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PLANT COMMUNITY HEMEROBY IS A RELIABLE INDICATOR OF THE DYNAMICS OF RECLAMATION OF LANDS DISTURBED BY MINING

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Abstract

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Reliable indicators of success are needed to monitor the process of reclaiming disturbed land in order to understand the achievement of reclamation objectives. The formation of coherent dynamics of vegetation and soil development is ultimately a crucial condition for the success of reclaiming territory disturbed by surface mining and the possibility of using reclaimed land in agricultural production. The study revealed a relationship between the phytoindicator of vegetation hemeroby and the physical properties of technosols to prove its application as a measure of the restoration of the disturbed ecosystem in the reclamation process. The plant communities were classified into beta-, alpha-euhemerobic, polyhemerobic and metahemerobic levels of anthropogenic transformation. The technosols varied in the proportion of hemeroby levels of plant communities. The hemeroby level was consistent with the physical properties of technosols. A decrease in hemeroby level resulted in increased soil electrical conductivity, decreased soil penetration resistance and altered soil aggregate structure. The hemeroby of plant communities is a dependable phytoindicator of ecosystem restoration during reclamation.

Key words: soil compaction, floodplain, soil penetration resistance, aggregate structure, soil electrical conductivity, plant community, phytoindication, naturalness.

Introduction

Open-pit mining causes a risk of land degradation due to alteration of landscape forms, loss of vegetation cover and soil layers with favourable conditions for aggregation and accumulation of organic matter, as well as available nutrients for plants (Zvomuya et al., 2006)50, 100, and 150% of mandatory TRD. Mining companies must carry out reclamation to avoid negative environmental impacts and to return disturbed land to economic use (Mborah et al., 2015)the choice of variables that must be considered in deciding a particular post-mining land-use. Literature reviews were conducted to identify the major factors needed to be considered in the selection of a post-mining land-use. This paper also looks at the most commonly practiced and accepted post-mining land-use techniques. Factors identified as important in the selection process include land resources (e.g. physical, biological and cultural characteristics. Reclamation can be performed by restoring the form of the landscape close to the initial shape (de Haas, Schepers, 2022), by using the former topsoil as a plant substrate distributed on top of bedrock (Gunathunga et al., 2023), and planting of trees (Shupranova et al., 2022) and herbaceous plants in accordance with the planned post-mining land-use project (Thomas et al., 2015). Potentially productive rocks can also be used for reclamation (Zadorozhnaya et al., 2018). Soil-forming anthropogenic materials exhibit very diverse constituents, broad spatial variability and temporal discontinuities as a result of human activity (Huot et al., 2015). Certain extreme soil conditions can occur on mined land that inhibit plant growth, including physical conditions, severe nutrient deficiencies and toxicity (Bradshaw, 1997).

Reclaimed mine soils are anthropogenic soils created on lands disturbed by mining activities (Buta et al., 2019). Marginal lands are often degraded due to low soil fertility and other environmental constraints, such as poor chemical and physical properties, inaccessibility, waterlogging, and unfavourable terrain (Guzman et al., 2019). The null time for the development process of mine soils is the time when the soil material is suitable to be used as a substrate for plant growth (Sena et al., 2021; Zhukov, Arabadzhy-Tipenko, 2021)and particularly in Appalachia, USA. Mined land reforestation is of interest in this and other regions where forests are the dominant pre-mining land use. This study evaluated mine soil development on surface-mined sites reforested according to the Forestry Reclamation Approach, representing a chronosequence of time ranging from 0 to 19 years after reclamation. Soils were sampled in depth increments to 50 cm and analyzed for a suite of soil physical and chemical characteristics. Overall, soil fines (silt + clay. The composition of mine soils determines their pedogenesis trajectory (Huot et al., 2015). The properties of mine soils depend directly on the soil type and the physical and geochemical properties of the rock layers from which they originate (Iskandar et al., 2022). The direction of land reclamation dynamics is dependent on the design of the artificial soil-like formation resulting from the technological stage of reclamation (Guan et al., 2022). The reclamation process is long and the most significant part of it takes place during the biological phase of reclamation, when both positive and negative features of the original construction of the technosols can manifest themselves (Campbell et al., 2019).

The investigation of chronoseries is a common methodological approach to assess the dynamics of land reclamation (Wei et al., 2022). This approach assumes synchronised rates of reclamation in technosols of different composition and origin. Chronosequences are suitable for studying plant succession on time scales of decades to thousands of years, where there is evidence that sites of different ages are developing along the same trajectory (Walker, Reddell, 2007). They can also be used to study aspects of soil development that occur between temporally associated locations on timescales of centuries to thousands of years (Bardgett et al., 2005). Chronosequences are not well suited to studying successional trajectories that are seriously broken or interrupted in time, as there are often significant difficulties in identifying the temporal relationships between stages (Walker et al., 2010).The assessment of successional dynamics in vegetation and soil cover of reclaimed landscapes using the time sequence method is not the most appropriate, and alternative approaches need to be developed to assess the dynamics of disturbed land reclamation.

Reliable indicators of success are needed to understand the achievement of restoration objectives and can be used to monitor the process of reclaiming disturbed land (Negara et al., 2020). The formation of coherent dynamics of vegetation and soil development is ultimately a condition for the success of reclamation of the territory disturbed by open-pit mining and the possibility of using reclaimed land in agricultural production (Józefowska et al., 2023). Therefore, the aim of our study is to find out the relation between the phytoindication indicator of vegetation cover hemeroby and physical properties of technosols in order to prove its use as a measure of restoration of the disturbed ecosystem in the process of reclamation.

Material and methods

Field studies were conducted at the research station of the Dnipro State Agrarian and Economic University in the city of Pokrov (Dnipro region, Ukraine) (47°39'3" N, 34°8'40.28" E). The studies were performed on an artificial edaphotope, which was a planned overburden 2 m thick, taken from different depths of the open pit where manganese ore was mined (Yorkina et al., 2019; Zhukov et al., 2021). The experimental site for research and determination of the optimal thickness of the bulk soil layer was created between 1968 and 1970. Crops were grown on the territory until the beginning of the 20th century, but then this practice was discontinued. After that, the territory began to spontaneously vegetate with herbaceous grasses.

The climate of the territory is continental with an average annual temperature of 11.14 ± 0.30 °C. The average annual precipitation is 329–507 mm. The landscape is dominated by vast, slightly undulating plains. The most common geologic surface rock is loess and loess-like loams, which are several tens of meters thick. The study area belongs to the Central Pontic Grassland Zone (EuroVegMap). The natural vegetation cover is dominated by cereals and herbs. Two types of technosols were studied: lithosols and pedosols. The profile of pedosols consists of two horizons: the upper one is made up of bulk soil mass, and the lower one is made up of redeposited rocks or a dumped mixture of rocks. The lithosols are composed of rocks and their profile consists of one horizon. The lithosols formed on loess-like loams, grey–green and red–brown clays were studied.

During May 2019–2021, we measured the physical properties of the soil and recorded the presence of all types of vascular plants at four test sites within the respective type of technosol (pedosols and lithosols on red–brown, grey–green clays and loess-like loams). Surveys were conducted within 105 test plots of 3x3 m within each polygon. The sample plots were placed along seven transects with 15 sample plots in each transect. The sites were adjacent to each other, so each polygon measured 21x45 m with a total area of 945 m^2. The total database contains information on measurements at 1260 test sites (4 types of technosols × 105 replications in each type of technosol × 3 years of research).

The projected coverage of plant species was documented as a percentage. The species we used for the purposes of this study were usually infrared taxa. The critical specimens were collected and identified by microscopy. Plant taxonomy was based on Euro+Med Plantbase (http://ww2.bgbm.org/EuroPlusMed). The fidelity of diagnostic species for anthropogenic transformation levels was determined using the fidelity coefficient (phi coefficient) with a threshold of 25 (50 for highly diagnostic species). Species with a frequency of occurrence > 25% (for highly constant species > 50%) were considered constant, and species with a projective cover > 10% were considered dominant (Lavrinenko et al., 2023). The phi coefficient was calculated using the *indicspecies* library (Cáceres, 2013). The Frank and Klotz scale was used to assess the hemeroby of the plant community (Frank, Klotz, 1990). The original scales were converted to a 100-point scale. The weighted average of the hemeroby scores, taking into account the projective cover of plant species, was used to characterise the plant community hemeroby of each sample (Yorkina et al., 2022).

The electrical conductivity of the soil, the aggregate structure of soil, and the soil penetration resistance were measured in the centre of each 3 × 3 m test plot. The soil penetration resistance was measured in the field with a handheld *Eijkelkamp* penetrometer to a depth of 50 at 5 cm intervals (Kunah et al., 2019)on grey-green clay were chosen as the objects of the investigation. The simulation of moisture content in Nikopol Manganese Ore Basin technosols was performed using the Penman-Monteith approach and evaluated the role of the dependence of soils' surface albedo on the humidity in the intensity of evapotranspiration. The research was conducted during 2013–2015 at the station for research on reclaimed land within the Nikopol Manganese Ore Basin (city Pokrov, Ukraine. The mean measurement error of the device is ± 8%. The measurements were made with a cone with a cross section of 1 cm^2. At each point, the soil penetration resistance was measured only once. To measure the electrical conductivity of the soil *in situ*, we used the HI 76305 sensor (Hanna Instruments, Woodsocket, R.I.) in combination with the handheld device HI 993310 (Kunakh et al., 2020). The distribution of soil aggregate fractions by size was measured in accordance with the recommendations of the 'Methodology for the collection and analysis of soil samples' (Kroetsch, Wang, 2008). Descriptive statistics, ANOVA, analysis of components of relative variance, were calculated using the statistical software STATISTICA.

Results

The plant community at the reclamation area was represented by 70 plant species. The hemeroby index of plants varied from 12 to 100 (Table 1). The indicators of the beta-euhemerobic level were 9 plant species, among which 1 species (*Festuca valesiaca*) was a unique indicator. The indicators of the alpha-euhemerobic level were 10 plant species among which 3 species were unique indicators (*Eryngium campestre*, *Galium verum* and *Euphorbia stepposa*). The indicators of the polyheterobic level were 19 plant species, among which 5 species were unique indicators (*Linaria genistifolia*, *Pilosella officinarum*, *Chondrilla juncea*, *Dactylis glomerata* and *Stellaria holostea*). The indicators of the metaheterobic level were 13 plant species, among which 2 species were unique indicators (*Vicia cracca*, *Rumex confertus*). The hemeroby index of the community was 85.4 ± 0.18 and varied from 65.9 to 97.9 (Fig. 1). The polyhemerobic level of anthropogenic transformation was the most frequent (45.1% of records), while plant communities with metahemerobic (30.1%) and alpha-euhemerobic (20.2%) levels of transformation were somewhat less frequent (Table 2). The beta-euhemerobic communities were the rarest (4.7%). The technosols differed in the proportion of hemeroby levels of plant communities. From the results of the multivariate correspondence analysis, it was found that in the gradient of anthropogenic transformation conditions from metahemerobic to beta-euhemerobic conditions, the technosols formed a series: lithosols on red–brown clays → lithosols on loess-like clays → pedosols → lithosols on grey–green clays.

The level of hemeroby of plant communities was able to explain 2.2% of the variation in soil electrical conductivity (F = 11.5, P < 0.001). The lowest level of soil electrical conductivity was found under conditions of metahemerobic level of anthro-

Table 1. Frank–Klotz hemeroby index values (data normalised to the range of 0–100 with regional correction) and indicator plant groups to determine the level of hemeroby of the communities: '+' indicates a diagnostic type of anthropogenic transformation level or several levels. Phi is the fidelity index, *P*-value is the level of its significance after 999 iterations.

Species	Frank–Klotz	*Beta-euhemerobe*	*Alpha-euhemerobe*	*Polyhemerobe*	*Metahemerobe*	Phi	P-value
Lotus ucrainicus	43	+	+	+	–	0.05	0.47
Echium vulgare	58	+	+	+	–	0.05	0.74
Convolvulus arvensis	88	+	+	+	–	0.03	0.77
Onobrychis viciifolia	51	+	+	+	–	0.02	0.90
Melilotus officinalis	44	+	+	–	–	0.40	0.00
Agropyron cristatum	39	+	+	–	–	0.24	0.00
Tragopogon dubius	94	+	+	–	–	0.22	0.00
Cirsium arvense	97	+	+	–	–	0.14	0.02
Reseda lutea	95	+	+	–	–	0.10	0.08
Carduus acanthoides	60	+	+	–	–	0.09	0.09
Lepidium perfoliatum	86	+	+	–	–	0.08	0.10
Lactuca tatarica	80	+	+	–	–	0.07	0.11
Consolida regalis	99	+	+	–	–	0.07	0.28
Silene dichotoma	77	+	–	+	+	0.04	0.58
Elytrigia repens	85	+	–	+	–	0.07	0.22
Seseli campestre	54	+	–	+	–	0.04	0.61
Anisantha tectorum	97	+	–	+	–	0.04	0.78
Taraxacum campylodes	92	+	–	–	+	0.03	0.88
Jacobaea vulgaris	74	+	–	–	–	0.35	0.00
Alyssum desertorum	98	+	–	–	–	0.28	0.00
Bromus hordeaceus	79	+	–	–	–	0.25	0.00
Xanthium strumarium	100	+	–	–	–	0.22	0.00
Centaurea diffusa	97	+	–	–	–	0.17	0.01
Erysimum diffusum	87	+	–	–	–	0.13	0.02
Anthemis arvensis	82	+	–	–	–	0.13	0.02
Koeleria cristata	12	+	–	–	–	0.10	0.04

Table 1. Continued.

Species	**Frank–Klotz**	***Beta-euhemerobe***	***Alpha-euhemerobe***	***Polyhemerobe***	***Metahemerobe***	**Phi**	**P-value**
Poa pratensis	62	+	–	–	–	0.10	0.05
Elaeagnus angustifolia	74	+	–	–	–	0.10	0.08
Festuca valesiaca	28	+	–	–	–	0.04	0.91
Bromus squarrosus	99	–	+	+	+	0.22	0.00
Medicago sativa	78	–	+	+	+	0.13	0.03
Ambrosia artemisiifolia	94	–	+	+	+	0.07	0.24
Atriplex micrantha	95	–	+	+	+	0.06	0.47
Sonchus arvensis	96	–	+	+	+	0.06	0.54
Sanguisorba officinalis	48	–	+	+	+	0.05	0.65
Securigera varia	50	–	+	+	+	0.04	0.67
Prunus armeniaca	61	–	+	–	+	0.03	1.00
Rhaponticum repens	91	–	+	–	–	0.09	0.04
Lactuca serriola	99	–	+	–	–	0.08	0.18
Hypericum elegans	43	–	+	–	–	0.08	0.12
Thesium ramosum	25	–	+	–	–	0.06	0.25
Eryngium campestre	23	–	+	–	–	0.05	0.22
Galium verum	27	–	+	–	–	0.05	0.49
Euphorbia stepposa	23	–	+	–	–	0.02	0.92
Senecio leucanthemifolius	93	–	–	+	+	0.28	0.00
Melilotus albus	97	–	–	+	+	0.20	0.00
Achillea millefolium	87	–	–	+	+	0.19	0.00
Xeranthemum annuum	95	–	–	+	+	0.10	0.07
Melica transsilvanica	19	–	–	+	+	0.09	0.09
Filipendula vulgaris	47	–	–	+	+	0.07	0.25
Erigeron acris	83	–	–	+	+	0.05	0.66
Euphorbia esula	54	–	–	+	+	0.05	0.64
Medicago falcata	47	–	–	+	+	0.05	0.58
Aegilops cylindrica	96	–	–	+	+	0.04	0.75
Medicago lupulina	33	–	–	+	+	0.04	0.82
Rosa canina	44	–	–	+	–	0.08	0.09
Agrimonia eupatoria	41	–	–	+	–	0.06	0.31
Crepis tectorum	100	–	–	+	–	0.06	0.30
Linaria genistifolia	33	–	–	+	–	0.05	0.45
Pilosella officinarum	51	–	–	+	–	0.05	0.42
Chondrilla juncea	52	–	–	+	–	0.04	1.00
Dactylis glomerata	86	–	–	+	–	0.04	1.00
Stellaria holostea	18	–	–	+	–	0.04	1.00
Falcaria vulgaris	87	–	–	–	+	0.21	0.00
Pyrus communis	64	–	–	–	+	0.14	0.56
Hieracium virosum	41	–	–	–	+	0.11	0.02
Artemisia absinthium	86	–	–	–	+	0.11	0.05
Helichrysum arenarium	22	–	–	–	+	0.08	0.19
Vicia cracca	93	–	–	–	+	0.05	0.48
Rumex confertus	97	–	–	–	+	0.04	0.56

pogenic transformation of plant communities (planned comparison $F = 29.1$, $P < 0.001$) (Fig. 2). The alpha-euhemerobic, beta-euhemerobic and polyhemerobic levels did not differ in soil electrical conductivity (planned comparison $F = 0.04$, $P = 0.83$). The aggregate fractions can be divided into three groups (Fig. 3). The group of aggregates with sizes > 10, 7–10, 5–7, 0.25–0.5 and < 0.25 increased their content with an increase in the level of hemeroby of the plant community. The group of aggregates with sizes 3–5, 2–3 and 1–2 mm decreased their proportion with an increase in the hemeroby of the plant community. The aggregates with a size of 0.5–1 mm did not statistically significantly depend on the level of hemeroby.

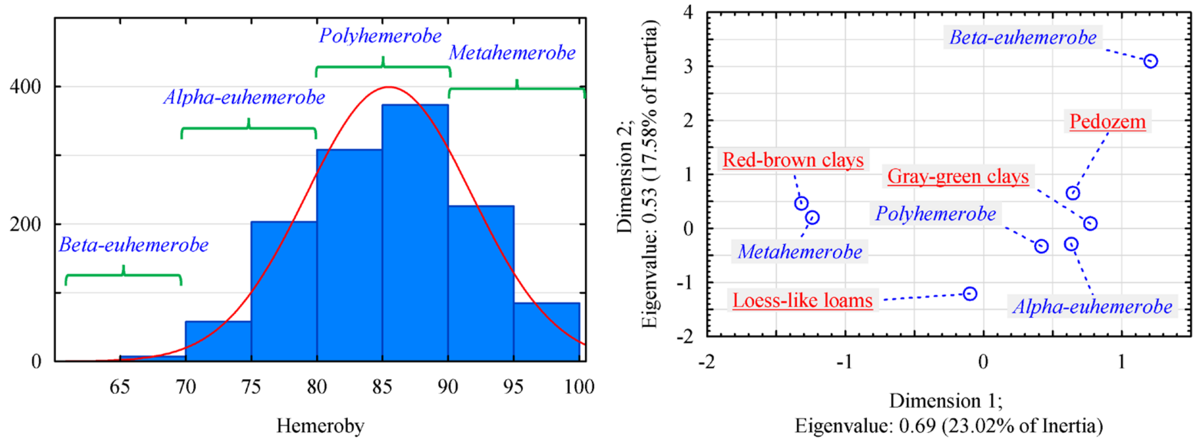

Fig. 1. Distribution of hemeroby level scores multiple analysis of correspondence between technosol types and hemeroby levels. Types of technosols: Red–brown clays are lithosols on red–brown clays; Loess-like loams are lithosols on loess-like loams; Pedozem are pedosols with a humified bulk layer; Grey–green clays are lithosols on grey–green clays.

Table 2. The proportion of hemeroby levels in technosols types (in %).

Technosol	Hemeroby level			
	Beta-euhemerobe	**Alpha-euhemerobe**	**Polyhemerobe**	**Metahemerobe**
Grey–green clays	7.3	23.2	55.6	14.0
Loess-like loams	2.5	21.0	45.1	31.4
Pedozem	7.6	26.3	48.6	17.5
Red–brown clays	1.3	10.2	31.1	57.5
Total	4.7	20.2	45.1	30.1

The soil penetration resistance increased with the increase of hemeroby at all studied depths (Fig. 4). The variation of soil penetration resistance explained by the level of hemeroby had three local maxima: in the upper soil layer 0–5 cm, in the layer 25–30 cm and in the layer 45–50 cm. The most significant differences in soil penetration resistance values were between the beta-hemeroby level and other levels of anthropogenic transformation. The differences between the metahemerobic, polyhemerobic and alpha-hemerobic levels in terms of soil penetration resistance were not statistically significant for depths of 0–5 cm (planned comparison $F = 1.15$, $P = 0.28$), 5–10 cm (planned comparison $F = 2.23$, $P = 0.14$) and 10–15 cm (planned comparison $F = 0.028$, $P = 0.87$). The soil penetration resistance at greater depths differed statistically significantly between the different levels of hemeroby.

Discussion

A significant amount of land degraded by previous mining activities requires restoration (Bieloborodova, Bessonova, 2023; Bradshaw, 1997). The reclamation of degraded land should be cost-effective and efficient (Xie, van Zyl, 2022). The natural succession processes demonstrate that soils can be restored without

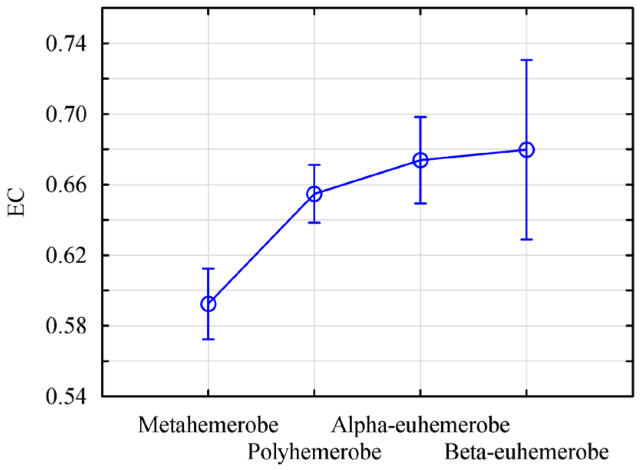

Fig. 2. Dependence of the electrical conductivity of technosols on the level of hemeroby of the plant community. The abscissa is the level of hemeroby, and the ordinate is the observed electrical conductivity of the soil, dS/m. The vertical lines indicate the 95% confidence interval.

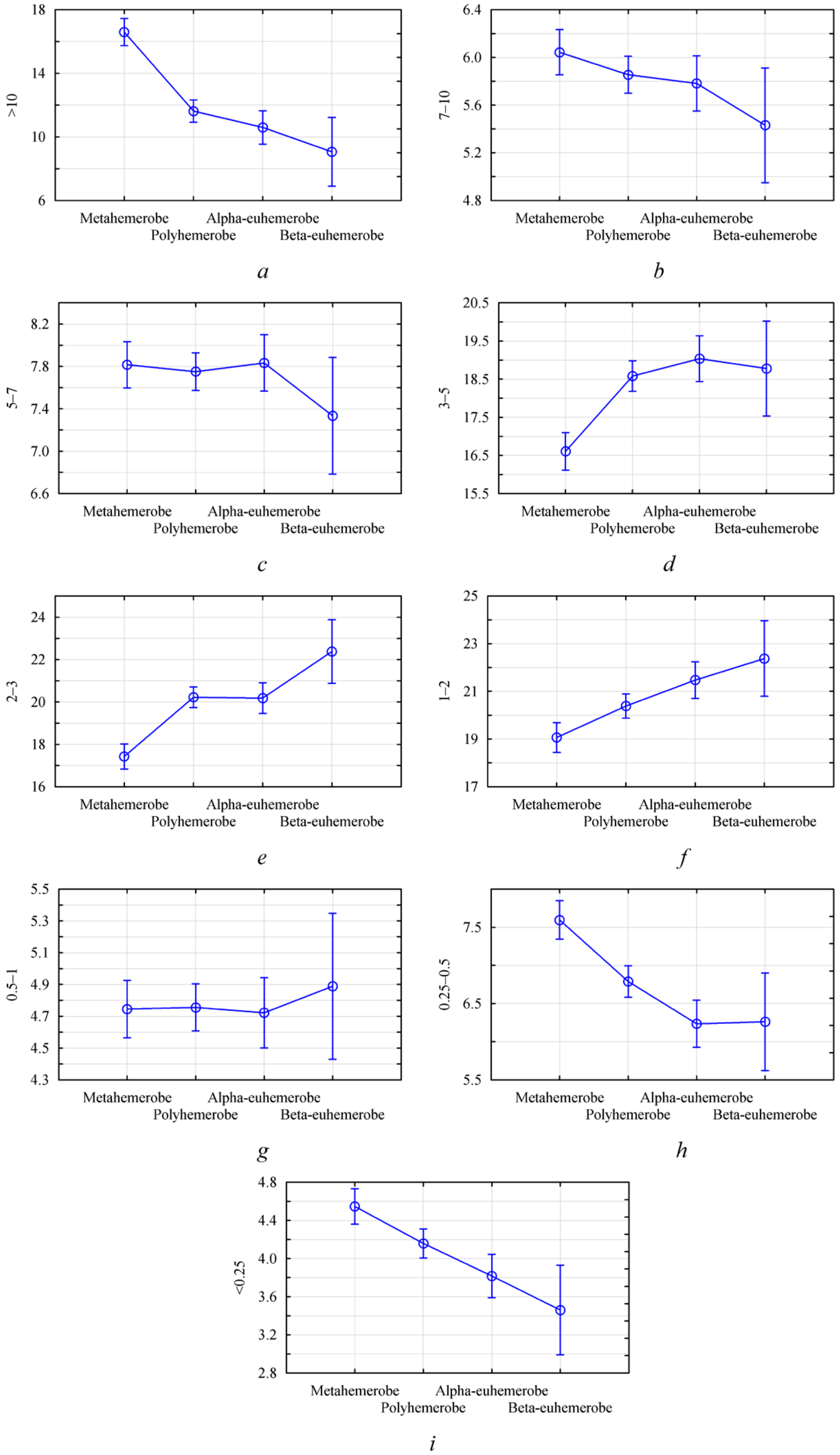

Fig. 3. The dependence of the amount of aggregate fractions on the level of hemeroby of the plant community. The abscissa is the level of hemeroby, and the ordinate is the content of aggregate fractions, % by size: *a*) > 10 mm ($R^2 = 0.08$, $F = 38.4$, $P < 0.001$), *b*) 7–10 mm ($R^2 = 0.003$, $F = 2.3$, $P = 0.073$), *c*) 5–7 mm ($R^2 = 0.001$, $F = 0.9$, $P = 0.42$), *d*) 3–5 mm ($R^2 = 0.037$, $F = 17.2$, $P < 0.001$), *e*) 2–3 mm ($R^2 = 0.053$, $F = 24.4$, $P < 0.001$), *f*) 1–2 mm ($R^2 = 0.021$, $F = 10.2$, $P < 0.001$), *g*) 0.5–1 mm ($R^2 = 0.002$, $F = 0.14$, $P = 0.93$), *h*) 0.25–0.5 mm ($R^2 = 0.038$, $F = 17.4$, $P < 0.001$), *i*) <0.25 mm ($R^2 = 0.024$, $F = 11.3$, $P < 0.001$). The vertical lines indicate the 95% confidence interval.

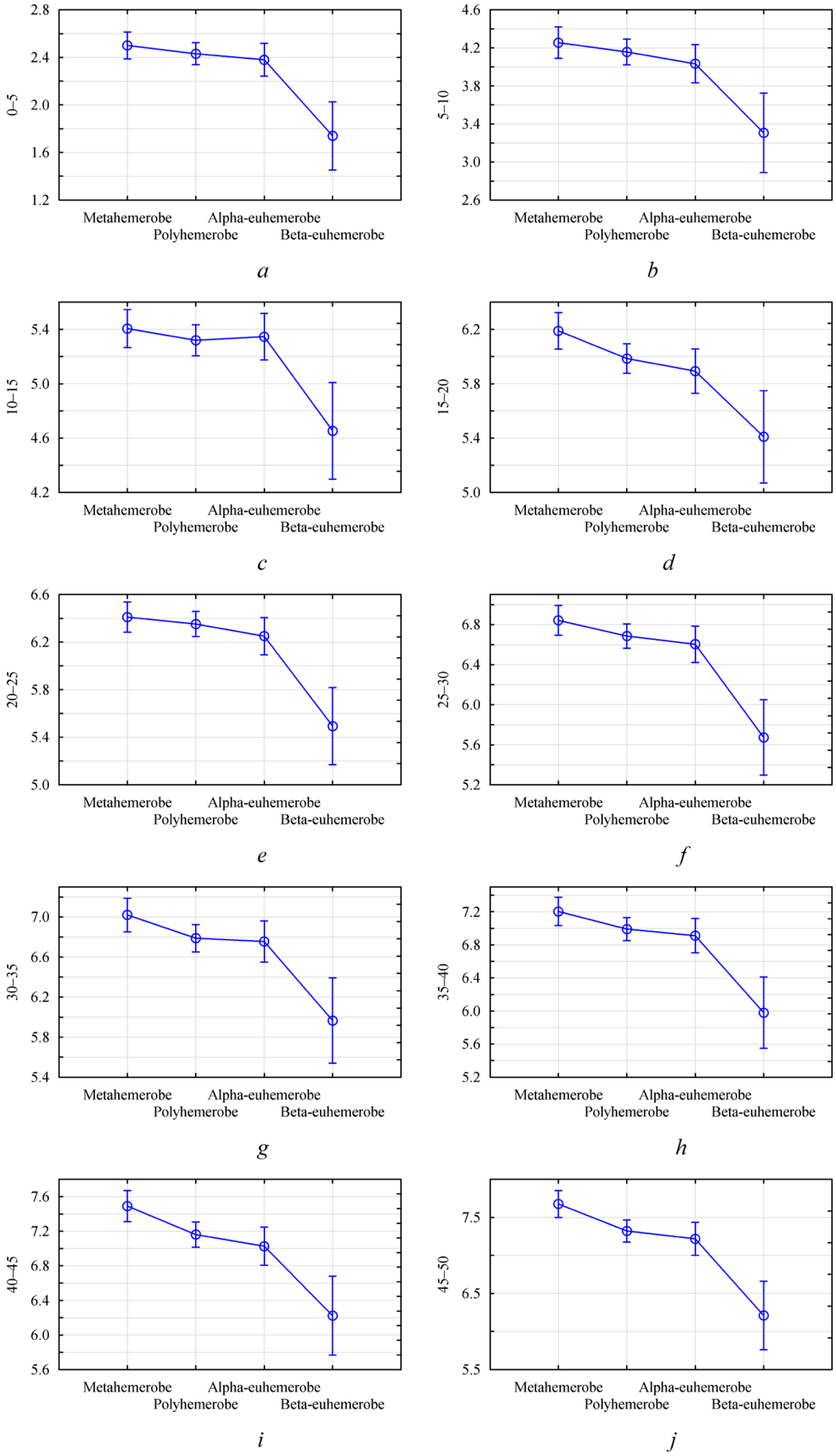

Fig. 4. The dependence of soil penetration resistance on the level of hemeroby of the plant community. The abscissa is the level of hemeroby, and the ordinate is the soil penetration resistance in MPa at the depth: *a*) 0–5 cm ($R^2 = 0.018$, $F = 8.0$, $P < 0.001$), *b*) 5–10 cm ($R^2 = 0.014$, $F = 6.1$, $P < 0.001$), *c*) 10–15 cm ($R^2 = 0.012$, $F = 5.0$, $P < 0.001$), *d*) 15–20 cm ($R^2 = 0.016$, $F = 7.0$, $P < 0.001$), *e*) 20–25 cm ($R^2 = 0.022$, $F = 9.3$, $P < 0.001$), *f*) 25–30 cm ($R^2 = 0.025$, $F = 10.9$, $P < 0.001$), *g*) 30–35 cm ($R^2 = 0.017$, $F = 7.2$, $P < 0.001$), *h*) 35–40 cm ($R^2 = 0.022$, $F = 9.2$, $P < 0.001$), *i*) 40–45 cm ($R^2 = 0.023$, $F = 10.1$, $P < 0.001$), *j*) 45–50 cm ($R^2 = 0.031$, $F = 13.1$, $P < 0.001$). The vertical lines indicate the 95% confidence interval.

any assistance, creating fully functioning soils (Bradshaw, 1997; Savosko et al., 2022). Revegetation of mining substrates remaining after open-pit mining can be an effective land reclamation measure, similar to the revegetation of abandoned land (Buta et al., 2019).

The hemeroby of a plant community is usually considered as a marker of the level of anthropogenic transformation from natural to the most disturbed conditions (Tian et al., 2020). Our work considers the possibility of using the hemeroby indicator to reflect ecosystem recovery, i.e. to monitor the reclamation process. The starting conditions of reclamation can be considered as the state of the ecosystem with the highest level of hemeroby, which should decrease over time during the reclamation process. The target function of the reclamation process is to achieve the state of the highest naturalness (Bradshaw, 1997). The results of our studies indicate varying levels of anthropogenic transformation in plant communities on the reclamation site, ranging from metahemerobic to beta-euhemerobic levels. The different types of technosols exhibit unique proportions of communities with varying levels of hemeroby. The prevalence of metahemerobic communities suggests a decelerated reclamation process, resulting in the ecosystem remaining in a state similar to its initial level of anthropogenic transformation. The lithosols on red–brown clays demonstrate a delay in the recovery process during reclamation. The prevalence of beta-euhemerobic communities indicates a faster reclamation process, which is typical for pedosols. The findings can be explained by the fact that technological activity results in the formation of initial anthropogenic materials that exhibit high lateral and vertical variability (Huot et al., 2015). The heterogeneity of technosols results in varying rates of reclamation processes and, consequently, different rates of hemeroby reduction. For instance, lateral variations in composition, grain size, and porosity can be observed in limited deposits of technosols, which affect soil development (Néel et al., 2003). Local heterogeneities, such as variations in texture and compaction of layers, can affect soil hydrodynamics and restrict the growth of organisms (Santini, Fey, 2015). Cracks and interfaces between the layers can create favourable areas for mixing and weathering processes (Huot et al., 2014). The use of humified soil is an effective strategy for restoring disturbed soil cover and reclaiming land. However, it is important to note that this strategy may not always be feasible. In cases where rocks without a humified layer are available, technosols can be created instead. The hemeroby index suggests that the rate of lithosol reclamation on grey–green clays is comparable to that of pedosol reclamation, indicating the potential use of rocks for land reclamation.

The electrical conductivity of the soil demonstrates a tendency to increase its values during the course of reclamation. The electrical conductivity of soil is a complex indicator that depends on the ratio of solid, liquid and air phases of the soil and on the mineralisation of the soil solution (Friedman, 2005). The soil phase ratio as a factor of electrical conductivity explains the effect of organic matter content on soil electrical conductivity, as organic matter significantly affects the formation of aggregates and the structure of the vapour space in the soil (Rahimi et al., 2000). There is evidence that electrical conductivity decreases during reclamation, which is due to a decrease in soil moisture and soluble salt content (Sun et al., 2011). In our case, the most important factor that can explain the increase in soil electrical conductivity is the increase in soil moisture content as a result of the reduction in hemeroby. The accumulation of organic matter and the improvement of the soil's ability to form aggregates also contribute to the increase in available moisture content for plants.

Aggregation processes involving inorganic and organic anthropogenic materials occur in anthropogenic soils (Badin et al., 2009). The key property that determines physical, chemical and biological soil regimes, among the parameters that describe soil functions, is soil aggregate structure. This property is poorly understood in technosols (Monserie et al., 2009). Technosols undergo pedogenic processes similar to those in natural soils under similar pedoclimatic conditions. The dominant chemical reaction is decarbonation, and the biophysical reaction is aggregate formation. Séré et al. (2010) found significant evolution of macrostructure, water-holding properties and evidence of microstructuring (Séré et al., 2010). However, anthropogenic soils generally exhibit poor development of aggregate structure (Bronick, Lal, 2005)flocculation and cementation of particles. It is mediated by soil organic carbon (SOC. Technosols form blocky peds due to drying cracks (Huot et al., 2015). Changes in their aggregate structure affect pore space and water-physical properties (Jangorzo et al., 2013). The plant root system forms the granular structure of the upper layer of technosols (Kozłowski et al., 2023) the natural landscape is damaged, along with soils, and new anthropogenic landforms are created which require reclamation. Usually, the evaluation of the effects of reclamation (mostly forestry. Our research has shown that a decrease in soil hemeroby is accompanied by a decrease in the proportion of aggregates larger than 5 mm and smaller than 0.5 mm, while there is an increase in aggregates of 1–5 mm in size. These findings do not correspond to the traditional classification of aggregates by size into microaggregates (aggregates smaller than 0.25 mm), mesoaggregates (aggregates 0.25–10 mm) and macroaggregates (aggregates larger than 10 mm) (Shein et al., 2001). Mesoaggregates are defined as agronomically valuable because they positively contribute to the formation of conditions that are favourable for plant growth and productivity (Medvedev, 2008). However, it is important to note that these generalisations were made for agrosols and may not be fully applicable to technosols. Our research has shown that the boundary of macroaggregates shifts from 10 to 5 mm, and the boundary of microaggregates shifts from 0.25 to 0.5 mm. The formation and maintenance mechanisms of mechanical stability differ between size groups of aggregates, as well as their internal organisation (Tisdall, Oades, 1982). The properties of aggregates are dependent on the bonding mechanisms of soil grains, in which organic matter plays a significant role. The low level of organic matter in technosols is assumed to be the reason for the change in the boundaries of aggregate size classes. It is also assumed that these boundaries will approach those observed in natural soils or agrosols as the ecosystem becomes more naturalised during reclamation.

Soil penetration resistance measures the strength of a soil against deformation or compaction (Reintam et al., 2009). It is the force required to penetrate the soil surface or to a certain depth in the soil (Arriaga et al., 2011). Soil strength is a complex property that is influenced by numerous factors, including composition, structure, moisture content, density, load history and vegetation (Guérif, 1990). The interaction of these factors affects soil resistance to penetration. The development of plant roots is significantly influenced by the biological and physicochemical properties of the soil (Bengough et al., 2011). The increased mechanical resistance caused by soil drying or compaction affects soil porosity, all aspects of root growth, rooting depth and root morphology (de Lima et al., 2012)compression index (CI. Soil penetration resistance is a key factor affecting root development. Increased soil penetration resistance reduces the rate of root elongation and affects the branching pattern (Bécel et al., 2012). The roots of plants potentially affect soil strength by increasing the shear strength of the soil, either directly through mechanical resistance and anchoring or indirectly through the loss of soil water through transpiration (Kumi et al., 2023). Root development can be restricted by physical soil conditions, especially soil compaction. The compaction of the soil increases the resistance to the development of the plant root system and, as a result, negatively affects the absorption of water and nutrients by plants, restricts plant growth and reduces agricultural productivity (Unger & Kaspar, 1994)review the contributions of Dr. Howard M. Taylor (1924-1991. There is a feedback loop between soil strength and the growth and functioning of the root system (Kumi et al., 2023).

A decrease in hemeroby is linked to a reduction in soil penetration resistance at all measured depths. The most sensitive values were observed at depths of 0–5, 25–30, and 45–50 cm. This phenomenon can be attributed to the significant impact of plant root systems on soil strength variability. The sod horizon, which is the upper root-saturated layer, experiences a decrease in penetration resistance as the density of vegetation cover increases and its loosening effect takes hold. Increasing vegetation density can reduce solar radiation reaching the soil surface, which minimises water loss. Soil moisture has a negative relationship with penetration resistance. This is consistent with the increase in soil electrical conductivity due to increased moisture during reclamation. The zone of strong development of fibrous root systems of herbaceous plants is typically limited to a depth of 25–30 cm, as described in soil transects. The changes in penetration resistance at a depth of 45–50 cm may be the result of the influence of plant taproots. The revegetation of mine soils leads to an increase in root biomass and litter accumulation (Li et al., 2023), which subsequently decomposes to form soil organic matter (Zhu et al., 2020). The development of soils formed from man-made materials is driven by organisms through the accumulation and decomposition of organic matter on the surface. It is important to note that this process is objective and does not involve any subjective evaluation (Bini, Gaballo, 2006). Increasing the amount of organic matter in artificially created soil alters its structure and physical and chemical properties (Dexter et al., 2008). Soil organic matter is crucial in determining various soil properties, including water-holding capacity, macropore formation, nutrient sequestration and adsorption and biological diversity (Fu et al., 2010). Therefore, an increase in vegetation density and diversity is a clear indication of a decrease in hemeroby, which directly impacts the variability of physical properties of technosols.

Conclusion

Technosols of different compositions and origins have a variety of properties, resulting in very different rates of reclamation within the same type of technosol. Therefore, using phytoindication to study the dynamics of land reclamation disturbed by surface mining has a significant advantage over traditional approaches such as chronosequences. The hemeroby of plant communities is a reliable phytoindicator of ecosystem restoration during the reclamation process. The hemeroby changes demonstrate coordinated dynamics with changes in the physical condition of technosoil in the process of reclamation, the direction of which indicates an improvement in the conditions of existence of soil biota and vegetation cover. The transformations of soil properties in the course of reclamation can also be explained by the influence of vegetation cover on artificial soils.

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