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FOREST RECLAMATION OF TECHNOGENIC LANDS: A CASE STUDY OF ASH AND SLAG DUMPS

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Abstract: Forest reclamation of technogenic landscapes represents a considerable ecological intervention, addressing environmental challenges caused by industrial transformation of the environment. This comprehensive study investigates vegetation restoration and ecological rehabilitation on ash and slag dumps of the Burshtyn Thermal Power Plant, revealing innovative strategies for ecosystem recovery with forest reclamation in severely degraded environments. The research explores spontaneous succession and strategic phytorecultivation, analyzing the species diversity and ecological characteristics of woody vegetation on ash and slag dumps. Surprisingly, native species predominated (65 % of tree species), challenging previous assumptions about vegetation restoration in anthropogenically transformed landscapes. Pioneer species like *Betula pendula*, *Salix caprea* and *Populus* spp. emerged as critical agents of ecological transformation, capable of rapidly establishing vegetation cover and initiating complex successional processes. Nitrogen-fixing species such as *Alnus glutinosa* and *Hippophae rhamnoides* were highlighted for their unique ability to restore ecosystems on technogenic substrates. The study recommends a diverse ensemble of tree and shrub species with exceptional adaptive capabilities, demonstrating a sophisticated biological approach to landscape restoration. Practical recommendations include strategic species selection, understanding spontaneous succession dynamics and implementing supplementary restoration techniques. By providing a comprehensive framework for ecological restoration, this research contributes to environmental management and sustainable landscape rehabilitation, offering innovative approaches to transforming degraded industrial territories into functional ecosystems.

Keywords: forest reclamation, phytorecultivation, technogenic landscapes, ecological restoration.

1. INTRODUCTION

Technogenic landscapes pose significant ecological challenges, and as territories of environmental risks, require innovative approaches to restore ecosystems transformed by industrial activities. Restoration of degraded landscapes encompasses a systematic multistage approach, characterized by integrated intervention strategies. The biological reconstruction phase represents a pivotal intervention strategy, incorporating sophisticated agrotechnical and phytoameliorative methodologies (Řehounkova et al., 2011, Aronson et al., 2016). These interventions are strategically designed to reestablish ecological habitat conditions and reinstate fundamental ecosystem functionality, whilst regenerate potential socioeconomic and agricultural landscape values.

Modern ecological restoration approaches emphasize near-natural recultivation strategies for degraded territories, which aim to reconstruct landscapes with enhanced ecological integrity and potential economic sustainability (Lin et al., 2024). The near-natural restoration paradigm shows ecological resilience, demonstrating the capacity to stabilize successional trajectories, particularly in post-industrial and post-mining landscapes (Zhang et al., 2023). Notably, this approach facilitates the emergence of high-biodiversity communities, potentially including rare and specialized species assemblages, which represent significant conservation value (Lin et al., 2024).

Phytorecultivation emerges as a critical biological rehabilitation strategy, involving the strategic selection of plant species with exceptional adaptive capabilities (Brown & Amacher, 2010). The fundamental aim is to establish resilient plant communities capable of not just surviving, but actively thriving in technologically altered environments, characterized by extreme and challenging conditions (Bhatia et al., 2023). This approach represents an ecological intervention, transforming degraded industrial territories into potential sites of biological regeneration and environmental recovery.

Forest reclamation represents a fundamental aspect of phytorecultivation, providing an integrated framework for landscape restoration and ecological recovery. This approach focuses on restoring forest ecosystems, profoundly affected by industrial exploitation, mining activities, or severe land degradation (Tischew & Lorenz, 2005; Savosko et al., 2021). Through the selection and establishment of native and pioneering tree species with high remediation potential, forest reclamation not only reinstates vegetative cover but also drives essential ecological processes, including soil restoration, biodiversity conservation, and the enhancement of ecosystem resilience (Adams, 2017; Šebelíková et al., 2019). Thereby, a crucial aspect of forest reclamation is the strategic selection of plant species with appropriate capacities to cope with site-specific environmental conditions and the implementation of sustainable management practices to promote natural succession and long-term ecosystem functionality.

Ash and slag dumps of thermal power plants, as neoedaphotops with no natural analogues, represent unique substrates for the establishment and development of plant cover, especially forest cover. Considering the environmental risks posed by these thermal energy facilities, investigating the floristic diversity and the patterns of vegetation restoration, natural colonization process and species establishment are a critical priority for devising measures to rehabilitate potentially hazardous sites. Forest reclamation of destroyed sites has many benefits such as better soil bonding, stimulating of the development of ground flora, activating of the pedological processes in the substrate of the root system, preventing insolation and drying of the soil, blowing of strong winds and dust rising (Mustafa et al., 2012; Gajic et al., 2018). Inclusion of shrubs and subshrubs along with tree species in tree plantations could help in interception of particles due to dense layers close to the ground. Forest reclamation is particularly promising, as it is a long-term, comprehensive and effective method that not only improves the ecological condition of man-made territories, but also creates new opportunities for their use in social and economic contexts (Aronson, 2016; Lin et al., 2024).

The primary consideration in developing recultivation measures is determining the appropriate type of vegetation and species composition to establish. Spontaneous succession often facilitates the restoration of valuable ecosystems through the gradual establishment of species whose ecological requirements align with local site conditions (Řehounková et al., 2011; Żołnierz et al., 2015). However, plant establishment on ash and slag dumps is constrained by several factors, including heavy metal toxicity, salinity, high pH levels and the deficiency of nitrogen and organic

matter (Pandey & Singh, 2015; Gajic et al., 2018). These challenging edaphic conditions shape the vegetation, allowing only species thriving under such harsh conditions to establish (Pandey & Singh, 2015; Řehounková et al., 2011; Pietrzykowski, 2019).

Consequently, spontaneous succession is considered to be an advanced and effective approach for restoration in these environments. There is evidence that in areas such as ash and slag dumps, forest cover can naturally establish itself over a period of two decades (Yuan et al., 2020). However, there is currently limited knowledge regarding the patterns of natural colonization of tree species and the formation of forest ecosystems in these environments. Investigating the condition of plant cover and species diversity of woody vegetation on ash and slag dumps will provide a crucial basis for developing effective strategies for forest reclamation of technogenic landscapes. This research is essential for understanding the ecological processes at play and for optimizing approaches to restoring disturbed lands through forest reclamation.

Therefore, the aim of this study is: (1) to investigate the species diversity of woody vegetation of ash and slag dumps of Bursthyn TPP; (2) to estimate native woody species abilities to survive in conditions of ash and slag dumps; (3) to suggest the list of species recommended for forest reclamation; (4) to develop recommendations for forest reclamation of technogenic lands (on the example of ash and slag dumps of Burshtyn TPP) .

2. RESEARCH OBJECTIVE, METHODOLOGY AND DATA

The study area is the Burshtyn Thermal Power Plant – the largest TPP in the Western Ukraine with the capacities of 2400 MW (Mylenka 2009; Kovaliv 2013). Burshtyn TPP is located in Halytskyi district, Ivano-Frankivsk region. The ash and slag dumps of Burshtyn TPP are special hydraulic engineering structures designed for the storage of solid waste from coal combustion. More than 200 ha of land are used for the ash and slag dumps of Burshtyn TPP. The study area is the ash and slag dump site №3, which is used actively and located 5 km from Burshtyn TPP, covering in total 91 ha. The overall storage facility of ash and slag dump site №3 is 24,6 million m^3, currently filled for 98.5 % of its capacity (Environmental Impact Assessment Report, 2019).

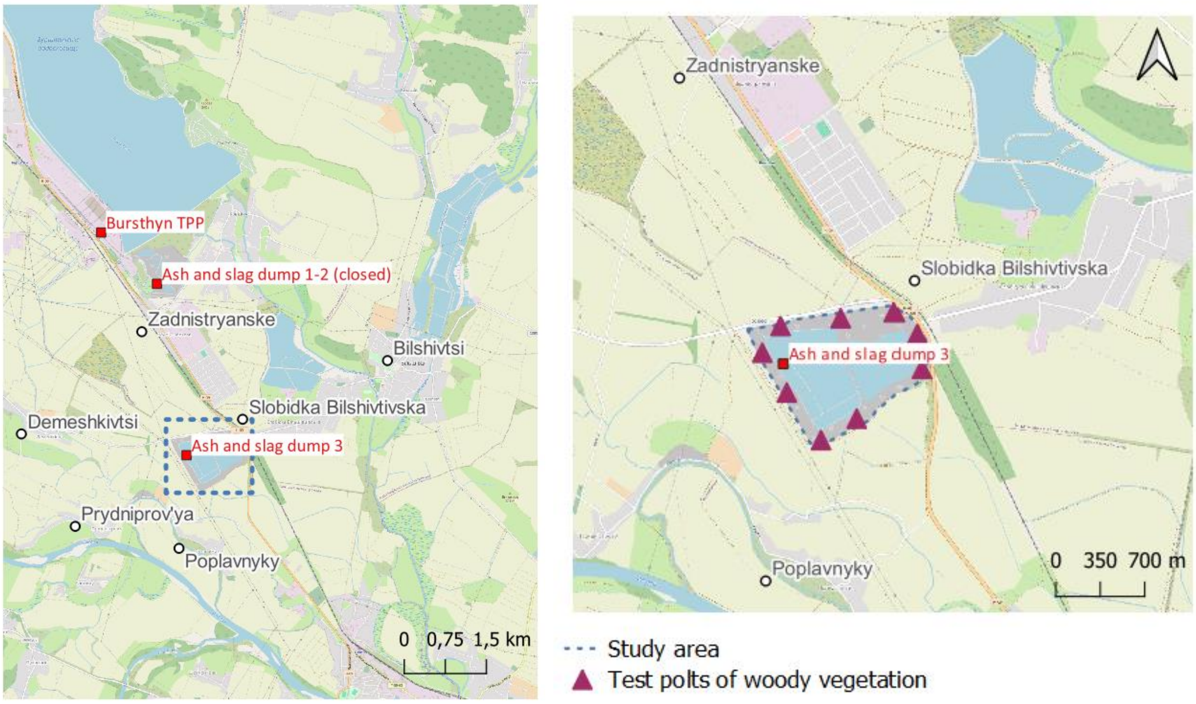


Figure 1. Study area – the territory of ash and slag dump 3 of Burshtyn TPP (QGIS 3.22.5, using OpenStreetMap data)

Study area vegetation was sampled during 2020-2021 on the territory of ash and slag dump №3 of Burshtyn TPP (Fig. 1). The territory was studied using the route method. Observations were made along and across the territory due to the prepared route. The method of trial plots was used to study the vegetation. On the territory of the most representative places test plots with an area of 20×20 m^2 were laid, and a comprehensive list of the flora was completed.

A systematic analysis was conducted on the herbarium material collected with the help of the route method. The names of plants from technogenic lands are given according to modern nomenclature reports (Mosyakin & Fedoronchuk, 1999). For the ecological analysis of the vegetation the database "Datenbank biologisch-ökologischer Merkmale der Flora von Deutschland" (Biolflor) (Klotz et al, 2002), "The World flora online" (WFO, 2024), and literary sources, in particular "Ecoflora of Ukraine" (2000-2010) were used. Based on systematic and ecological analysis of vegetation, recommendations for forest reclamation of ash and slag dumps have been developed.

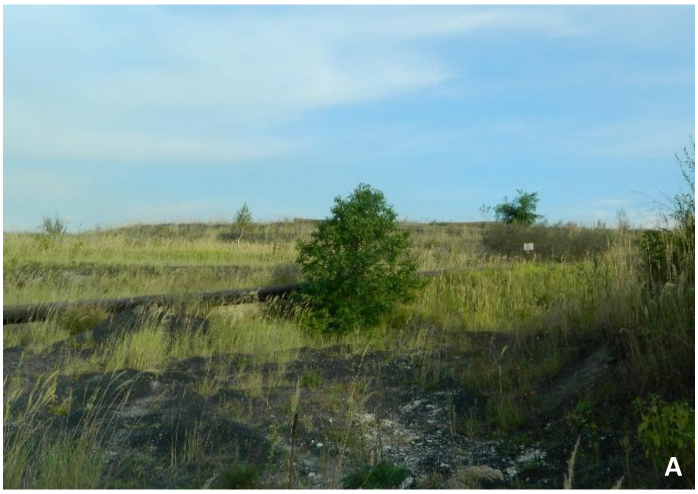
3. RESULTS AND DISCUSSION

At the first stage of revegetation, the establishment of species that rapidly colonize disturbed areas is crucial, as technogenic lands are typically first colonized by herbaceous vegetation. As pioneer species, herbaceous plants add organic nutrients and ameliorate surface, which helps to establish more demanding species in the future. In general, tree species can serve as pioneer species on post-industrial sites, facilitating the restoration of degraded lands. For example, a reclaimed coal mine ecosystem, colonized by vegetation from the surrounding ecosystem, reached a self-sustaining state with trees,dominating after 20 years (Żołnierz et al. 2015; Yuan et al, 2020). However, some results show that in case of ash and slag dumps, trees may not become established at the initial stage of succession (Mustafa, 2012).

Importantly, woody species have significant impact on the formation of phytodiversity on devastated areas, with their share increasing during succession transformations (Kopiy et al., 2019). For instance, woody and shrubby species can contribute to the settlement of shade-tolerant species (Alday et al., 2014). Thus, woody vegetation significantly influences the establishment of plant cover and plant communities on degraded lands.

We analyzed the species diversity of woody vegetation of ash and slag dump № 3, where natural overgrowth has been occurring for several decades. We identified 23 species of tree and shrub species growing on the territory of the study area, which accounts for 16% of the total floristic diversity of ash and slag dump № 3. Among all tree species, 15 species (65 %) were native.

The predominance of native species on the ash and slag dumps was an unexpected result, since a number of previous studies of phytodiversity of technogenic lands (Prach & Hobbs, 2008) showed the dominance of non-native (alien) species in ecosystems that have undergone anthropogenic transformation. In particular, studies of the dendroflora of post-mining areas of the metallurgical region showed the predominance of allochthonous or non-native species there (Savosko et al., 2021). It has been established that alien species actively colonize reclamation areas with a gradual decrease in their share during successive changes - on post-mining sites, an increase in native species over time was found (Alday et al., 2014), i.e., the local flora shows greater resistance and displaces alien species. This confirms the key role of natural vegetation regeneration through spontaneous colonization. Thus, native plant species are considered the most effective nurse plants for phytorecultivation of degraded areas (Pandey & Singh, 2015; Kiehl et al., 2010; Gajic et al., 2018). The use of local plants ensures rapid vegetation recovery and the seamless integration of the restored ecosystem into the surrounding landscape.



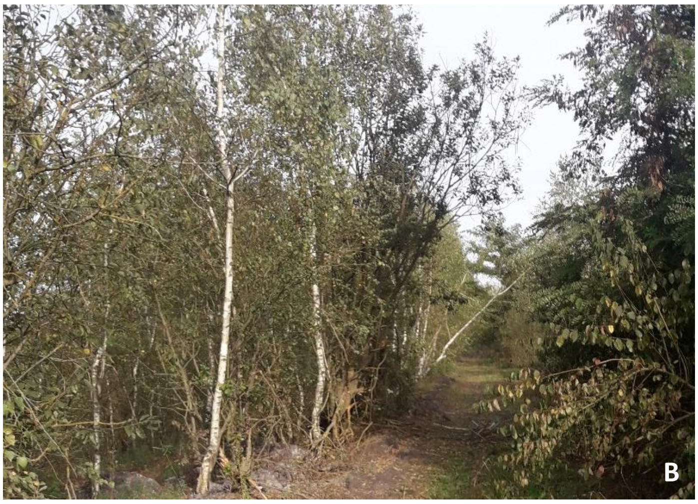


Figure 2. (A) Establishment of woody vegetation on ash and slag dumps; (B) woody communities on ash and slag dump № 3 aged 10-15 years

Research showed (Řehounkova et al., 2011; Żołnierz et al., 2015; Yuan et al., 2020) that around the 20th year vegetation on post-industrial sites is stabilized – it includes trees also shrubs, mainly *Salix caprea*, *Populus spp*. and especially *Betula pendula*, occasionally *Acer pseudoplatanus*, *Fraxinus excelsior*, *Rosa canina*, *Sambucus nigra*, *Crataegus* spp. and others. Such spontaneous succession leads there to a woodland with domination of *Betula pendula* (Tischew & Lorenz, 2005; Řehounkova et al., 2011).

For forest reclamation of ash and slag dumps we suggested *Populus* spp., *Salix* spp., *Betula pendula* and *Alnus glutinosa*. These species could help fix slopes and provide protection from erosion. Co-dominant species could be *Crataegus monogyna* and *Euonymus europaea*. Recommended shrubs species are *Rosa canina* and *Sambucus nigra*. Using *Hippophae rhamnoides* is limited by quantity of light so it could be used only in open space without other trees.

Species of early succession were *Populus deltoides*, *Robinia psevdoacacia*, mixed *Populus* and *Salix* vegetation together with *Alnus* spp. were effective in the restoration process (Savosko et al., 2021; Kopiy et al., 2019). Besides, *Populus* and *Salix* have shown a high potential for element accumulation and remediation (Nissim & Labrecque, 2021). Also there is recommendation for *Quercus robur*, *Fraxinus excelsior*, *Pinus sylvestris* and *Alnus* ssp. (*Alnus incana* and *Alnus glutinosa*) (Pietrzykowski, 2019). *Tilia cordata*, *Sorbus aucuparia*, *Acer campestre* could be the following species. Shrub forest layers include *Sambucus*, *Eonymus*, *Viburnum* (Savosko et al., 2021).

Among our recommendations for forest reclamation there is one non-native species – *Robinia pseudoacacia*. This species easily establishes on the spoiled heaps, but it needs to be controlled as an invasive species (Pietrzykowski, 2019; Żołnierz et al., 2015). Moreover, this species has spread across the territory of ash and slag dumps as a result of natural succession (Fig. 3). The root system of *Robinia* is deep and binds the substrate and stimulates the development of pedological processes, also belonging to nitrogen-fixing plants. So, this species can also be used for forest reclamation of ash and slag dumps.

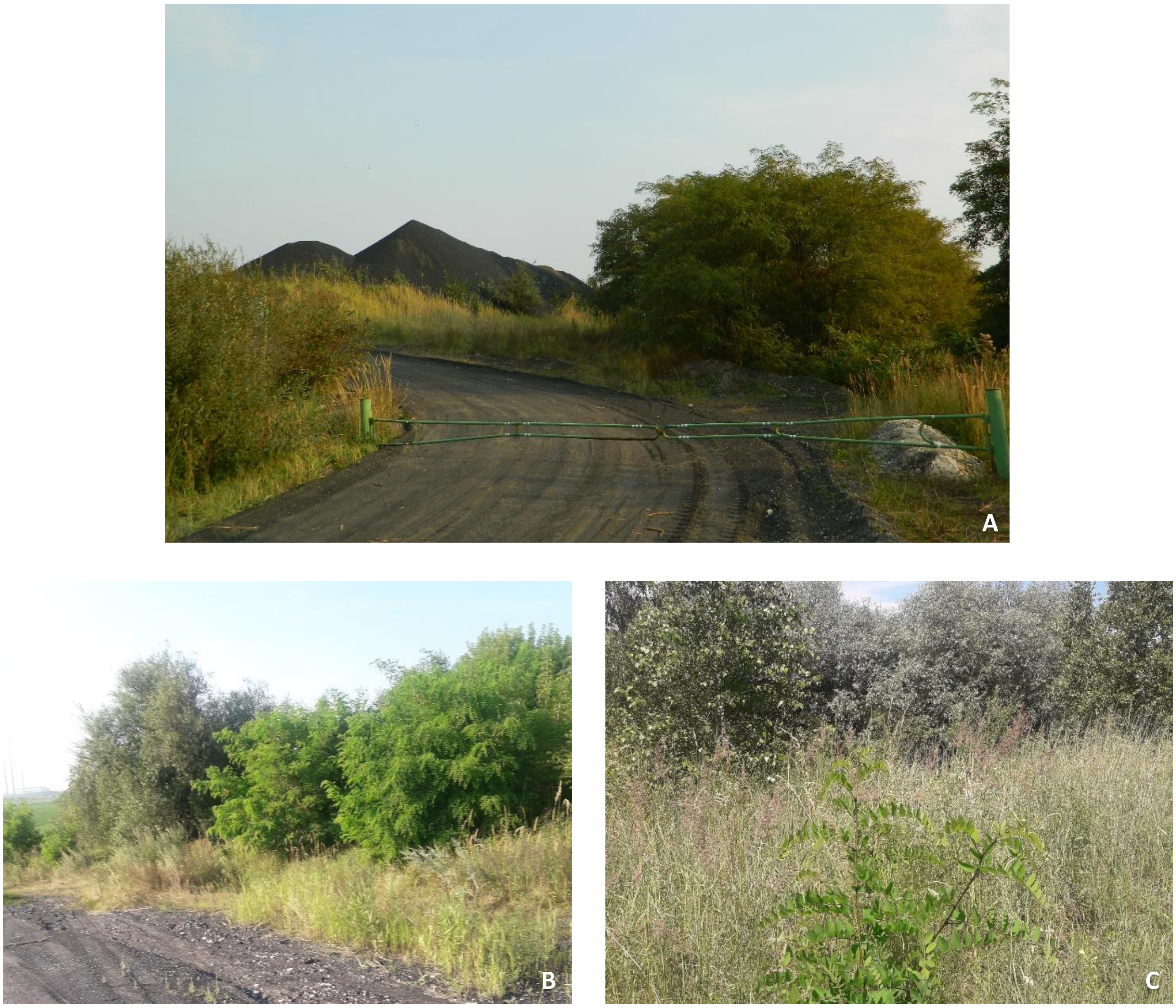


Figure 3. *Robinia pseudoacacia* on the territory of ash and slag dump 3 of Burshtyn TPP: (A, B) *R. pseudoacacia* in the composition of woody vegetation on ash and slag dumps; (C) spontaneous establishment of *Robinia* on the territory of ash and slag dumps

The recommended tree and shrub species represent a diverse ecological ensemble with remarkable adaptive capabilities and significant roles in forest reclamation of ash and slag dumps. Pioneer species such as *Betula pendula*, *Populus tremula*, and *Salix caprea* showcase extraordinary colonization capabilities, rapidly establishing themselves on disturbed territories. *Alnus glutinosa* and *Hippophae rhamnoides* emerge as particularly noteworthy nitrogen-fixing species, demonstrating exceptional potential for soil restoration. These species demonstrate high light requirements and adaptability to diverse soil conditions, playing a crucial role in primary succession and landscape transformation processes (Martinik et al., 2024).

Shade-tolerant species like *Carpinus betulus*, *Euonymus europaea*, and *Sambucus nigra* represent the undergrowth and co-dominant strata, contributing to the complex vertical structure of forest ecosystems (Łuczak et al., 2019). These species typically prefer nutrient-rich soils and demonstrate nuanced ecological requirements, often indicating stable and mature forest environments.

Drought-resistant species such as *Crataegus monogyna*, *Pinus sylvestris*, and *Rosa canina* showed resilience, capable of surviving in challenging environmental conditions (Łuczak et al., 2019; Krasova et al,. 2022). These species often occupy marginal ecological niches, including forest edges and open landscapes, demonstrating significant adaptive potential.

The comprehensive analysis underscores the multifaceted ecological roles of these species, highlighting their potential in forest reclamation, ecosystem restoration, and biodiversity conservation. Their varied life forms, from trees to shrubs, and their diverse ecological positions contribute to the complex dynamics of forest regeneration and environmental rehabilitation.

This ecological ensemble represents a sophisticated biological strategy for landscape restoration, embodying the principles of phytorecultivation by leveraging the inherent adaptive capabilities of native plant species.

It is important to note that precisely the pioneer tree species determined the reclamation quality in the long term, which is called the "trigger effect" in the succession trajectory (Yuan et al., 2020). Succession of forest reclamation process needs to be directed here depending on the target, for example, by selective cutting or planting of desirable trees.

Besides of site-specific woody revegetation, there is a variety of natural methods for the introduction of target plant species on sites: transferring of fresh seed-containing hay, elimination of undesirable species, mowing, harvesting, transferring of seed-containing soil (Řehounkova et al., 2011). Sowing of regional seed mixtures together with hay transferring and other management measures are appropriate restoration measures to achieve successful revegetation and forest reclamation (Řehounkova et al., 2011; Kirmer et al., 2019).

Successful methods of site treatment and biodiversity support are mowing and mulching, which could be applied during the restoration process together with forest reclamation on ash and slag dumps. Adding of weed-free mulch supports the restoration process, as it offers many environmental benefits, such as reducing soil erosion and retaining moisture (Kiehl et al., 2010; Kirmer et al., 2019), which ultimately supports the establishment of vegetation on degradeted sites. Additionally, mulch layers can help in regulating soil temperature, promoting the growth of plant species, critical for successful forest restoration.

Mowing as well as mulching suppress competition from the herb layer and help establishment of other species (Řehounkova et al., 2011, Kirmer et al., 2019). Vegetation mowing can be an effective technique in forest reclamation, as it helps control the growth of invasive species, prevents the overgrowth of pioneer plants, and promotes the establishment of more desirable tree species. Mowing can help in some cases, e.g, when the succession is blocked by some expansive or invasive species, like *Calamagrostis epigejos* (Řehounkova et al., 2011). By reducing competition and managing vegetation cover, mowing supports the development of a balanced plant community that is crucial for long-term forest restoration.

4. CONCLUSIONS

The investigation of forest reclamation on the ash and slag dumps of the Burshtyn Thermal Power Plant provides valuable insights into ecological restoration. The study found that native woody species, comprising 65% of the vegetation, demonstrate resilience and adaptability, gradually displacing non-native species and facilitating ecosystem recovery. Pioneer tree species such as *Populus* spp., *Betula pendula*, and *Salix caprea* play a critical role in initiating ecological transformation, with their colonization triggering succession dynamics that improves reclamation quality. The research recommends a diverse ecological strategy, incorporating pioneer species, shade-tolerant vegetation, drought-resistant species, and nitrogen-fixers to foster ecosystem regeneration. The study emphasizes native species selection, managing spontaneous succession, and supplementary techniques like mulching, which optimize restoration outcomes. The findings offer a broader framework for the ecological rehabilitation of technogenic landscapes, providing insights into plant adaptability, ecosystem interactions, and strategies for transforming degraded industrial sites into biodiverse, functional ecosystems. This approach highlights the importance of forest reclamation as a dynamic ecological process with both ecological and socio-economic benefits.

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Уляна Семак, Галина Мельниченко, Богдан Стефанишин. Лісова рекультивація техногенних земель на прикладі золошлаковідвалів. *Журнал Прикарпатського університету імені Василя Стефаника. Біологія*, **11** (2024), С.146–С.155.

Лісова рекультивація техногенних ландшафтів – це комплекс заходів, спрямованих на вирішення екологічних проблем, що спричинені техногенною трансформацією навколишнього середовища. Представлене дослідження описує особливості формування деревної рослинності на золошлаковідвалах Бурштинської ТЕС, розкриваючи концепцію відновлення деградованих екосистем шляхом лісової рекультивація. Аналіз видового різноманіття та екологічних характеристик дендрофлори золошлаковідвалів розкриває закономірності спонтанної сукцесії та перспективи фітомеліоративних заходів. Результати дослідження показали переважання аборигенних видів (65 % видового спектру) у дендрофлорі золошлаковідвалу № 3, що ставить під сумнів попередні припущення про заселення адвентивними видами антропогенно трансформованих ландшафтів. Піонерні види, серед яких *Betula pendula*, *Salix caprea* та *Populus* spp., завдяки здатності швидко формувати деревостани та ініціювати складні сукцесійні процеси, зарекомендували себе як ключові види для лісової рекультивації в умовах техногенних екотопів. Такі азотфіксуючі види як *Alnus glutinosa* та *Hippophae rhamnoides* мають вагоме значення для встановлення рослинності на збіднених на поживні речовини техногенних субстратах. Результатом дослідження є список рекомендованих для лісової рекультивації деревних та чагарникових видів, що завдяки їх екологічним особливостям та адаптивному потенціалу можуть бути ефективними для відновлення техногенно трансформованих ландшафтів. Практичні рекомендації щодо лісової рекультивації включають також ряд заходів, що сприятимуть відновленню рослинного покриву на техногенних субстратах. Запропонований комплексний підхід до лісової рекультивації закладає теоретичне підґрунтя для розробки заходів відновлення деградованих промислових територій та перетворення їх у функціональні екосистеми.

Ключові слова: лісова рекультивація, фіторекультивація, техногенні ландшафти, екологічне відновлення.