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SUITABILITY OF SOILS DEVELOPED ON THE BASIS OF BLACK COAL ASH AS A FOREST HABITAT

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Abstract. The aim of the study was to evaluate the usefulness – as a forest habitat – the technogenic soils developed by applying overlays, containing organic matter in the waste substances, onto the layer of black coal ash. Properties of these soils, located in the power plant "Dolna Odra" in Nowe Czarnowo (West-Pomeranian Province), were studied in 2015, i.e. 13 years after founding the experiment upon the use of waste materials in soilless land reclamation. Analysis required samples from the ash overlays and bottoms of the soils, in which, through applying methods commonly used in soil science, the following properties were determined to enable calculation of the indicators used in the evaluation: forest soil trophism index (FSTI), soil site index (SSI), and mine soil quality index (MSQI). Values of FSTI allowed to classify studied soils as forest habitats, values of SSI – as mixed forests and forest habitats, and values of MSQI – as mixed forest habitats.

Keywords: reclamation, ash, afforestation, soil fertility indices

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INTRODUCTION

Among the reasons for which the landfills of ash – by-products of coal combustion – are burdensome to the environment, is dust (Siuta 2005). One of the effective and relatively low-cost ways of preventing this process is the introduction of vegetation, including afforestation. Difficulties in afforestation of anthropogenic soils arise from their properties, having no equivalents in nature (Pietrzykowski *et al.* 2013, Uzarowicz and Zagórski 2015, Tomaszewicz and Chudecka 2016). An effective forest reclamation requires a repair of chemical and physical properties of the ash ground (Pacewicz *et al.* 2006, 2007, Wróbel *et al.* 2006). The increase in the effectiveness of trees planting occurring after application of organic matter, including sewage sludge, was comparable with the use of pasty material layers, regardless of whether the sludge is mixed with the ash (Pacewicz *et al.* 2007, Bajor *et al.* 2014, Pietrzykowski *et al.* 2015), or overlays containing organic components are placed on ash (Nowak 2007, Nowak and Zieliński 2008, Nowak 2012), or trees are planted in holes treated with sewage sludge (Gilewska and Otremba 2010).

In order to determine the potential habitat type of the forest, one should take into account the geographical and climatic conditions, type of trees, undergrowth vegetation, and soil properties (Lasota *et al.* 2011). Natural stand and undergrowth vegetation does not occur on anthropogenic lands created from ashes. In this case, determination of the potential habitat type of forest can be made only on the basis of results of current soil science research that allow to calculate the forest soil trophism index – FSTI (Brożek 2001) and soil site index – SSI (Brożek *et al.* 2008, 2011). These indices were used in the studies characterizing the forest habitats on natural soils (Trawczyńska and Tołoczko 2007, Kondras *et al*. 2012), on post-agricultural soils (Wanic and Błońska 2011, Meller *et al.* 2013), and on reclaimed areas (Pietrzykowski *et al.* 2010, 2011). To determine the suitability for afforestation, the reclaimed landfill of ash, also mine soil quality index – MSQI (Pietrzykowski 2014, 2016), can be used to assess the post-mining wooded lands.

MATERIALS AND METHODS

Within the experimental object founded in Power Plant "Dolna Odra" in Nowe Czarnowo (West-Pomeranian Province) in 2002, 4 lysimeters were made. They were filled with ash, on the surface of which the 40 cm layer of overlay was applied to ultimately fulfill the role of humus horizon. In lysimeters L-1 and L-2, the overlay was a blend of low peat and ash in the volume ratio of 1:3 (overlay 1), while in lysimeters L-3 and L-4, the overlay consisted of: conifers bark, loose sand, compost produced by means of GWDA, and fermented municipal sewage sludge (having a composition of dry matter: 70% sludge, 30% straw) in the volume ratio of 1:1:2:4 (overlay 2) (Stankowski *et al.* 2005).

In September 2015, lysimeters surfaces were covered in 100% with vegetation. Soil samples were collected from each lysimeter from the overlay (0–40 cm) and ash (40–150 cm). For determination of physical properties, samples were collected preserving their structure, and for chemical properties analyses – collective samples neglecting the structure preservation. Bulk density, capillary capacity and non-capillary porosity were determined in soil samples collected with the structure preservation using Kopecky's cylinders of 100 cm^3 capacity.

The collective samples collected with no structure preservation, after air-drying, were subject to the following determinations:

- grain composition by the method of Casagrande with modification of Prószyński; sand content by sieve method; granulometric division was accepted according to PTG (1989, 2011);
- pH applying potentiometry in water and potassium chloride of 1 $mol \cdot dm^{-3}$ concentration and soil/solution weight ratio of 1:2.5;
- total contents of C and N using elemental CHNS analyzer;
- contents of alkaline cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) extracted using ammonia acetate at concentration of 1 $mol \cdot dm^{-3}$;
- hydrolytic acidity by means of the Kappen method;
- available phosphorus content – colorimetry according to by method of Egner-Riehm.

Achieved results allowed for calculating the forest soil trophism index – FSTI (Brożek 2001), soil site index – SSI (Brożek *et al*. 2008), and mine soil quality index (MSQI), which was used by Pietrzykowski (2016) to assess the post-mining wooded lands.

RESULTS AND DISCUSSION

Soils in lysimeters with the sequence of horizons: Aan-2Can correspond to humus industrial soils (AIpr) according to the Systematics of Polish Soils (PTG 2011), while according to WRB (2014), to the group of *Technosols.*

Values of the forest soil trophism index (FSTI) for soils from lysimeters no. 1–2 (with overlay 1) were in the range of 37.5–38.0 (Table 1). The increase in FSTI value to 37.8 for soils from lysimeters no. 3–4 (with overlay 2), was caused by almost 2-fold narrower ratio of C:N (Table 1), resulting from the establishment of the overlay with a higher proportion of organic matter, including nitrogen. Brożek and Zwydak (2003) presented division of soils based on FSTI values into: dystrophic (to 10.0), oligotrophic (10.1–16.0), mesotrophic (16.1–26.0), eutrophic (26.1–36.0), and hypertrophic (>36.0). Values of FSTI

TABLE 1. THE NUMERICAL INDICES AND VALUES OF FOREST SOIL TROPHISM INDEX (FSTI) CALCULATED ACC. TO THE CRITERIA OF BROŻEK (2001)

Lysi-meter	Thickness (cm)	Fraction [%]			Indices			C/N	$I_{C/N}$	pH in H_2O	I_{pH}	BC [cmol·dm^{-3}]	I_{BC}	Isum	FSTI
		>1.0	0.1–0.02	<0.02	I_{skel}	I_{silt}	I_{clay}								
1	0–40 overlay 1	1.2	44.4	24.0	0	9	8	25	3	7.80	9	25.1	10	39	37.5
	40–150 ash	0.4	35.0	16.0	0	9	8	68	1	8.82	10	19.9	9	37	
2	0–40 overlay 1	0.3	43.5	24.0	0	9	8	33	1	8.10	10	21.9	10	38	38.0
	40–150 ash	0.4	31.1	20.0	0	9	8	58	1	8.56	10	20.4	10	38	
3	0–40 overlay 2	1.8	16.1	11.0	0	8	7	15	7	7.42	9	12.1	9	40	37.8
	40–150 ash	1.2	30.4	19.0	0	9	8	44	1	8.35	10	17.2	9	37	
4	0–40 overlay 2	4.5	13.0	11.0	0	7	7	12	8	7.13	9	12.0	9	40	37.8
	40–150 ash	2.5	29.0	20.0	0	9	8	35	1	8.49	10	18.2	9	37	

Explanation: BC – base capacity; I_{skel}, I_{silt}, I_{clay}, $I_{C/N}$, I_{pH}, I_{BC} – numerical indices calculated acc. to the criteria of Brożek (2001) concerning respectively: fraction of skeleton (I_{skel}), fraction of silt (I_{silt}), fraction of clay (I_{clay}), degree of organic matter decomposition ($I_{C/N}$), pH (I_{pH}) and base capacity (I_{BC}); I_{sum} – weighed sum of numerical indices for tested soils were within the range of 37.5–38.0, which indicates their hypertrophic character identified with the forest habitat.

Values of the soil site index (SSI) amounted to 31–33 for soils from lysimeters no. 1 and 2 (with overlay 1) and 34–35 for soils from lysimeters no. 3 and 4 with overlay 2 (Table 2). Like for FSTI, higher SSI values for soils with overlay 2 resulted from its abundance in nitrogen. According to Brożek *et al.* (2011), ranges of SSI values for forest habitats are as follows: coniferous forests 4–13, mixed coniferous forests 14–23, mixed forests 24–33, and forests 34–40. These values allow to classify soils from lysimeters no. 1 and 2 as potent habitats of mixed forests, whereas soils from lysimeters no. 3 and 4 – as forest habitats. However, according to Lasota *et al.* (2011), in the 1st natural-forest area, i.e. Baltic Natural – Forest Province, climatic conditions allow such species as beech, sessile oak and hornbeam to achieve better growth on soils with lower SSI values as compared to other lowland areas. These authors asked for the reduction of the lower limit value of SSI for the Baltic Natural – Forest Province: for mixed forests to 21, and for forests to 29, which means that tested soils, regardless of the overlay, meet the conditions of the forest habitats.

TABLE 2. THE ELEMENTS AND VALUES OF SOIL SITE INDEX (SSI) CALCULATED ACC. TO THE CRITERIA OF BROŻEK *ET AL.* (2008)

Lysimeter	Czsv	Sv	Yv/Czsv	N2/C	Wczs	Ws	Wy	Wn	SSI
1	215.2	202.8	0.009	0.016	7	9	10	7	33
2	260.2	211.6	0.0052	0.014	7	9	10	5	31
3	234.4	203.7	0.011	0.032	7	9	10	8	34
4	242.0	207.9	0.016	0.037	7	9	10	9	35

Explanation: Czsv − resource of clay fraction (with diameter <0.02 mm) expressed in kg per 1.5 m^3 of soil; Sv − sum of cations: Ca^{+2}, Mg^{+2}, K^+, Na^+ expressed in moles per 1.5 m^3 of soil; Yv/Czsv − total acidity expressed in kg of H^+ ions to 1.5 m^3 of soil, divided by content of clay fraction expressed in kg per 1.5 m^3 of soil; N2/C − percentage participation of total nitrogen in overlay divided by C: N ratio in overlay; Wczs − index of resource of clay fraction (with diameter <0.02 mm) expressed in kg per 1.5 m^3 of soil; Ws − index of sum of cations: Ca^{+2}, Mg^{+2}, K^+, Na^+ expressed in moles per 1.5 m^3 of soil; Wy − index of total acidity expressed in kg of H^+ ions to 1.5 m^3 of soil, divided by content of clay fraction expressed in kg per 1.5 m^3 of soil; Wn − index of percentage participation of total nitrogen in overlay divided by C: N ratio in overlay

In conclusion, calculated FSTI and SSI indicators make possible to classify the soils from lysimeters as a potential habitat of forests. This is consistent with the division shown by Krzaklewski *et al.* (2011), on reclaimed post-mine dumps, where soils with the 100-percent coverage of spontaneously emerging herbaceous vegetation, such as these tested here, belong to the category IV – fertile formations, which represent potential habitat of mixed fresh forests or fresh forests. However, it should be considered whether soils made of ashes, the pH reaction of which may exceed levels considered phytotoxic for the majority of plants (Krzaklewski *et al*. 2005), may be assessed using the same parameters as the natural soils. Therefore, to assess the fertility of a soil in lysimeters, also the mine soil quality index (MSQI) was used as an indicator. It was used to determine the potential forest habitats on technogenic soils (Pietrzykowski 2016). It should be noted that when calculating MSQI, more partial indicators are taken into consideration than for FSTI and SSI. There are among them indicators of capillary and air capacity, which have low values in reclaimed soils reducing the growth of vegetation (Gilewska and Otremba 2007, Greinert *et al*. 2009). In addition, for alkaline soils with the pH reaction not identified in natural forest soils (Brożek and Zwydak 2003), value of partial acidity indicator decreases, hence reducing the MSQI value (Pietrzykowski 2014) and indicating the deterioration in soil fertility.

Values of the mine soil quality index presented in Table 3 were calculated by modifications of partial Wab indicators. In paper by Pietrzykowski (2010), these indicators were determined based on the C:N ratio in the initial horizon of the overlay humus (Olf), while in the present study, they were determined according to C:N ratio in overlay. Values of MSQI amounted from 0.618 to 0.638, suggesting that these soils can be classified as potent habitats of mixed forests accepting – proposed by Pietrzykowski (2016) – the ranges of MSQI for individual habitat types:

MSQI<0.420 − potential coniferous forests habitats;
MSQI 0.421–0.540 − potential mixed coniferous forests habitats;
MSQI 0.541–0.680 − potential mixed forests habitats;
MSQI>0.680 – potential forests habitats.

TABLE 3. THE ELEMENTS AND VALUES OF MINE SOIL QUALITY INDEX (MSQI) CALCULATED ACC. TO THE CRITERIA OF PIETRZYKOWSKI (2016)

Lysimeter	Partial indices and value calculations for particular feature										MSQI
	Wgp	Wgi	Wgs	Wg	Wz	Wp	Wk	Wab	Wpw	Wpp	
1	0.35	0.05	0.00	0.40	1	0.15	0.3	1	1	0.3	0.628
2	0.35	0.10	0.00	0.45	1	0.15	0.3	1	1	0.3	0.638
3	0.30	0.10	0.00	0.40	1	0.15	0.3	1	1	0.2	0.618
4	0.30	0.15	0.00	0.45	1	0.15	0.3	1	1	0.3	0.638

Explanation: Wgp − index of silt fraction; Wgi − index of clay fraction; Wgs − index of skeleton; Wg − particle size index, Wg = (Wgp + Wgi) - Wgs; Wz − nutrient abundance index (exchangeable cations forms: Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}); Wp − abundance of available phosphorus index; Wk − acidity index calculated by accumulation of H^{+} ions (based on pH in KCl); Wab − biological activity index based on C:N ratio in layer 0−40 cm; Wpw − water capillary capacity index; Wpp − air capacity index; MSQI =[(Wgp + Wgi) - Wgs] × 0.2 + Wz × 0.25 + Wp × 0.05 + Wk × 0.2 + Wab × 0.1 + Wpw × 0.1 + Wpp × 0.1

Summing up the results, we can conclude that, depending on the applied indicator, the tested soils can be considered as a potential habitat of mixed forests or forests. The problem to be solved is the selection of tree and shrub species for soils formed from the ashes. Research on the forest reclamation of ash dumps indicate the usefulness of such tree species as: silver birch (*Betula pendula* L.), northern red oak (*Qercus rubra* L.), common ash (*Fraxinus excelsior* L.), maple ash (*Acer negundo* L.), Norway maple (*Acer platanoides* L.), silver berry (*Elaeagnus angustifolia* L.), black locust (*Robinia pseudoacacia* L.) and Scots pine (*Pinus sylvestris* L.) (Gilewska and Otremba 2010, Nowak 2012, Strączyńska *et al.* 2009, Pietrzykowski *et al.* 2010a, Pacewicz *et al.* 2006) and shrubs: common dogwood (*Cornus sanguine* L.), Siberian peashrub (*Caragana arborescens* L.), European smoketree (*Cotinus coggygria* L.), green alder (*Alnus viridis* L.), common sea buckthorn (*Hippophae rhamnoides* L.) and rugosa rose (*Rosa rugosa* L.) (Nowak 2007, Nowak and Zieliński 2008, Pietrzykowski *et al.* 2015, Strączyńska and Strączyński 2007, Wróbel *et al*. 2006). However, foreign species present among them, such as northern red oak, black locust, and maple ash, that are considered as invasive in Poland, may negatively affect the natural properties of the forest habitat (Danielewicz and Wiatrowska 2014, Tokarska-Guzik *et al*. 2012). Therefore, it would be safer for the environment to introduce classic forest-forming species for habitats of mixed forests. In Polish conditions, major species would be English oak and beech, while auxiliary species: fir, hornbeam, lime tree, maple, and pine (Brożek 2014).

CONCLUSIONS

1. Reclamation of black coal ash landfill, involving the imposition of a layer of material enriched in organic matter, caused the formation of anthropogenic soils suitable for afforestation.
2. Depending on the indicators applied for assessment, tested soils, regardless of the overlay, were classified as habitats of: hypertrophic forests (based on FSTI), forests (based on SSI and taking into account the localization in Baltic Natural – Forest Province as well as mixed forests (based on MSQI).

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