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Assessment of tree vitality, biomass and morphology of Scots pine (*Pinus sylvestris* L.) root systems growing on reclaimed landfill waste after zinc and lead flotation

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Abstract. The stability of introduced stands depends not only on aboveground but also on the belowground biomass. Results from reclaimed sites often indicate good growth of the aboveground part of stands, but data on the development of root systems are still lacking. Our aim was to assess the vitality of trees, their biomass and the morphology of the root systems of Scots pine (*Pinus sylvestris* L.) introduced on reclaimed landfill waste after zinc and lead flotation in Bukowno (southern Poland). The landfill site was reclaimed 20 years ago and reclamation treatments involved isolation and covering with mineral substrate layers (110–150 cm thickness) which formed a technogenic soil profile. Four research plots (10 m × 10 m) were set up in pure pine stands where soil profiles consisted entirely of flotation waste. Trees on the plots were assayed according to the Kraft and IUFRO classification system. In total, 15 trees of average growth parameters and bio-sociological position (I and II Kraft class) were selected for biomass and root system analyses and the root systems were excavated, washed, measured, weighed and photographed.

Our results support pine as a useful species in reforestation of post-mining areas. However, although pine trees were characterised by good vitality, their root systems were shallow and their depth reduced by up to 60 cm due to strong skeletal loamy substrate. Individual root biomass ranged from 1.2 to 9.1 kg and was comparable to pine root biomass on other reclaimed mining sites. This indicates that during restoration, the thickness of the substrate covering the flotation waste should be increased or the amount of skeletal substrate in the top layers of technosol reduced.

Keywords: reforestation, technosols, stand, belowground biomass, heavy metals

1. Introduction

The basic task of reclamation from the point of view of the dynamics of restoration of the ecosystem in post-mining areas is the initiation of the soil-formation process (Bradshaw 1983; Pietrzykowski 2015). Soil reconstruction methods can be broadly divided into technical ones, in which the full profile of the reconstructed soil is reproduced, or biological ones, in which the restoration of the initial organic layer takes place using mainly the humus-forming plants (Pietrzykowski, Krzaklewski 2014; Pietrzykowski 2015). The technology of the restoration of the full soil profile is limited by the availability of the rock overburden, which is beneficial from the point of view of its soil formation abilities. With a shortage of high-quality soils, soil reconstruction techniques at the stage of biological reclamation use the so-called green fertilisers, that is, humus-forming plants capable of fixing atmospheric nitrogen (Pietrzykowski, Krzaklewski 2009).

From the point of view of forestry, land reclamation in Poland is conducted according to the developed procedures consisting of the technical and biological reclamation stages and finally afforestation (management).

The varied and often unfavourable and rapidly changing properties of technogenic soils in post-industrial areas enable the right selection of tree species, with high adaptation abilities to habitat conditions, crucial for the success of reclamation and afforestation (Knoche et al. 2002; Pietrzykowski et al. 2014).

The main unfavourable characteristics of technogenic soils that affects the reduction in the trophic level include acidification, alkalisation, low bioavailability of nutrients and di-

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sturbances in their quantitative relations, as well as heavy metal pollution, defective air–water relations and compaction (Katzur, Haubold-Rosar 1996, Knoche et al. 2002; Pietrzykowski 2014).

This, in turn, affects the poor supply of nutrients to trees, their growth and healthiness and, in the long term, the stability of introduced stands and, as a consequence, a successful forest reclamation (Katzur, Haubold-Rosar 1996; Knoche et al. 2002, Pietrzykowski 2015).

In forest ecosystems, there is a significant amount of belowground biomass, being equally important as aboveground biomass in the circulation of matter and energy (Waring, Schlesinger 1985). The root system of trees conventionally consists of coarse roots (d > 2 mm) and fine roots (d < 2 mm) (Millikin, Bledsoe 1999).

Coarse roots are primarily responsible for mechanical stability, whilst fine roots are responsible for the mineral nutrition of trees (Böhm 1985; Danjon, Reubens 2008). For these reasons, knowledge of the biomass of root systemsas well as of their development and deformation is important in the perspective of the evaluation of a mineral nutrition strategy and stability of tree stands planted in post-mining areas (Pietrzykowski, Woś 2010; Pietrzykowski et al. 2010).

The distribution of roots in the soil profile, as the so-called biological depth (Puchalski, Prusinkiewicz 1990), is a factor assessing the development of soils in post-mining areas (Pietrzykowski, Woś 2010) and the development of the biological life of soils, that is, microorganisms inhabiting the rhizosphere (Węgorek 2003). In addition, the studies of root biomass in post-mining areas may also have a local significance in the assessment of the possibility of regulating the amount of carbon accumulated in young forest ecosystems (Rodrigue et al. 2002).

The aim of the study is to assess the viability of and analyse the biomass and morphology of the root systems of Scots pine planted on the zinc and lead ore post-flotation waste landfill site, whose reclamation treatments involved insulation and appropriate covering with mineral substrate layers. This type of waste, which is produced in huge quantities in the mining industry of non-ferrous ores throughout the world, is classified as hazardous to the biological reclamation of land, because it contains significant amounts of toxic heavy metals. Therefore, the assessment and optimisation of the methods of such waste management and land reclamation is important for environmental protection not only on a local but also on a global scale.

2. Research area

The research area was the reclaimed former zinc and lead ore post-flotation waste landfill site of ZGH 'Bolesław' S.A. open-pit mine in Bukowno (N 50 17.781, E 19 29.195). The landfill is situated about 40 km northwest of Cracow. According to the natural-forest regionalisation, the mineis located in Małopolska Region IV, Upper Silesian mesoregion (Zielony, Kliczkowska 2012).

The aboveground settling ponds of post-flotation waste pose a high threat to natural environment causing soil contamination with trace elements due to dust emission and migration of elements in the effluent waters (Krzaklewski et al. 2004). For this reason, the use of post-flotation waste to fill the pit excavation after the exploitation of zinc–lead ores was to reduce the area occupied by the aboveground settling ponds and their negative impact on the environment (Technical project ... 1992). The exploitation of zinc–lead ores within the mining area was carried out in the period 1955–1985.

The area of the reclaimed land covered 9.28 ha, including the waste-refilled excavation with an area of 7.64 ha and the adjacent 'shelterbelt' of fast-growing trees (mainly poplars). Before being filled with the post-flotation waste, the excavation had a depth of approximately 20 m and a capacity of more than 1500,000 m^3. After depositing the post-flotation waste in the pit and flattening out its surface to the ordinate of the adjacent areas, an insulation layer was made of Keuper and Permian clays or other materials similar to the compact soils to prevent infiltration of rainwater into the rock mass.

Subsequently, the insulation layer was covered with a top layer of substrate that is used as a soil formation medium. The applied technology refers to the so-called 'soil' reclamation method, consisting in covering post-industrial sites with a layer of properly thick and fertile (humus and mineral-humus) soil horizons obtained from the forefield of open-pit mines or areas designated for industrial facilities (e.g. settling ponds, landfills) (Krzaklewski 2017).

Following the agrotechnical treatments, the site was afforested mainly with pioneer species: Scots pine (*Pinus sylvestris* L.), or in admixture with European larch (*Larix decidua* Mill.) and silver birch (*Betula pendula* Roth) (Technical project ... 1992). Over the next 20 years, no tending treatments (cleaning, thinning, etc.) were carried out in these stands.

3. Methods

In the first stage of the research, four one-are areas with a size of 10 m ×10 m were set up in the transect located in the patches of pure 20-year-old pine stands. In order to examine the full profile of the technogenic soil, soil was removed from each research plot with an excavator to a depth of the post-flotation waste (up to 120–160 cm depth). In the soil profiles, soil morphology and the distribution of roots in the profile were described in detail, and photographic documentation was prepared.

Then, soil samples were taken from the distinguished soil horizons (Olf, AinCan and Can) for laboratory identification.

The samples taken from mineral horizons were determined for particle size distribution with a Fritsch GmbH Laser Particle

Sizer ANALYSETTE 22; pH in H_2O and in 1 mol dm^3 KCl by the potentiometric method in the ratio of 1:2.5; electrical conductivity (EC) with the soil-to-solution ratio of 1:5; and the content of $CaCO_3$ (carbonates) by the Scheibler method, and all soil samples (i.e. together with the samples from organic horizons) were determined for the content of organic carbon (C_{org}) and total nitrogen (Nt) using the TruMac®– CNS analyser and Zn, Cd and Pb content after digestion in the mixture of HNO_3 and 60% $HClO_4$ in the ratio of 1:3, with a CP OES ICAP 6000 Series spectrophotometer. On each research plot, diameter at breast height (dbh) and height (h) were measured, and all trees were classified for their vitality and development with the use of the Kraft biological classification and IUFRO system.

Next, in the main part of the research involving root systems, 15 sample trees with average growth parameters and biosocial position in the stand (i.e. trees in Kraft's classes I and II) were selected for biomass and root system analyses.

The sample trees were given numbers (from 1 to 15), and the aboveground parts were cut at the root collar. The root systems were dug out with an excavator. Then, they were rinsed with water under pressure. After drying, the fresh roots were weighed (using a hook scale Mensor WM150P2 with an accuracy of 1.0 g) and the diameter at the root collar and the vertical and horizontal distribution range and levels of coarse roots (diameter, d > 1 cm) were measured. Each root system was photographed, and its morphology was described. Photographs of root systems were subject to graphic processing using CorelDRAW® Graphics Suite X8.

In order to determine the moisture and dry mass of roots, a composite tissue sample was taken from stump wood. The moisture content of the roots was determined in the laboratory by the dry weight method after drying the samples at 105°C to a constant dry mass.

In the description of morphology of pine root systems, the Nörr scale (2003) was applied with slight modification and used in the studies of Scots pine roots in the reclaimed areas and described by Pietrzykowski et al. (2010). The following types of root deformation are distinguished:

1. a taproot system, typical of Scots pine, developed under free growth conditions on the sandy loam soils most suitable for this species;
2. a taproot system, already slightly flattened, with a visible slight deformation of the primary root;
3. deformed system, clearly flattened, twisted taproot, strong growth of lateral roots;
4. strongly deformed system, flattened, strongly twisted primary root, permanent deformation.

In order to compare the ratio of root biomass to aboveground biomass of each sample tree, the total biomass of the stem and branches was determined using the empirical formula developed for Scots pine growing on the reclaimed post-mining sites in Poland (Pietrzykowski, Socha 2011):

$$B_{nadz} = 0.102080 \cdot (D^2 \cdot H)^{0.793199}$$

where
$B_{a.g.}$ is theaboveground biomass of the tree [kg],
DBH is the diameter at breast height [cm],
H is the height [m].

4. Results and discussion

According to the Systematics of Polish Soils (Systematyka gleb Polski 2011), the soils of the reclaimed site were classified as anthropogenic, initial industrial soils, whilst according to the IUSS Working Group WRB classification (2015), they were classified as Technosols. The studied soils are characterised by a profile structure with the following horizons and layers: Olf (initial organic horizon with raw humus layer, with a thickness of 4–5 cm), AinCan (organic-mineral horizon with the traces of parent rock, with a thickness of 5–8 cm), Can1 (anthropogenic parent rock horizon, skeleton less, with a thickness of 25–35 cm), Can2 (anthropogenic highly skeletal horizon, i.e. > 50% of the skeletal material, with a thickness of 60–80 cm), Can3 (anthropogenic horizon forming an insulating layer, made of clayey substrate, with a thickness of 20–30 cm) and Can4 (separated post-flotation waste). The deepest insulating layer was used to separate the profile from being overgrown by woody plants from post-flotation wastes. From the point of view of land reclamation, this is an example of technogenic soil created in the phase of technical reclamation by applying fertilisers to the appropriate insulation layers and soil formation medium (Fig. 1).

The studied soils were characterised by neutral or alkaline reaction (pH in H_2O from 7.1 to 7.9 and in KCl from 6.9 to 7.7 in mineral horizons). The organic carbon content in the top organic-mineral horizons (AinCan) was, on an average, 1.4%, and the total nitrogen was 0.076%. The results obtained showed higher values compared to the mean values for the soil under the 25-year-old pine stands in the filling sand excavation of the 'Szczakowa' open-cast mine (C_{org} = 0.32–0.40%; Nt = 0.01–0.03%; Józefowska et al. 2016), which indicates a successful soil development process on the site under consideration. The content of trace elements (Zn, Cd and Pb) varied in the soil profile. The highest contents of Zn, Cd and Pb were in the post-flotation wastes (Can4), followed by the Can2 horizon, built of dolomite rocks rich in these trace elements. In other distinguished mineral soil horizons, the content of these elements was clearly lower (Table 1).

In assessing the rate of the soil formation process, the accumulation rate and the quality of the soil organic matter (SOM) are of fundamental importance (Pietrzykowski, Krzaklewski 2007); however, the assessment of soil biological properties is not less important (Chodak et al. 2009). A simple and very useful indicator of the assessment of biological soil depth in reclaimed areas is the assessment of the extent and intensity of

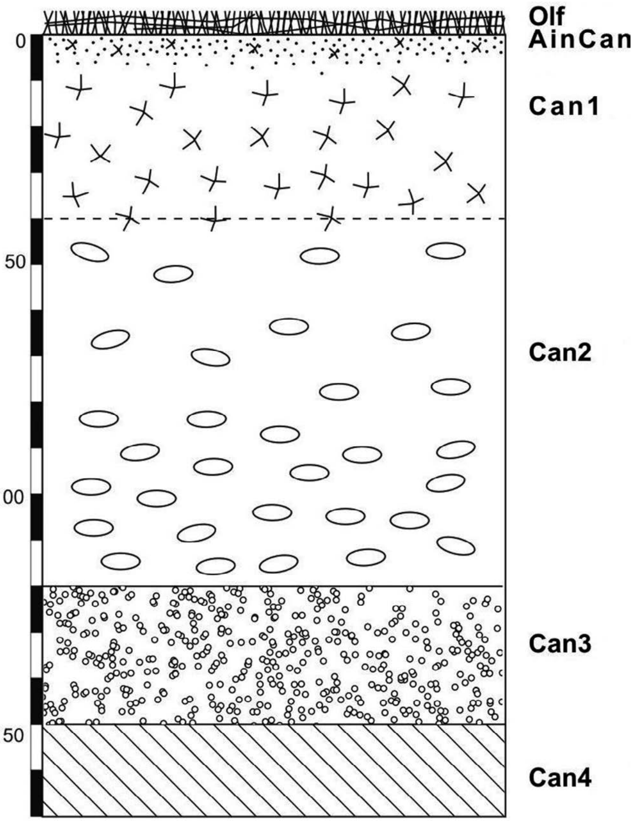

Figure 1. Scheme of reconstructed technogenic soil profile on reclaimed landfill waste after zinc and lead flotation with clay insulating layer and layers of substrate used as soil formation medium, Olf – pine litter, AinCan – sandy loam; Can1 – sandy loam; Can2 – loam, strong skeletal (70–80%), Can3 – clay insulating layer; Can4 – flotation waste

root occurrence in the soil profile, longused in habitat science (Puchalski, Prusinkiewicz 1990). The studied soils are characterised by the occurrence of tree roots to a depth of 60 cm, whereas the thickness of the layers covering the post-flotation waste deposits found in soil profiles was 110–150 cm.

The depth of the roots is limited by the strong skeletal structure of the substrate and the compacted deeper soil layers ofthe profile. A strongly skeletal horizon (with skeleton above 50%) in the studied soils occurs at a depth of 30–40 cm, constituting a significant barrier to the development of tree roots (Fig. 1). In terms of physical properties, the studied soils are similar to the soils formed from parent rocks with a stronger skeleton structure (rankers, rendzinas, etc.). Such conditions in natural forest habitats are typical for the soils of the mountains, foothills and uplands highlands, such as rendzinas of a nearby reclaimed site in the Kraków-Częstochowa Upland (Brożek, Zwydak 2010).

According to the yield and volume tables for stands by Szymkiewicz (2001), pine stands aged 20 years on the reclaimed post-flotation waste landfill were characterised by the site index class I. Stand density was high and amounted to an average of 7,350 trees ha^{-1}, with a standard error (SE) of 650 trees ha^{-1}, which is characteristic of untended stands (Szymański 2000). The average diameter at breast height of a given stand was 8 cm (at SE of 0.2 cm) and the average height was 11.5 m (at SE 0.2 m). A distinct shift of trees in biological classes, that is, in stand layers, was noted.

Most of the trees grew in the upper layer of the studied stand, as is the case in this stage of stand development, composed of light-demanding species (Szymański 2000); however, a distinct intermediate stand was established. In terms of vitality, trees normally developed and those of normal vitality prevailed in the studied stands (46%), whilst the proportion of less-developed trees with reduced vitality was relatively high (28%). Trees moving to higher biosocial classes predominated (55%), and the proportion of those falling to lower biosocial classes (31%) in the stands was relatively high.

This phenomenon is a natural consequence of intensive growth of trees in this phase of stand development, that is, it the juvenile phase, especially in the case of light-demanding tree species (Szymański 2000). In terms of silvicultural value, valuable trees prevailed in the examined stands (56%), whilst the proportion of undesirable trees amounted to 18%. Such a proportion of trees with poorer vitality, leaning and invaluable, is the result of the natural stand dynamics, connected with establishing the biosocial position of trees in the stand and a strong competition in the juvenile phase of stand development (Szymański 2000).

In the investigated stands, trees of average quality (according to IUFRO – utility wood, class 50) prevailed. Under the examined site conditions, the assessed parameters of trees can be considered satisfactory or even prospective in terms of future potential and productivity of stands on the reclaimed site (Table 2).

On sandy soils, which are the optimal site for Scots pine, the trees develop a deep, taproot system, which is characterised by a strong primary root that extends more or less vertically into the soil profile (Köstler et al. 1968; Jaworski 2004). However, the pine root systems can undergo significant adaptations to the growth conditions of a given habitat. The pines growing on the soils affected by zonal changes in moisture content, compactness, air–water relations or permeability often develop a flattened, disk-like root system (Köstler et al. 1968; Jaworski 2004).

The examined root systems showed transformations and deformations compared to a typical pine root system (Fig. 2). About 13% of these root systems were evaluated for the seconddegree of deformation, 67% for the third degree and 20% for the fourth and the strongest degree of deformation according to the deformation scale by Pietrzykowski et al. (2010). Under the conditions of a reclaimed post-flotation waste landfill, the root systems developed mainly in the vertical direction being limited by a shallow skeleton horizon (with a skeleton of above 50%).

The root systems of pine trees were characterised by the disappearance of the taproot, whilst lateral roots increased in diameter. The root system in these site conditions was usually flat, with shallow widely spread strong lateral roots and fine roots growing out of them deep into the soil. The vertical range of the coarse roots (d > 1 cm) was from 21 to 51 cm (an average of 36.3 cm), whilst the horizontal range from 68 to 216 cm (an average of 139.4 cm) (Table 3). In addition, the board-like swellings on the lateral roots were also visible, which in these conditions may ensure tree stability (Jaworski 2004).

Part of the root systems developed a characteristic form of fibrous root systems on the borderline with skeletal horizons. It is a phenomenon typical of soils affected by zonal variation in fertility or moisture conditions (Jaworski 2004). The observed deformations of pine root systems are, like in some other forest habitats, an example of adaptation to soils with shallow skeletal horizons.

In the future, when planning the reclamation and afforestation of such sites using the presented technology, two variants could be considered: to significantly increase (two to three times) the thickness of the substrate layer used as a soil formation medium covering waste deposits above the insulating layer, which can be very costintensive and dependent on the availability of the appropriate substrates material, or

Table 1. Selected technosol properties on reclaimed landfill waste after zinc and lead flotation

Soil horizons	Properties				EC	$CaCO_3$	C_{org}	Nt	Zn	Cd	Pb
	dust (0,05–0,002 mm)	loam (<0,02 mm)	pH w H_2O	pH w KCl							
	[%]				[µS cm^{-1}]		[%]		[mg kg^{-1}]		
Olf	n.o.[1]	n.o.	n.o.	n.o.	n.o.	n.o.	34.2±3.7	1.01±0.06	3224.0±324.3	27.5±3.0	1026.5±136.8
AinCan	27±10[2]	6±1	7.1±0.1	6.9±0.1	110.8±26.2	3.1±2.0	1.4±0.3	0.076±0.031	867.0±247.2	6.7±1.6	284.4±86.5
Can1	28±7	9±1	7.6±0.2	7.3±0.2	91.5±26.4	17.4±15.9	0.5±0.2	0.019±0.002	1241±690.4	11.5±8.0	606.9±436.5
Can2	39±3	15±3	7.9±0.1	7.7±0.1	179.5±3.5	58.0±8.0	n.o.	n.o.	3550.6±533.1	37.4±10.2	1600.3±247.3
Can3	74±1	26±1	7.9±0.1	7.4±0.1	233.5±47.5	47.3±36.8	n.o.	n.o.	272.9±129.2	1.8±0.7	77.4±18.5
Can4	39±10	3±2	7.7±0.1	7.6±0.1	1321,5±21.5	72.1±1.5	n.o.	n.o.	2871.7±115.5	42.8±3.8	2115.9±405.4

[1]n.o. – not specified; [2]mean±standard error (SE)

Table 2. Distribution structure of trees in Kraft and IUFRO classes in Scots pine stands growing on reclaimed landfill waste after zinc and lead flotation

Kraft classification			Number of trees	%
Dominant stand	I	predominant trees	48	25
	II	dominant trees	79	41
	III	co-dominant trees	31	16
Suppressed stand	IVa	intermediate trees, with restricted lateral crown growth	12	6
	IVb	intermediate trees, the crown under canopy cover	14	7
	Va	suppressed trees, with crowns still alive	7	4
	Vb	suppressed trees, with dead crowns	2	1

IUFRO classification			Number of trees	%
Biological position				
Stand layer	100	upper layer	124	64
	200	middle layer	46	24
	300	lower layer	23	12
Vitality	10	luxuriant trees	50	26
	20	trees normally developed	89	46
	30	trees weakly developed	54	28
Growth tendency	1	trees with an accelerated rate of growth	107	55
	2	trees with a normal rate of growth	26	13
	3	trees with a decelerated rate of growth	60	31
Silvicultural position				
Silvicultural value	400	valuable, outstanding tree	50	26
	500	usable wood	108	56
	600	poor to unusable quality	35	18
Trunk quality	40	valuable wood	3	2
	50	normal wood	134	69
	60	substandard wood	56	29
Crown length	4	deep crown, > 0.5 tree hight	33	17
	5	medium	87	45
	6	shallow, < 0.25 tree hight	73	38

to improve physical characteristics of compacted soil substrate and the use of less skeletal substrates in the restoration of technosol.

Sample trees from which root systems were taken were characterised by the following parameters: diameter at breast height from 7.5 to 13.6 cm, height from 7.9 to 11.1 m and the calculated aboveground biomass from 15.3 to 43.0 kg. The biomass (dry mass) of the root systems ranged from 1.2 kg (at d_0 = 9.4 cm and dbh = 7.5 cm) to 9.1 kg (at d_0 = 17.8 cm and dbh = 13.6 cm) (Table 3) and was similar to the biomass of the root systems of the 12- to 23-year-old pines growing on the reclaimed external waste heap of the KWB 'Bełchatów' open-cast coal mine (from 0.74 kg at d_0 = 6.8 cm to 7.52 kg at d_0 = 14.3 cm) and in the excavation of the 'Szczakowa' open-cast sand mine (from 0.74 kg at d_0 = 6.8 cm to 43.45 kg at d_0 = 21.1 cm) (Pietrzykowski et al. 2010).

Similar results were obtained in the studies conducted in natural habitats in southern Finland, where it was found that the root biomass of individual pines aged 18 and 19 years was 5.5 and 8.3 kg, respectively, with a diameter of 9 and 11 cm (Vanninen et al. 1996). The share of biomass of forest tree roots in natural ecosystems is usually estimated at approximately 20%, compared to aboveground wood biomass (Lieth, Whittaker 1975; Miller et al. 2006). However, this figure varies depending on the tree species, stand density and habitat conditions.

On the reclaimed post-mining sites, deformations of the tree root systems and too small root biomass compared to the aboveground biomass may negatively affect the stability of the planted stands (Pietrzykowski et al. 2010). In the case of the examined pine root systems of the trees growing on the reclaimed post-flotation waste landfill site, the ratio of root biomass to the aboveground biomass ($B_{root}/B_{a.g.}$) varied and ranged from 8% to 21%, and to 14%, on an average. The cited studies conducted in reclaimed areas (Pietrzykowski et al. 2010) showed similar figures for the pines from the Bełchatów external waste heap, where the values of $B_{root}/B_{a.g.}$ ratio ranged from 10% to 14%.

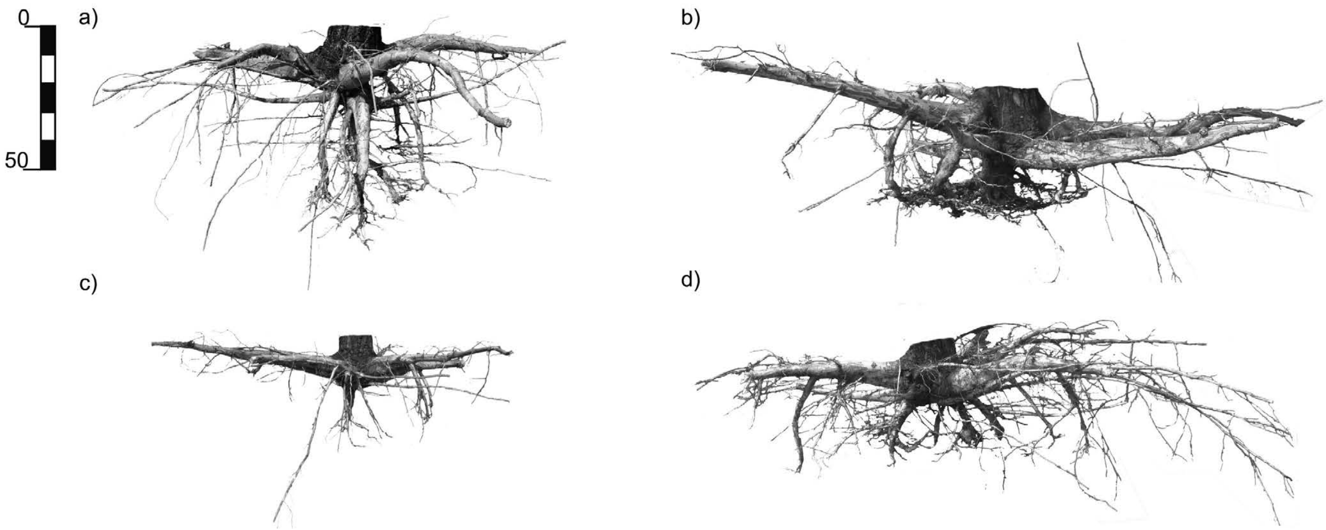

Figure 2. Root systems of 20-year-old pine trees growing on reconstructed technogenic soil, with varied deformation degree according to used scale in the work: a) 2nd degree deformation; b) and c) 3rd degree of deformation; d) 4th degree of deformation

However, the values of $B_{root}/B_{a.g.}$ ratio shown in this study were higher in comparison with the results of the cited studies (Pietrzykowski et al. 2010) for the pines growing in the excavation of the 'Szczakowa' open-cast sand mine with a shallow groundwater table (from 6.4% to 7%).

5. Conclusions

The reclamation technology applied, consisting in covering the post-flotation waste deposited in the excavation with an insulation layer and the available on-site mineral substrates, followed by afforestation, has proved effective. After 20 years, the effects are satisfactory, which is manifested by the formation of initial organic horizon indicating the proper soil and forest habitat development.

Scots pine growing on a reconstructed technogenic soil was characterised by good vitality and growth parameters; although the transformation in the morphology of the root system from the taproot typical of pine into a flattened system was visible in the morphology of the root systems, the transformation of the taproot typical for a pine tree into a flattened system was found. The observed deformations are, however, a sign of a good adaptation (plasticity) of pine growth under the conditions of a strong skeletal mineral substrate material used for soil reconstruction.

Based on the conducted research, to improve the reclamation technology, it is recommended to increase the thickness of the substrates covering the post-flotation waste or to reduce the amount of the skeletal substrate in the top layer in order to improve the growth conditions of tree roots on such sites.

Conflict of interests

The authors declare the lack of potential conflicts of interest.

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Table 3. Characteristics of growth and root systems parameters of 20-year-old pine trees growing on reclaimed landfill waste after zinc and lead flotation

	Aboveground part				Belowground part			B_{korz}/B_{nadz}
	d_0	dbh	h	B_{nadz}	Z_{pion}	Z_{poz}	B_{korz}	
	[cm]		[m]	[kg]	[cm]		[kg]	[%]
Mean	13.3	10.0	9.9	24.5	36.3	139.4	3.7	14
Minimum	9.4	7.5	7.9	15.3	20.0	68.0	1.2	8
Maksimum	17.8	13.6	11.1	43.0	51.0	216.0	9.1	21
Standard error (SE)	0.6	0.4	0.2	1.8	2.4	10.4	0.5	1

d_0 – diameter at root collar; dbh – diameter at breast height; h – height; B_{nadz} – aboveground biomass; Z_{pion} – vertical depth of roots; Z_{poz} – horizontal length of roots; B_{korz} – coarse roots biomass; B_{korz}/B_{nadz} – root biomass to aboveground tree biomass ratio

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Authors' contribution

M.P. – the concept and schedule of the research, preparation and supervision of the text of the article; B.W. – measurements, calculations, preparation of the text of the article; M.P. – measurements, preparation of the text of the article, J.L.-C. – preparation of the text of the article, drawings.

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