onset of biological succession. In 2001, square grids (4 × 4 m) were marked and drilled with a soil auger (up to a depth of 1.5 m) in all the research plots. Next, the thickness of organic and mineral horizons was measured and soil samples from these horizons were collected. Furthermore, the mass of L/Of horizon from a plot of 1 $m^2$ in 3 replications was determined and samples were dried in a laboratory. To measure the volumetric density of mineral horizons (topsoil), samples were put into 250 $cm^3$ cylinders (3 per each surface). Vegetation coverage was determined using the Braun-Blanquet method (100 $m^2$ phytosociological surveys); the community biomass was determined according to a yield method in the case of herbaceous plants and on the basis of measurements of tree stands and empirical formulas (Sulinski 1997; Weiner 2004). Biodiversity of communities is expressed as the 'H' Shannon diversity index (Begon et al. 1986).

The soil samples from initial organic-mineral (Ai) and transitional mineral horizons (AC) were dried and sieved in the lab with a 2 mm screen. The samples from the organic horizons (raw litter and humus horizon, L/Of) were ground and mixed to ensure homogeneity. The following measurements were performed: organic carbon ($C_{org}$) content using the infra-red absorption method; nitrogen (N) content using the method of measuring thermal conductivity with a Leco CNS 2000 analyzer; humus composition in organic-mineral horizon (Ai) by extracting a mixture of 0.1 n NaOH and 0.1 m $Na_4P_2O_7 10H_2O$ (Kononowa 1968); particle size distribution using the Prószyński aerometric method (measurement of soil suspension density in the course of gradual soil particle sedimentation under constant temperature using an aerometer); sand fractions were determined using sieves (Ostrowska et al. 1991); pH in $H_2O$ at a soil solution ratio of 1:2.5 using the potentiometer method (by microcomputer pH/conductometer Elmetron CPC-551); carbonate using the acid neutralization method (Van Reeuwijk 1995). The initial organic-mineral horizon Ai (> 0.5% $C_{org}$) and transitional mineral horizon AC (< 0.5% $C_{org}$) were classified on the basis of organic carbon content and colour. The significance of differences between the average values of soil horizon features (such as thickness, pH, C/N ratio, C and N content) were statistically evaluated using one-way analysis of variance (ANOVA), Tukey's $t$-significance test (verification of differences between age groups) and Student's $t$-test for independent variables (verification of differences between successional and reclaimed sites) ($P < 0.05$).

Based on carbon accumulation in the soil and biomass and using conversion factors known in ecology (Odum 1971; Krebs 2001), the energy trapped in ecosystem components was calculated. An equivalent of 20 kJ × 1 g biomass (dry) was assumed (Krebs 2001; Weiner 2004) for plant matter which contained very little protein but a high content of poly- and oligosaccharides. In the case of soil organic matter (SOM) with a complex structure, it is preferable to determine the carbon content and assume 41 kJ for 1 g of carbon as indicated in literature (Weiner 2004).

## RESULTS AND DISCUSSION

### Soil parameters

The initial organic-mineral horizons were characterized by graining of sands with a silt fraction from 1 to 17% and a clay fraction from 1 to 5%. Bulk density of soil was from 1.6 to 1.7 g/cm$^3$. In both categories, the L/Of upper organic horizons had pH $_{H_2O}$ from 4.4 to 5.1, and in the initial organic horizon Ai horizon pH $_{H_2O}$ was from 5.1 to 5.4 (Table 1). Significant differences between soil pH $_{H_2O}$ in reclaimed and non-reclaimed areas only occurred in L/Of horizons in the oldest plots (the 25-years-old group).

The initial organic horizon (L/Of) occurred under communities from succession and under trees introduced as a part of reclamation treatments in areas of 17 years or older. In the reclaimed areas, the depth of the L/Of horizon was nearly twice as much in all the age groups compared to areas under communities from succession. The thickness of Ai (organic-mineral initial horizon with > 0.5% $C_{org}$) increased significantly with the age of the surface (Table 1), however, in non-reclaimed areas it was approximately twice thicker than in reclaimed areas. As in the case of areas with communities from succession, the differences were statistically significant between the 17 and 25-years-old age groups (Table 1). Similarly, an increase in time in the depth of Ai horizon was shown on sandy reclaimed soils in Lusatian Mine District (Rumpel et al. 1999), Florida (USA) mineral sand open casts (Daniels et al. 2001) and the bank of the Sulphur Mine in Piaseczno (South Poland).

There was an increase in the percentage of $C_{org}$ in the Ai horizon corresponding to the age of the area; however differences between the age groups in chronosequence were not statistically significant yet. In the case of successional soils under communities, carbon content in soils aged from 17 to 25 years in the Ai horizon was more marked (from 0.55% to 0.79%) than in reclaimed soils (from 0.67% to 0.78%). In reclaimed areas, carbon content in the Ai horizon of 17-years-old soils was significantly higher than in soils of the same age developing under successional communities (Table 1), which was related to the positive impact of cultivation and green manure ploughing-in.

The data from the Lusatian Mining District in Germany (Rumpel et al. 1999) showed a significantly higher content of organic carbon in the upper organic-mineral horizons of initial soils in carbonated deposits under pine sites amounting to 6.5% in 32-years-old soils (Rumpel et al. 1999). However, the high $C_{org}$ content reported in initial soils in spoil banks following the mining of lignite may be connected with the participation of carbon of geological origin. Based on studies in a spoil bank in Piaseczno, Wegorek (2003) reported the $C_{org}$ content in sandy soils after 30 years of reclaims lower than 0.4%, emphasizing the dependence of carbon content on the grain size distribution. According to studies in Spain it was reported that the organic carbon content in upper horizons of initial soils was 3.0% already in the 5th year from the beginning of reclaims (Valera et al. 1993). In the newest, 5-years-old surfaces, the Ai horizon with $C_{org}$ content of 0.5% at least did not form yet. In the lower transitional organic-mineral initial horizon showing features of parent rock (AC), the percentage of organic carbon in both area categories was similar, and in chronosequence there were no upward tendencies.

**Carbon accumulation and community biomass**

Total accumulation of organic carbon in the soil (in the organic and organic mineral horizons) was 0.394 Mg/ha in the case of the youngest 5-years-old sites from succession and it increased statistically significantly to 4.640 Mg/ha in the oldest, 25-years-old sites. In the reclaimed sites, the carbon accumulation in the soil was considerably higher and amounted to 3.912 Mg/ha in the youngest 5-years-old areas and 7.402 Mg/ha in the case of the oldest 25-years-old sites. In the reclaimed area category, the total increase in carbon accumulation in soil in chronosequence from 5 to 25 years was not significant (Table 2). Humus in successional soils consisted of carbon trapped with humic and fulvic acid ($C_{HA}$ + $C_{FA}$) which increased chronosequentially and ranged from 0.575 in 17-years-old soils to 1.401 (Mg/ha) in 25-years-old soils. However, in this soil type the humus content varied more than in the case of reclaimed soils. In the reclaimed soils $C_{HA}$ + $C_{FA}$ ranged from 1.529 in 17-years-old soils to 2.028 in 25-years-old soils (Table 2). The relatively high content of C trapped with fractions of humic and fulvic acids in soil humus in both types of soils was characteristic of sandy soils with low organic matter decomposition rates (Kononowa 1968; Zier et al. 1999). The ratio of $C_{HA}/C_{FA}$ in the humus of successional soils also increased chronosequentially and ranged from 0.6 in 17-years-old soils to 0.8 in 25-years-old soils. In the oldest 25-years-old soils, this ratio was diversified and ranged from 0.4 to 1.4. In reclaimed soils the $C_{HA}/C_{FA}$ ratio decreased with age and ranged from 1.7 in 17-years-old soils to 0.9 in 25-years-old soils (Table 2). The $C_{HA}/C_{FA}$ ratios presented above indicate that humus in these soils consisted predominantly of fulvic acid, which was typical of podzolic forest soils (Kononowa 1968). Similarly, there was a high content of fulvic acids in humus in reclaimed soils in the former lignite mines in Canada (Anderson 1977).

Distinct differences between the categories of reclaimed and non-reclaimed sites occurred in aboveground phytocoenosis biomass. In this case trees played a crucial role as their participation in the aboveground biomass increased very intensively with the age of the area (Table 2). In the youngest areas, the aboveground biomass of herbaceous vegetation communities with relatively few tree seedlings and cuttings was similar and amounted to 0.140 Mg/ha in sites with succession and 0.130 Mg/ha in reclaimed areas. Examples quoted in literature referring to the aboveground biomass amount of pioneering communities from succession (dominated by *Corynephorus canescens*) in inland dunes were considerably lower at 0.027 Mg/ha (De Kovel et al. 2000). In the investigated reclaimed sites ranging in age from 17 to 25 years, the aboveground biomass of trees in communities rose twice from 30.189 Mg/ha to 61.070 Mg/ha. These quantities were similar to the biomass of arborescent communities from succession in 45-years-old inland dunes amounting to 75 Mg/ha (De Kovel et al. 2000) and forest communities developing on the poorest habitats of dry coniferous forests of the temperate climatic zone amounting to approximately 60 Mg/ha (Weiner 2004). The aboveground biomass of forest habitats of the temperate climatic zone was much higher and amounted from approximately 300 to 350 Mg/ha (Lieth, Whittaker 1975). The biomass of mixed stands in southern Poland (Niepolomicka Forest) was estimated on average at 158.5 Mg/ha, however, these values depended on the species composition of tree stands (Orzel et al. 2005).

In areas with succession the aboveground tree biomass was on average 3 times lower and the increase with age was not so high, however, herbaceous plants and shrubs had a much larger share in the community biomass than in reclaimed areas where there was a marked increase with age in crown density resulting in less light for herbaceous vegetation (Pietrzykowski 2005). In 17-years-old areas, the aboveground community biomass was 19.589 Mg/ha, which in comparison with the biomass amount in 25-years-old sites amounting to 19.048 Mg/ha may indicate periodic stagnation in the biomass growth of communities from succession. In studies of succession on inland dunes, a visible increase in biomass amount at succession stage was found (De Kovel et al. 2000). The obtained results allow to conclude that the conducted reclamation treatment had a significant and positive effect on the amount of aboveground community biomass, i.e. on the productivity of habitats. If we assume that the biomass of communities from succession in areas which are

Table 2. Organic carbon accumulation and biomass of communities in ecosystem components on reclaimed areas and areas left to succession exemplified by the Szczakowa sand mine cast

| Site category | Age of areas (years) | Total $C_{org}$ accumulation in soil (Mg/ha) $n = 36$ | Fractions C $C_{HA} + C_{FA}/C_{org}$* (Mg/ha) $n = 3$ | $C_{HA}/C_{FA}$ | Aboveground biomass (Mg/ha) | | | Root biomass (Mg/ha) | Carbon in biomass (Mg/ha) | C biomass/$C_{org}$ soil |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | herbaceous and shrubs ($n = 9$) | trees** ($n = 3$) | total aboveground | | | |
| S | 5 | 0.394 (0.156) | np | np | 0.140 (0.027) | np | 0.140 | 0.140 | 0.056 | 0.14 |
| | 17 | 2.425 (1.247) | 0.575 | 9.1 | 1.573 (1.070) | 10.303 (1.837) | 11.876 | 2.532 | 4.750 | 1.96 |
| | 20 | 2.820 (2.393) | 0.618 | 8.6 | 0.677 (0.515) | 18.912 (1.190) | 19.589 | 1.754 | 7.836 | 2.78 |
| | 25 | 4.640 (3.601) | 1.401 | 12.0 | 0.857 (0.664) | 18.191 (4.446) | 19.048 | 3.535 | 7.619 | 1.64 |
| R | 5 | 3.912 (2.607) | np | np | 0.130 (0.080) | np | 0.130 | 0.130 | 0.052 | 0.01 |
| | 17 | 5.404 (2.418) | 1.529 | 17.2 | 0.135 (0.173) | 30.189 (19.440) | 30.324 | 3.129 | 12.130 | 2.24 |
| | 20 | 6.684 (3.818) | 1.811 | 11.4 | 0.052 (0.049) | 55.156 (24.349) | 55.208 | 3.418 | 22.082 | 3.30 |
| | 25 | 7.402 (4.968) | 2.028 | 13.1 | 0.041 (0.059) | 61.070 (40.404) | 61.111 | 3.298 | 24.444 | 3.30 |

S – areas left for succession; R – reclaimed area; *$C_{HA} + C_{FA}/C$ org – organic carbon in humic and fulvic acids to total organic carbon ratio in Ai horizon; ** total wood and assimilatory organ biomass of trees with dbh > 7 cm; estimation of 1 g C → 2.5 g biomass was used; 394 (156) – $\bar{x}$ (SD); np – not present

Table 3. Energy trapped in ecosystem components ((kJ/ha) × $10^6$) on reclaimed areas and areas left to succession exemplified by the Szczakowa sand mine cast

| Site category | Age of areas (years) | $C_{org}$ soil ($n = 36$) | Fractions of SOM ($n = 3$) | | Aboveground biomass | | | Root biomass ($n = 3$) | Total vegetation (roots + aboveground) | Total ($C_{org}$ soil + roots and vegetation aboveground biomass) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $C_{HA}$ | $C_{FA}$ | herbaceous and shrubs ($n = 9$) | trees** ($n = 3$) | total vegetation aboveground | | | |
| S | 5 | 16.2 | np | np | 2.8 | np | 2.8 | 2.8 | 5.6 | 21.8 |
| | 17 | 99.4 | 9.1 | 14.5 | 31.5 | 206.1 | 237.5 | 35.1 | 272.6 | 372.0 |
| | 20 | 115.6 | 10.0 | 15.4 | 13.5 | 378.2 | 391.8 | 62.6 | 454.4 | 570.0 |
| | 25 | 190.2 | 22.8 | 34.6 | 17.1 | 363.8 | 381.0 | 66.0 | 446.9 | 637.2 |
| R | 5 | 160.4 | np | np | 2.6 | np | 2.6 | 2.6 | 5.2 | 165.6 |
| | 17 | 221.6 | 38.1 | 24.6 | 2.7 | 560.2 | 562.9 | 50.6 | 613.5 | 835.1 |
| | 20 | 274.0 | 31.2 | 43.0 | 1.0 | 1,103.1 | 1,104.2 | 190.4 | 1,294.6 | 1,568.6 |
| | 25 | 303.5 | 39.8 | 43.4 | 0.8 | 1,221.4 | 1,222.2 | 215.7 | 1,438.0 | 1,741.4 |

S – areas left for succession; R – reclaimed area; *$C_{HA}$; $C_{FA}$ – organic carbon in humic and fulvic acids in Ai horizon; ** total wood and assimilatory organ biomass of trees with dbh > 7 cm; estimation of 1 g C → 2.5 g biomass was used; np – not present not undergoing reclamation may be an indicator of potential habitat productivity, then the reclamation brought their 2 to 3-fold increase.

The estimated root biomass (assumed as 0.2 of wood biomass by Lieth and Whittaker 1975; Miller et al. 2006) for arborescent communities in reclaimed areas was from 3.129 to 3.418 Mg/ha, and in areas with succession from 1.754 to 3.535 Mg/ha (Table 2). In herbaceous communities, the estimated root mass was up to several dozen times lower and differences between categories were not large. The forest community root biomass in the temperate zone is estimated from 42 Mg/ha (coniferous forests) to 44 Mg/ha (deciduous forests), of which 50 to 60% of the mass is located in the upper 30 cm of the soil (Jackson et al. 1996; Helmisaari et al. 2002).

The ratio of carbon accumulated in the aboveground community biomass to carbon accumulated in the soil (C biomass/$C_{org}$ soil) differed depending on the site category. In areas with succession it was from 0.14 in 5-years-old sites to 2.78 in 17-years-old sites, and in reclaimed areas from 0.01 in the youngest 5-years-old sites and much more, even 24 in 17- years-old sites and 3.30 in 20 and 25-years-old sites. It indicates significant differences in relation to forest ecosystems of the temperate climatic zone where the ratio of C biomass/$C_{org}$ soil is on average 1.13, however the ratio decreases for biomass along with the cooling of the climate or decreasing soil trophy (Lieth, Whittaker 1975).

**Energy trapped in ecosystem**

The studied ecosystems differed largely in the amount of energy trapped during photosynthesis in plant biomass and in soil organic matter (SOM), both in comparable age groups and in chronosequence growth rate. The accumulation of energy trapped in SOM forming under 5-years-old communities from succession was $16.2 \times 10^6$ (kJ/ha) and it increased considerably with the age of the area to $190.2 \times 10^6$ (kJ/ha) under 25-years-old communities (Table 3). In reclaimed areas the accumulation of energy trapped in SOM was higher, however the difference from the areas from succession decreased in subsequent age groups. In the youngest reclaimed areas, energy trapped in SOM was $160.4 \times 10^6$ (kJ/ha), i.e. 10 times higher than in the same age group with communities from succession, but only 1.6 times higher in the oldest 25-years-old areas, i.e. $303.5 \times 10^6$ (kJ/ha) (Table 2). Significantly higher accumulation of energy in soils in the youngest reclaimed areas was connected with the initially higher content of organic matter in soil provided as a part of reclamation treatments, including green manure from lupine planting. In the ecosystem developing by way of natural succession, energy trapped in SOM showed a more dynamic chronosequence growth rate in the group of up to 25 years. However, in both cases, the share of energy trapped in humus fractions (humic and fulvic acids) was similar and did not exceed 20 percent (Table 3). This indicates a similar level of SOM development assessed on the basis of trapped humus fractions.

Total energy trapped in the aboveground vegetation biomass was approximately 2 to 3 times lower in sites with succession in comparison with reclaimed sites. The energy trapped in the aboveground community biomass from succession was from $237.5 \times 10^6$ (kJ/ha) in 17-years-old sites to $391.8 \times 10^6$ (kJ/ha) in 20-years-old sites and $381.0 \times 10^6$ (kJ/ha) in the oldest 25-years-old sites. These values may generally be regarded as relatively low. For instance, the annual energy production trapped in biomass in coniferous forests of the temperate zone (southern Poland) was estimated at over $140 \times 10^6$ (kJ/ha/year), and in deciduous forests at over $220 \times 10^6$ (kJ/ha/year) (Weiner, Grodzinski 1984). What differed was the allocation of accumulated energy in different layers of the community, i.e. herbaceous vegetation, shrubs and trees. In communities which developed by way of natural succession, the amount of energy trapped in the herbaceous plant and shrub layer was much higher in the whole chronosequence than in reclaimed soils. Phytosociological studies showed that this was related to the proximity of trees to one another (as trees were much closer to one another in reclaimed areas where they were regularly spaced when planted than in groups of trees from natural succession) and the availability of light to the undergrowth. In both cases, the tree layer had a dominant share in trapping energy in the biomass. However, a marked increase in accumulation in the chronosequence of 5 to 25 years was much higher in reclaimed areas. It was connected with a large biomass increase of the introduced trees and increased productivity of the ecosystem.

Similarly, total energy accumulation in the ecosystem (on the basis of energy accumulation connected with carbon in soil and in aboveground and root biomass) was significantly higher in reclaimed areas, adequately assessed $165.6 \times 10^6$ (kJ/ha) in the youngest 5-years-old sites and $1,741.4 \times 10^6$ (kJ/ha) in the oldest 25-years-old sites (Table 3). This was a nearly ten-fold increase in the studied time interval. In the areas where natural succession was allowed to take place, total energy accumulation after 25 years was nearly 3 times lower, however, there was a 30-fold increase in the chronosequence (from 5 to 25 years)

Table 4. Shannon diversity index 'H' and abundance of species (number of species) in plant communities depending on the age and category of areas in the Szczakowa sand mine cast

| Age of areas (years) | Areas left to succession | | | | Reclaimed areas | | | |
|---|---|---|---|---|---|---|---|---|
| | 5 | 17 | 20 | 25 | 5 | 17 | 20 | 25 |
| Shannon diversity index 'H' | 1.05 | 1.28 | 1.20 | 1.43 | 1.01 | 1.18 | 1.33 | 1.62 |
| Number of vascular plant species (total) | 13 | 34 | 46 | 48 | 11 | 25 | 35 | 58 |
| Number of shrub and tree species | 2 | 4 | 13 | 10 | 0 | 7 | 8 | 11 |
| Number of moss and lichen species | 0 | 4 | 3 | 5 | 0 | 5 | 2 | 6 |
| Total number of species* | 85 | | | | 77 | | | |

*The sum of species over the whole period including vascular plants, mosses and lichens (standardized per 100 $m^2$)

of energy accumulated in the process of succession. In the ecosystems developing by way of succession, the ratio of energy accumulated in biomass to energy trapped in SOM was also more balanced and did not exceed 3:1. In reclaimed areas in the youngest 5-years-old group, energy accumulated in biomass was more than 60 times lower than in soil; in 17-years-old soils and in successional soils it was 2:1, but in older soils it amounted to 4:1. This shows that in the ecosystem developing by way of natural succession there is a direct relation between the accumulation of energy in plant biomass and accumulation in soils developing under communities. In the latter case, the reclamation treatment significantly accelerated energy accumulation in biomass in relation to energy accumulation in SOM.

**Succession and diversity of plant communities**

In both comparable site categories, community abundance expressed as the number of species (richness of species) increased in the time sequence. Approximately a dozen species were found in the youngest 5-years-old sites and several dozen in the oldest 25-years-old sites (Table 4). The total number of species from succession reported in all time sequences in sites from succession was 85 including 78 vascular plants and 7 moss and lichen species and it was higher than in reclaimed sites where the total number was 77 including 70 vascular plant species and 7 moss and lichen species (Table 4). It was quite high compared to the total number of vascular plant species in the vicinity of a sand excavation in the Bledowska desert region (106 species) (Rahmonow, Śnieszko 2001), and compared to the surface-mined sites in Central Europe (e.g. external dump of KWB Belchatow, 33 species after 20 years of reclaim) (Pajak 2003); internal dump of Przyjazn Narodow – Lusatian coal-seams, 60 species after 25 years of reclaim (Krzaklewski, Pietrzykowski 2001) or natural sand dune sites (up to 25 species) (Falinska 1997). In post-mining sites, time is the most important factor affecting the expansion of plant species in the colonization process (Wali 1999) with primary succession and clearly distinguishable stages (Jochimsen 1987; Pietch 1996). However, in the case of longer time intervals, the number of species may decrease as phytocoenoses are in the initial stage of phytosociological relations (Wolf 1987).

Of all the inventoried species in the non-reclaimed areas, there were 15 forest community species, 25 shrub species and 38 non-forest species. In the reclaimed areas there were 13 forest community species, 23 shrub species and 34 non-forest species (Fig. 2). An increase in the number of forest species of the *Vaccinio-Piceeta* (BR.-BL. 1939) (Fig. 2) association class reported with time in the research plots was particularly significant from the aspect of assessing the forest succession processes. The following species occurred among forest communities both in non-reclaimed and in reclaimed areas: *Chimaphila umbellata, Deschampsia flexuosa, Fagus sylvatica, Orthilia secunda, Pinus sylvestris, Pyrola minor, Pyrola rotundifolia, Quercus petraea, Quercus robur, Epipactis atrorubens, Epipactis helleborine.* Apart from the above-mentioned forest community species, the following ones were also reported in reclaimed areas: *Moenes uniflora* and *Poa nemoralis,* whereas *Vaccinium vitis-idea, Hieracium sabaudum, Hieracium murorum, Betula pubescens*

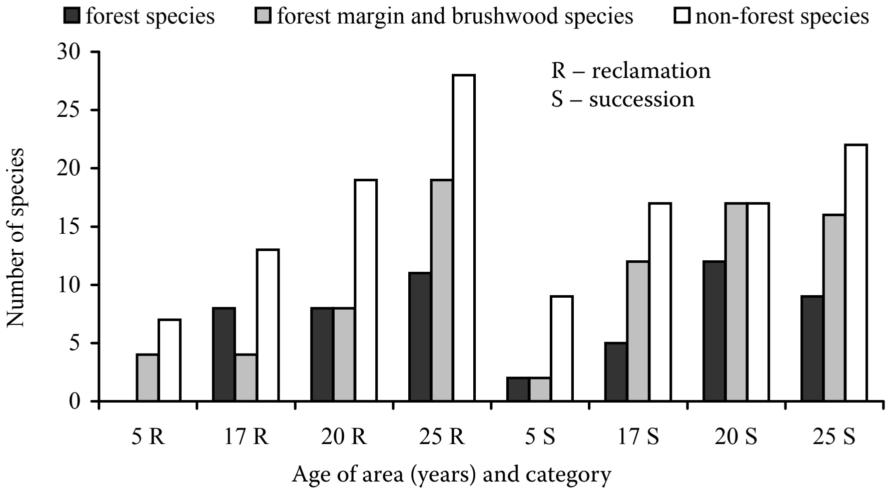


Fig. 2. Number of forest and non-forest species in communities at different age on reclaimed and non-reclaimed sites on a sand mine-cast (South Poland)

were reported in non-reclaimed areas. A reported slight decrease in the number of forest species for areas with succession ranging from 20 (12 species) to 25 years (9 species) showed possible regression. Biocoenoses developing by way of succession in post-mining sites are often the home to rare plant species (Adamowski, Conti 1991; Krzaklewski, Fraczek 1999). This is due to diversified micro-habitat conditions depending on the lithology and cost management in sites under a plant community mosaic complex (Bauer 1970; Krzaklewski, Fraczek 1999). In the studied sites, species protected in Poland including *Malaxis monophyllos* and *Epipactis atrorubens* were reported more frequently in non-reclaimed sites, which affects the ecological value of these communities.

Plant community biodiversity expressed by the Shannon ('H') diversity index rose with the time gradient from approximately 1.0 to 1.4–1.6 (Table 4). In post-mining areas, community diversity expressed by this index usually increased with time during succession (Wali 1999). Similarly, in the early stages of the synanthropization process of plant coverage there was usually a clear increase in floral diversity, however community impoverishment and domination by small groups of species (Falinska 1997) occurred after some time. In both categories, the 'H' values for the oldest communities were similar to the values for coniferous forest communities of the temperate climatic zone (Falinska 1997).

## SUMMARY AND CONCLUSIONS

The results of the study show that reclamations in opencast sand queries significantly accelerate biomass growth and pedogenic processes, including the formation of humus horizons as well as C and N accumulation in the recreated ecosystem. The biomass and soil features differed the most in the compared site categories of the sand open cast, especially in organic horizons. However in reclaimed areas, the thickness of initial organic-mineral and organic horizons was on average twice higher. Distinct differences between the studied sites occurred in the aboveground community biomass. In this case, trees played a crucial role as their participation in the aboveground biomass increases very intensively with the age of the area. The amount of carbon and energy trapped in biomass and soil was twice higher in a forest ecosystem restored on post-mining areas of a sand opencast mine during the full-scale reclamation treatment including technical restoration of biotope, biological reclaim and reforestation than in an ecosystem developing by way of succession following the biotope restoration. The results show that the full reclamation treatment and reforestation increase not only the amount of energy accumulated in the restored ecosystem but also the distribution of accumulated energy in the layers of the community. In successional communities, the amount of energy trapped in green plants and shrubs was much higher in the whole chronosequence than in reclaimed areas where regularly spaced trees allowed no light to bottom layers which contribute a small share of the total community biomass. In both cases, trees had a dominant share in trapping energy in biomass although the increase in energy accumulation in this layer in a chronosequence was much higher in reclaimed areas. Thus, the reclamation treatment had a significant role in increasing the productivity of the developing ecosystem.

However, the other features characteristic of vascular plant communities did not show any equally large differences between site categories as soil characteristics did. In both site categories, the increase in the total number of species was clearly observed during primary succession, especially in the number of forest species of *Vaccinio-Piceeta* (BR.-BL. 1939) association classes. A similar increase in the Shannon ('H') diversity index of vascular plant communities was observed during the studied chronosequence (from 5 to 25 years). However, non-reclaimed successional sites became the habitat of plants rare in Poland with specific habitat requirements other than in reclaimed sites. This is why adding parts of open casts to existing communities which had developed by way of succession increases the ecological value of recreated ecosystems.

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## Vývoj rostlin a půdy a ekologická efektivnost rekultivací na místech po těžbě písku

**ABSTRAKT**: Cílem příspěvku je posoudit vývoj pozemního ekosystému, zejména jeho půdy a vegetace na místě po těžbě písku, který se nachází na jihu Polska. Lokality byly zčásti rekultivovány, zčásti ponechány přirozené sukcesi.

Předmětem studie bylo celkem 20 míst, která byla opuštěna před 5, 17, 20 a 25 lety. Tyto lokality byly zařazeny do dvou kategorií: rekultivované a nerekultivované. Vybrané charakteristiky nevyvinutých (prvotních) půd a další charakteristiky rostlinných společenstev byly zjišťovány včetně akumulace uhlíku v půdě; zjišťoval se i objem biomasy a diverzita společenstev. Ačkoliv studium rostlinných společenstev neukazovalo na stejné rozdíly mezi různými stanovišti, výsledky studie ukazují na to, že rekultivace významným způsobem zrychluje rozvoj ekosystémů. Na rozdíl od spontánní sukcese lesnická rekultivace významně zvýšila množství akumulace uhlíku v půdě i tloušťku humusového horizontu. Objem organického uhlíku jak v půdě, tak i v rostlinách byl dvakrát až třikrát vyšší a akumulace dusíku pětkrát vyšší ve srovnání s lokalitami s přirozenou sukcesí.

**Klíčová slova**: těžba písku; rekultivace; sukcese; nevyvinuté půdy; organický materiál; vývoj rostlin; biodiverzita

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