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WOODY PLANTS IN THE MONITORING AND RESTORATION OF CHEMICALLY DEGRADED SOILS IN POLAND: FROM DENDROMONITORING TO DENDROREMEDIATION AND ECOSYSTEM RESTORATION

MONITORING DRVENASTIH BILJAKA I SANACIJA HEMIJSKI DEGRADIRANIH ZEMLJIŠTA U POLJSKOJ: OD DENDROMONITORINGA DO DENDROREMEDIJACIJE I OBNOVE EKOSISTEMA

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ABSTRACT

Chemical degradation of soils is a complex environmental problem involving changes in soil properties, contaminant mobility and bioavailability, and interactions between contaminants, plants, and soil microorganisms. Woody plants may play a dual role: they can serve as long-term indicators of environmental change and contribute to the restoration of degraded soils and ecosystems. This narrative review integrates evidence on dendromonitoring, dendroremediation, and ecosystem restoration, with particular emphasis on chemically degraded, post-industrial and post-mining sites in Poland. The synthesis is based on peer-reviewed studies addressing woody plants in contaminated environments, with particular attention to research conducted in Poland and to studies relevant to the assessment, monitoring, and restoration of chemically degraded soils.

The literature indicates that woody plants provide valuable information on the spatial and temporal variability of soil contamination, including long-term environmental signals recorded in tree tissues and annual growth increments. Their effectiveness in dendroremediation depends on tree species, contaminant type, soil properties, pH, substrate characteristics, tree age, and exposure duration. Therefore, phytoremediation potential should not be assessed solely on contaminant concentrations in plant tissues or bioconcentration and translocation factors. Biomass production, plant survival, whole-plant accumulation and temporal changes should also be considered. The retention of contaminants in the root zone may represent a desirable feature in phytostabilisation.

The selection of woody species for degraded sites should consider both tolerance to adverse conditions and the ability to modify habitat properties and facilitate ecosystem development.

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On post-industrial and post-mining sites, natural succession and artificial afforestation should be regarded as complementary approaches. Overall, dendromonitoring, dendroremediation and ecosystem restoration are interconnected components of long-term management of chemically degraded soils, aiming to restore ecosystem functions, ecological stability and self-sustaining ecosystems.

Keywords*:* soil pollution; phytostabilisation; post-industrial landscapes; natural succession; woody biomass

APSTRAKT

Hemijska degradacija zemljišta predstavlja složen problem zaštite životne sredine koji obuhvata promene fizičkih, hemijskih i bioloških svojstava zemljišta, pokretljivosti i biodostupnosti zagađujućih materija, kao i njihove interakcije sa biljkama i zemljišnim mikroorganizmima. Drvenaste biljke mogu imati dvostruku ulogu: kao dugoročni bioindikatori promena u životnoj sredini i kao aktivni činioci u sanaciji degradiranih zemljišta i obnovi ekosistema. Ovaj pregledni rad narativnog tipa objedinjuje dosadašnja saznanja o dendromonitoringu, dendroremedijaciji i obnovi ekosistema, sa posebnim osvrtom na hemijski degradirana zemljišta i područja pod uticajem industrijskih aktivnosti i rudarstva u Poljskoj. Pregled obuhvata naučne radove koji su prošli recenzentski postupak i bave se ulogom drvenastih biljaka u zagađenim sredinama, pri čemu je poseban naglasak stavljen na istraživanja sprovedena u Poljskoj, kao i na studije relevantne za procenu stepena zagađenosti, praćenje promena i sanaciju hemijski degradiranih zemljišta.

Pregled literature pokazuje da drvenaste biljke pružaju značajne informacije o prostornoj i vremenskoj promenljivosti zagađenosti zemljišta, uključujući dugoročne pokazatelje promena u životnoj sredini sačuvane u biljnim tkivima i godišnjim prirastima stabala. Efikasnost dendroremedijacije zavisi od vrste drvenastih biljaka, vrste zagađujućih materija, svojstava zemljišta, pH vrednosti, karakteristika supstrata, starosti stabala i trajanja izloženosti zagađenju. Stoga se potencijal fitoremedijacije ne može procenjivati isključivo na osnovu koncentracija zagađujućih materija u biljnim tkivima ili vrednosti faktora biokoncentracije i translokacije. Pri proceni je potrebno uzeti u obzir i produkciju biomase, stopu preživljavanja biljaka, ukupnu akumulaciju zagađujućih materija u biljci i promene ovih pokazatelja tokom vremena. U procesu fitostabilizacije, zadržavanje zagađujućih materija u zoni korenovog sistema može predstavljati poželjno svojstvo, jer doprinosi smanjenju njihove pokretljivosti i rizika od daljeg širenja u životnoj sredini.

Pri izboru drvenastih vrsta za obnovu degradiranih područja potrebno je razmotriti kako njihovu tolerantnost na nepovoljne uslove staništa tako i sposobnost da menjaju svojstva supstrata i staništa i podstiču razvoj ekosistema. Na područjima degradiranim industrijskim aktivnostima i rudarstvom, prirodnu sukcesiju i veštačko pošumljavanje treba posmatrati kao međusobno dopunjujuće pristupe obnovi. Dendromonitoring, dendroremedijacija i obnova ekosistema predstavljaju povezane komponente dugoročnog upravljanja hemijski degradiranim zemljištima, usmerene na ponovno uspostavljanje funkcija ekosistema, povećanje ekološke stabilnosti i razvoj samoodrživih ekosistema.

Ključne reči: zagađenje zemljišta; fitostabilizacija; industrijski degradirana područja; prirodna sukcesija; drvenasta biomasa

INTRODUCTION

Soil degradation results from interacting physical, biological, and chemical processes that progressively reduce soil quality and impair ecosystem functioning. Chemical degradation is particularly persistent because contaminants introduced through mining, metallurgy, industrial activity, transport, and urbanization are not necessarily removed from the environment but may instead be redistributed among soil, water, and biota (Mukhtarov et al., 2026). Metals and metalloids are of particular concern because of their persistence, potential toxicity, and capacity to accumulate within biological systems (Krzesłowska et al., 2021). In mining-affected and post-industrial areas, contaminant enrichment frequently coincides with substantial changes in soil properties, including pH, salinity, nutrient balance, organic matter content, microbial activity, and water availability. Consequently, chemical soil degradation should not be understood simply as an increase in contaminant concentrations, but as a broader disturbance of the physicochemical environment controlling soil functioning and vegetation development (Pérez-Aguilar et al., 2026; Popek et al., 2025; Yashchenko et al., 2025).

The environmental significance of soil contamination cannot be adequately assessed from total elemental concentration alone. Mobility, environmental availability, and toxicity depend on soil pH, redox conditions, organic matter, mineral phases, interactions among co-occurring elements and, for elements occurring in multiple chemical forms or oxidation states, their speciation (Jiao et al., 2026; Kumar et al., 2019). This is relevant to several environmentally important elements, including chromium (Cr), mercury (Hg), and arsenic (As). The latter provides a particularly illustrative example because its inorganic and organic forms differ markedly in mobility, toxicity, and plant uptake. Moreover, contaminant speciation is dynamic rather than fixed – transformations may occur in soil, the rhizosphere, and plant tissues and may be affected by both plant metabolism and microorganisms (Budzyńska, Niedzielski, et al., 2024). Thus, contaminated soils are better viewed as dynamic soil-plant-microorganism systems than as passive reservoirs of contaminants.

Phytoremediation provides a nature-based approach for managing such environments by using plants to extract, immobilize, stabilize, or transform contaminants while maintaining soil structure and biological activity (Mahmud et al., 2026). Although much phytoremediation research has traditionally focused on herbaceous hyperaccumulators, the use of woody plants represents a complementary functional strategy, commonly referred to as dendroremediation (Khan et al., 2025; Mleczek, Gąsecka, et al., 2018a). Their large biomass, extensive and often deep root systems, long lifespan, and capacity to tolerate multiple environmental stresses allow them to interact with contaminated substrates over much longer periods. These characteristics are particularly relevant in post-industrial and mining-affected environments, where restoration often requires persistent vegetation cover, substrate stabilization, and gradual improvement of ecosystem functions rather than rapid contaminant removal alone.

However, dendroremediation potential is not an intrinsic property of a plant species. A recent global synthesis based on 2,766 observations from 243 studies showed that the response of woody plants to metal(loid) contamination is strongly controlled by plant taxon, contamination type, and exposure level, as well as environmental pH (Du et al., 2026). Species differ substantially in contamination uptake, root retention, translocation, tolerance, and biomass production, and the same species may display different remediation strategies under different soil conditions or when exposed to different chemical forms of the same elements (Budzyńska, Mleczek, et al., 2019; Mleczek et al., 2016). Plant age and exposure duration further modify these relationships (Lyubenova et al., 2024; Mleczek et al., 2019). Consequently, selecting

woody plants for remediation should integrate contaminant chemistry, soil conditions, species-specific traits, and the intended remediation endpoint.

A second limitation of conventional phytoremediation assessment is the frequent reliance on contaminant content in individual tissues or on indices such as the bioconcentration factor (BCF) and translocation factor (TF) (Sharma et al., 2022). These parameters are useful for describing uptake and internal distribution, but do not fully represent remediation capacity in long-lived plants. The total quantity of an element a tree accumulates depends on both its content in plant tissues and its biomass production. This distinction becomes increasingly important with time, as woody plants continue to develop large root and shoot systems over successive growing seasons. Multi-year studies have shown that whole-plant accumulation, and even relative differences among tree species, may change markedly over time, indicating that short-term screening may not reliably predict long-term dendroremediation performance (Budzyńska, Niedzielski, et al., 2024; Budzyńska, Rudnicki, et al., 2024; Panka et al., 2025).

The longevity of woody plants provides another important function that extends beyond remediation. Because wood forms incrementally, trees can retain temporally structured information on environmental conditions in their annual growth rings. Dendrochemical analysis can therefore complement conventional soil and environmental monitoring by providing retrospective information on long-term changes in elemental deposition and environmental pressure (Balraju et al., 2026; Budzyńska et al., 2023). At the same time, interpreting tree-ring chemistry requires caution because elemental distribution in wood is affected by species-specific physiology, wood anatomy, radial translocation, water availability, and site conditions (Górska, 2024; Górska & Roszyk, 2019). Recent studies from urban environments indicate that long-lived trees can integrate multi-decadal signals of anthropogenic pressure and provide valuable information on temporal environmental change (Balraju et al., 2025; Budzyńska et al., 2026; Sensuła & Fagel, 2023).

These two functions of woody plants – as recorders of environmental change and active agents of remediation and restoration – are usually considered separately, although they arise from closely related soil-tree interactions. A tree growing in a chemically degraded environment may simultaneously respond to contaminant mobility and speciation, modify rhizosphere chemistry, accumulate or immobilize elements, preserve environmental signals in wood, and ultimately become a structural component of a recovering ecosystem. This perspective directly links dendromonitoring, environmental chemistry, dendroremediation, and forest restoration.

Poland provides a useful case-study framework for examining these relations because of its mining-affected and post-industrial soils, long-term contaminated sites undergoing natural revegetation, and urban environments subjected to prolonged anthropogenic pressure (Mukhtarov et al., 2026; Popek et al., 2025; Robakowski et al., 2025). This review therefore aims to integrate chemical and forestry perspectives on the use of woody plants to monitor and restore chemically degraded soils in Poland. First, the chemical characteristics of soil degradation and the roles of contaminant mobility, speciation, and environmental availability are examined. Woody plants are then considered as long-term environmental indicators through dendromonitoring, followed by a discussion of contaminant uptake, transport, transformation, and accumulation in relation to dendroremediation. These processes are subsequently linked with species selection, site conditions, stand functioning, and forest ecosystem recovery (Drzewiecka et al., 2019; Kowalkowski et al., 2025; Lyubenova et al., 2024). Particular attention is given to the temporal scale - from short-term chemical transformations, through multi-year remediation, to multi-decadal environmental records preserved in wood. Finally,

recommendations are provided for integrating chemical monitoring, silvicultural practice, and long-term assessment of restoration outcomes in degraded environments.

CHEMICAL DEGRADATION OF SOILS IN POLAND

Major sources and contaminants

Chemical soil degradation in Poland reflects both natural geochemical variability and long-term anthropogenic pressure associated with mining, metallurgy, industrial production, waste disposal, transport and urban development (Wdowczyk et al., 2023; Zając et al., 2025). The national Monitoring of the Chemistry of Arable Soils, conducted by the Chief Inspectorate for Environmental Protection since 1995 at 216 permanent sites, evaluates changes in a broad range of soil properties, including trace element contents, pH, electrical conductivity, organic carbon, exchangeable cations and cation-exchange capacity (Chief Inspectorate for Environmental Protection, 2026). The program therefore shows that assessing soil quality requires considering the broader soil chemical environment rather than contaminant contents alone. At the same time, because this monitoring network focuses on arable soils, highly transformed mining, post-industrial, and urban sites require complementary site-specific investigations.

Among anthropogenic sources, mining and metallurgical activities are particularly important because they can introduce large and chemically complex mixtures of metals and metalloids into soils and generate waste materials with physicochemical properties markedly different from those of natural soils (Mazurek et al., 2025; Mu, 2025). The Polish national monitoring framework identifies industrial emissions, particularly those associated with mining and metallurgy, together with inappropriate industrial waste management, as major anthropogenic sources of trace element contamination of soils (Chief Inspectorate for Environmental Protection, 2026). Contaminants of particular environmental relevance include cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn), while metalloids such as As become especially important in areas influenced by mining and ore-processing activities. These elements differ substantially in mobility, plant availability, and toxicity. Their environmental significance therefore depends on both their abundance and the properties of the receiving soil (Mazurek et al., 2025; Zając et al., 2025).

Polish post-industrial and mining-affected environments further demonstrate that chemical degradation rarely results from a single contaminant. In a post-industrial area colonized by woody vegetation, elevated contents of trace elements occurred together with unusually high calcium (Ca) and sodium (Na) levels, strongly alkaline soil reaction, increased electrical conductivity, reduced soil organic matter, and unfavorable water-retention and cation-exchange properties. Such conditions generated simultaneous elemental, nutritional, salinity, and water stress, illustrating that the biological response of trees may be governed by the entire chemical matrix rather than by the concentration of an individual toxic element (Budzyńska et al., 2022). Similarly, mining residues may contain several potentially toxic elements simultaneously. Experimental studies using mining sludges have demonstrated simultaneous exposure to As, Cd, Hg, Pb, Zn, and other toxic elements (Budzyńska, Rudnicki, et al., 2024; Drzewiecka et al., 2019; Górska, 2024; Świątek et al., 2024).

Consequently, chemically degraded soils in Poland should be considered heterogeneous systems in which contaminant mixtures interact with altered soil properties and site history. Identifying the elements present is therefore only the first step. Evaluating their environmental

toxicity and transport strongly depend on their chemical form, speciation provides additional information necessary to understand their behavior in the soil–plant system.

Speciation and multi-element interactions

When contaminants occur in several chemical forms, environmental behavior cannot be explained solely on the basis of total concentration or even a general assessment of mobility. Speciation determines the chemical form in which a given element occurs and thus influences its solubility, adsorption, toxicity, and availability to plant roots. This is particularly important for redox-sensitive metalloids such as arsenic, whose inorganic forms, As(III) and As(V), and methylated forms differ significantly in their environmental behavior and biological impact (Budzyńska et al., 2025).

Studies on woody plants have shown that As speciation can strongly influence both uptake and the plant's subsequent response. In the case of Norway maple (*Acer platanoides*), the form of As supplied to the substrate affected uptake, translocation, morphology, and survival, demonstrating that total As concentration alone may not provide sufficient information to assess phytoremediation potential (Budzyńska et al., 2025). Furthermore, it should not be assumed that the form of As initially present in the environment will remain unchanged during exposure. Experiments with *Quercus robur* and *Tilia cordata* showed time-dependent transformations of inorganic and organic forms of As in both the culture medium and plant tissues, with microbial activity contributing to these processes (Budzyńska et al., 2021; Budzyńska, Izdebska, et al., 2024). Long-term field observations further showed that changes in total As content in soil were accompanied by significant changes in its speciation over five years, including a decreasing proportion of As(III) and an increasing proportion of organic forms of As (Budzyńska, Niedzielski, et al., 2024).

The environmental behavior of contaminants is further complicated by the simultaneous presence of other elements. Mining and post-industrial soils often contain mixtures of potentially toxic elements along with essential macro- and microelements. Interactions between these components can modify sorption, root uptake, translocation, and plant nutrition through competitive, antagonistic, or synergistic effects. Therefore, the response observed for a given element under experimental conditions with a single impurity may differ significantly from its behavior in a chemically complex field substrate.

Therefore, chemical characterization of degraded soils intended for monitoring or woody plant rehabilitation should go beyond total contaminant concentrations and include the main soil properties controlling mobility, relevant chemical species where speciation is environmentally important, and interactions created by co-occurring elements. This information provides the chemical context necessary to interpret the signals recorded by trees and distinguish environmental exposure from species- and site-specific responses.

DENDROMONITORING OF CHEMICALLY DEGRADED ENVIRONMENTS IN POLAND

Polish dendromonitoring studies on chemical degradation have focused mainly on environments subjected to long-term industrial, mining, and urban pressure. Although many of these studies primarily reconstruct atmospheric pollution rather than soil pollution itself, they are particularly relevant for degraded terrestrial environments because trees integrate long-term exposure to multiple contaminant transport pathways and simultaneously record changes in

growth. Available data cover industrial regions of southern Poland, historical mining areas, and more recently urban environments exposed to traffic and other anthropogenic factors.

A significant number of dendrochronological and dendrochemical studies using Scots pine (*Pinus sylvestris*) have been carried out in the highly industrialized Silesian region. Sensuła et al. (2017) combined tree-ring width measurements with radial profiles of Na, Mg, Fe, Ni, Cu, Zn, and Pb determined in pine trees growing near chemical factories. The analyzed chronology extended from the 1920s to 2010 and indicated changes in the elemental composition of wood, largely corresponding to periods of increased industrial activity and dust deposition. Complementary stable-isotope studies have shown that tree rings may also preserve physiological responses to industrial pressures. In *P. sylvestris* growing near a combined heat and power plant and steelworks in Silesia, variability in δ13C and internal water use efficiency in 1975–2012 reflected the combined influence of diffuse pollutants and local environmental conditions (Sensuła et al., 2017; Sensuła, 2016). More recent work from the same industrial region further illustrates both the potential and the complexity of dendrochemical interpretation. Sensuła and Fagel (2023) compared the radial contents of Na, Mg, Fe, Ni, Cu, Zn and Pb in pines growing near the steelworks with pines from a reference site. Despite comparison with the content of elements in atmospheric precipitation recorded at the monitoring station in Katowice, no simple linear relationship was found between the content of elements in individual tree rings. The authors concluded that wood chemical composition reflects the combined influence of regional and local pollution sources, atmospheric deposition, environmental conditions, and plant physiological processes, rather than a single external-exposure variable. This is particularly important for interpreting chemically degraded environments, where several sources of pollutants and environmental stressors typically operate simultaneously.

Dendrochemical approaches have also been applied to historical mining contaminants. In the Old Copper District near Iwiny in southwestern Poland, Dobrzańska et al. (2021) used tree rings of English oak (*Quercus robur*) to investigate the long-term impact of former copper mining and a historic tailings dump failure. Differences in trace element content and tree-ring width between industrial and control sites confirmed the persistent impact of mining-related disturbances, but the study also demonstrated methodological difficulties in attributing individual changes in wood chemistry to specific historical contaminants. This example is particularly significant because it demonstrates that dendrochemistry can identify long-term contrasts between degraded and reference environments, even when the precise year-to-year reconstruction remains uncertain.

Urban dendromonitoring in Poland subsequently extended this approach to diffuse, multi-source pollution. In Poznań, tree cores of Norway maple (*Acer platanoides*), silver birch (*Betula pendula* Roth) and black poplar (*Populus nigra*) growing near main roads were analyzed for 22 elements. Over a period of about three decades, a general increase in the content of most elements was observed from the pith towards the cambium, despite differences between tree species and sampling locations. No single species accumulated the highest content of all elements: *A. platanoides* showed the highest values for 13 of the elements analyzed, *B. pendula* for three, and *P. nigra* for six, which emphasizes that the effectiveness of dendromonitoring is specific to a given element and species (Budzyńska et al., 2023). The broadly similar temporal direction observed across species and locations was interpreted as evidence of increasing anthropogenic pressure during the analyzed period.

Another study extended the time perspective by analyzing *Picea abies* and *Quercus robur* growing along the main roads of Poznań. Elemental contents generally increased in younger

wood, particularly in sapwood, while changes in ring width and density provided additional information on how trees responded to the urban environment. In the oldest *Q. robur*, over 150 years old, the temporal patterns could be linked to the main phases of urban and industrial development, although climate and local hydrological conditions also contributed to the observed signal. Importantly, *Q. robur* individuals growing in different urban locations showed similar long-term trends in element deposition, whereas *P. abies* was more influenced by site-specific factors such as water availability and exposure to environmental stressors (Budzyńska et al., 2026).

In summary, Polish dendromonitoring studies (Table 1) show that tree rings can provide retrospective information in significantly different types of chemically transformed environments – from industrial forests and historical mining areas to contemporary urban systems. Their greatest value appears to lie not in reconstructing precise annual pollutant concentrations, but in identifying long-term trajectories, major environmental changes, and differences between sites or periods. Evidence from Poland also shows that combining elemental composition with tree-ring width, wood properties, stable isotopes, or independent monitoring records strengthens the environmental interpretation. At the same time, differences between species and localities must remain part of this interpretation and not be treated merely as analytical variation. This species-specific uptake and retention of elements, which underlies dendromonitoring, also determines whether woody plants can actively immobilize, translocate, or remove contaminants from degraded soils. The same case studies therefore show a natural transition from trees as environmental recorders to trees as active remediation agents.

Table 1. Selected Polish dendromonitoring studies using tree rings to assess long-term chemical environmental change, including study context, analyzed indicators, temporal coverage, major findings, and their interpretative significance for dendromonitoring

Tabela 1. Odabrana istraživanja dendromonitoringa u Poljskoj koja koriste godove drveća za procenu dugoročnih promena hemijskih karakteristika životne sredine, sa prikazom konteksta istraživanja, analiziranih pokazatelja, vremenskog obuhvata, glavnih rezultata i njihovog značaja za tumačenje nalaza dendromonitoringa

Study area, environmental pressure	Tree species	Analysed indicators	Temporal coverage	Main findings relevant to dendromonitoring	Interpretative significance	Reference
Silesia; heat and power plant and steelworks	*Pinus sylvestris*	$\delta^{13}C$ in glucose in tree rings, carbon isotope discriminati on, internal water use efficiency (iWUE)	1975-2012	$\delta^{13}C$ and iWUE varied by industrial emitter type and local environmental conditions; iWUE increased over the analyzed period.	Tree rings can record not only exposure to pollutants but also long-term physiological responses to combined industrial and environmenta l stress.	Sensuła et al., 2016
Silesia; vicinity of chemical factories	*Pinus sylvestris*	Tree-ring width; Na, Mg, Fe, Ni, Cu, Zn and Pb	1920-2010	Radial element profiles and tree-ring widths reflected long-term changes related to industrial development and dust deposition	Combining chemical composition with tree growth allows for a multi-decadal record of anthropogenic	Sensuła et al., 2017

Study area, environmental pressure	Tree species	Analysed indicators	Temporal coverage	Main findings relevant to dendromonitoring	Interpretative significance	Reference
				around the study area.	pressure on the environment.	
Iwiny, Old Copper District, SW Poland; former Cu mining and tailings storage facility impact	*Quercus robur*	Tree-ring width; Cd, Mn, Ni, Zn, Cr, Co, Pb, Cu, Fe, Al, and Ag	1959-2014	Trees in industrial facilities had higher contents of several elements and narrower rings than control trees. However, the 1967 tailings dam failure was not recorded as a clear chemical or growth signal.	Dendrochemistry can help identify long-term mining impacts, whereas short-term historical events may remain unresolved when contaminant bioavailability is low.	Dobrzańska et al., 2021
Southern Poland; steelworks and reference forest	*Pinus sylvestris*	Na, Mg, Fe, Ni, Cu, Zn and Pb; comparison with atmospheric wet-deposition records	1999-2012	Elemental patterns in wood did not show a simple linear relationship with element loads in rainfall.	Wood chemistry integrates several influences – including regional and local pollution sources, deposition and tree physiology – and should not be treated as a direct proxy for a single monitoring variable.	Sensuła & Fagel, 2023
Poznań; major urban roads and traffic-related anthropogenic pressure	*Acer platanoides*, *Betula pendula*, *Populus nigra*	Al, Ba, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Nd, Ni, Pb, Pr, Rb, Sb, Sr, Ti, Tl, and Zn; number of annual increments; wood density	1986-2019	Most analyzed elements showed increasing contents from pith towards cambium. Species differed markedly: *A. platanoides* had the highest contents for 13 elements, *B. pendula* for 3 and *P. nigra* for 6. A similar general temporal direction occurred across city locations.	Demonstrates strong species × element specificity, while the common temporal trend indicates the potential of multiple urban tree species for reconstructing longer-term environmental trajectories.	Budzyńska et al., 2023
Poznań; major urban roads,	*Picea abies*,	Al, Ba, Ca, Cr, Cs, Cu, Fe, K, Mg,	1850-2019	Elemental contents generally increased towards	Long-lived *Q. robur* appears particularly	Budzyńska et al., 2026

Study area, environmental pressure	Tree species	Analysed indicators	Temporal coverage	Main findings relevant to dendromonitoring	Interpretative significance	Reference
urbanization, traffic and changing climate	*Quercus robur*	Mn, Mo, Na, Ni, Pb, Rb, Sb, Sr., Ti, Tl, Zn, and Zr; tree-ring width; wood density		younger wood, especially sapwood. Long-lived *Q. robur* individuals from different locations showed relatively consistent temporal patterns, whereas *P. abies* was more strongly affected by local site conditions.	useful for integrating multi-decadal urban environmenta l change, but site hydrology and species-specific element redistribution remain important for interpretation.	

Dendroremediation of chemically degraded soils in Poland

Polish studies on woody plants growing in conditions contaminated with metalloids show that the dendroremediation potential cannot be attributed to a species regardless of the pollutant in question, its chemical form, substrate properties, and exposure time (Budzyńska et al., 2025; Budzyńska, Rudnicki, et al., 2024; Mleczek, Gąsecka, et al., 2018b). Experiments conducted under controlled conditions and on mining and post-industrial substrates revealed significant inter-species differences in the uptake and distribution of pollutants between plant organs. A common feature of many tree species studied is the preferential retention of potentially toxic elements in underground tissues, although the scale of this retention and the extent of translocation to stems and leaves vary considerably between species and elements. Studies conducted on *Acer platanoides*, *A. pseudoplatanus*, *Betula pendula*, *Quercus robur*, *Tilia cordata* and *Ulmus laevis* have shown that species that show relatively efficient uptake of one pollutant do not necessarily show a similar pattern for another. Consequently, the same woody species may contribute primarily to contaminant stabilization under one set of conditions while exhibiting greater translocation and removal potential under another (Budzyńska et al., 2017; Budzyńska, Krzesłowska, et al., 2019; Budzyńska, Mleczek, et al., 2019; Drzewiecka et al., 2019; Krzesłowska et al., 2021; Mleczek et al., 2016, 2019, 2022; Mleczek, Gąsecka, et al., 2018b; Mleczek, Goliński, et al., 2018).

These differences become particularly visible under complex chemical conditions. In mining residues, trees are simultaneously exposed to several potentially toxic elements, and their distribution in plants does not follow a single, species-specific pattern. Similarly, field observations in a Polish post-industrial area showed that *B. pendula*, *P. sylvestris* and *Salix viminalis* differed significantly in their element accumulation despite growing in the same highly alkaline, calcium- and sodium-rich conditions (Budzyńska et al., 2022). The reaction therefore reflected not only the biological characteristics of the species, but also the chemical environment controlling the availability of elements. This confirms that remediation strategies should not be inferred solely on the basis of total soil contamination.

Another important feature emerging from Polish dendroremediation research is that the apparent remediation efficiency of woody plants may change with plant age and exposure duration (Budzyńska, Izdebska, et al., 2024; Mleczek et al., 2019). Short-term hydroponic and pot experiments are particularly useful for identifying species-specific uptake patterns, toxicity

thresholds, and contaminant transformation, but provide only a partial picture of the long-term remediation capacity of trees. In woody plants, the amount of pollutant retained in the whole organism depends both on its content in individual tissues and on the amount of biomass produced. Therefore, a high content of elements in a small plant does not necessarily translate into a larger amount of contamination retained from the substrate. Conversely, a tree with lower contaminant content in its tissues may accumulate a greater total amount of the contaminant as root and shoot biomass increases over time. This distinction is particularly important when comparing woody plants with short-lived phytoremediation species and when extrapolating results from seedlings to older trees.

The importance of this temporal component was demonstrated in a three-year experiment with *T. cordata* and *Q. robur* growing in soil enriched with mining sludge contaminated with many elements (Budzyńska, Rudnicki, et al., 2024). Both species maintained growth under contaminated conditions, but their element accumulation patterns developed differently in subsequent growing seasons. *T. cordata* generally accumulated higher amounts of several elements studied in whole plants, including As, Hg, Mn, Pb, and Zn, while the importance of individual uptake and translocation processes varied between years. For some elements, significant accumulation became visible only after the second or third growing season. Therefore, an assessment based on a single, early sampling point may have resulted in a different species classification than an assessment after several years. Importantly, increasing biomass and increasing element accumulation in whole plants occurred simultaneously, demonstrating why tissue content and conventional uptake rates should be interpreted in conjunction with plant growth rather than in isolation.

A five-year study of naturally established *Q. robur* and *T. cordata* growing in an As-contaminated environment provided an even longer perspective (Budzyńska, Niedzielski, et al., 2024). The As concentration in soil decreased from 37.0 to 10.5 mg kg^{-1} under *Q. robur* and from 34.7 to 9.51 mg kg^{-1} under *T. cordata* during the observation period, corresponding to a maximum reduction of about 71.8%. At the same time, however, the relative productivity of both tree species was not constant. *T. cordata* showed stronger As accumulation in the first years, while *Q. robur* became more effective later in the study. In the fifth year, whole-plant As accumulation reached approximately 38.2 mg per individual of *Q. robur* compared to 30.6 mg per individual of *T. cordata*. If the assessment had been completed after only two or three growing seasons, *T. cordata* would have appeared to be the more effective species, illustrating the risk of extrapolating long-term dendroremediation results from short-term observations.

The same study also illustrates the need to distinguish between contaminant accumulation and effective transfer to harvestable biomass. Translocation coefficients remained below one for both species throughout the five-year period, indicating dominant As retention in the underground organs. From a classical phytoextraction perspective, limited transport to aboveground tissues may limit contaminant removal during harvest. However, in degraded landscapes, root retention can be beneficial when phytostabilization is the primary goal, as it can reduce contaminant movement through the soil-plant system and limit transfer to leaves. Therefore, a low translocation rate should not automatically be interpreted as poor remediation efficacy. Its meaning depends on the intended management objective.

In summary, Polish research indicates that dendroremediation should be viewed as a dynamic process, dependent on species and location, rather than a constant feature of individual tree species (Table 2). Early screening is still necessary to determine pollutant tolerance and uptake patterns, but long-term assessment requires simultaneous consideration of pollutant distribution, biomass production, plant survival, and changes occurring in subsequent growing

seasons. In the case of long-lived woody plants, accumulation in whole plants and its time course may therefore provide more reliable data on remediation potential than tissue content or BCF and TF values considered separately. These findings also shift the question from whether a tree can accumulate or stabilize pollutants to whether it can maintain these functions while continuing to grow under the specific conditions of a degraded site. This broader criterion links dendroremediation to selecting species that can contribute to long-term ecosystem restoration.

Table 2. Selected Polish studies illustrating species-, substrate-, contaminant-, and time-dependent variation in dendroremediation performance of woody plants in chemically degraded environments

Tabela 2. Odabrana istraživanja u Poljskoj koja prikazuju zavisnost efikasnosti dendroremedijacije drvenastih biljaka u hemijski degradiranim sredinama od biljne vrste, supstrata, vrste zagađujućih materija i trajanja izloženosti

Contaminant, degraded substrate	**Tree species**	**Study system**	**Key result**	**Dendroremediation implication**	**Reference**
As(III)	*Acer platanoides, Betula pendula, Quercus robur, Ulmus laevis*	Hydroponic experiment	Strong species-specific partitioning was observed. *A. platanoides* accumulated >80% of whole-plant As in the stem (TF = 10.8), whereas *Q. robur* retained >85% in roots (TF = 0.1).	The same contaminant can induce contrasting remediation strategies: effective translocation in *A. platanoides* versus predominantly root-based stabilization in *Q. robur.*	Budzyńska et al., 2017
Multi-element hazardous mining sludge	*Acer platanoides, Acer pseudoplatanus, Betula pendula, Quercus robur, Tilia cordata, Ulmus laevis*	Field experiment	All species accumulated and translocated more than one potentially toxic element. For Zn, BCF and TF exceeded 1 in all species, with particularly high values in *A. platanoides*, *U. laevis* and *A. pseudoplatanus*. Uptake patterns differed markedly from those previously obtained under controlled conditions.	Remediation capacity is both species- and element-specific and may change substantially with environmental conditions; controlled screening cannot be transferred directly to more realistic substrates.	Mleczek et al., 2016
As-contaminated mining sludge	*Acer platanoides, Acer pseudoplatanus, Betula pendula, Quercus robur, Tilia cordata, Ulmus laevis*	Pot experiment	Total As was accumulated predominantly in roots in all six species. Organic As forms dominated in many tree organs despite occurring at low concentration in the original mining sludge.	Root retention is a common response under highly contaminated conditions, while As transformation demonstrates that total As alone does not adequately describe plant–contaminant interactions.	Budzyńska, Mleczek et al., 2019

Contaminant, degraded substrate	Tree species	Study system	Key result	Dendroremediation implication	Reference
Mixture of flotation tailings and sewage sludge; multi-element contamination	*Tilia cordata, Ulmus laevis*	Pot experiment	One-year-old *T. cordata* failed to grow successfully, whereas two-year-old *T. cordata* showed the highest overall accumulation efficiency in the waste mixture; two-year-old *U. laevis* was less effective. Many elements were retained predominantly in roots.	Plant age can substantially alter both survival and apparent phytoextraction efficiency and should be considered together with species identity when selecting woody plants for degraded substrates.	Mleczek et al., 2019
Post-industrial soil with high Ca, Na, and trace element content	*Betula pendula, Pinus sylvestris , Salix viminalis*	Naturally established plants	Whole-plant biomass and accumulated amounts of most analyzed elements generally increased with plant age; the oldest specimens showed the greatest total element accumulation. Soil chemistry simultaneously restricted uptake of some trace elements.	Long-term remediation potential cannot be assessed from tissue content alone: increasing biomass can substantially increase the total amount of elements retained by woody vegetation.	Budzyńska et al., 2022
Mining sludge; multi-element contamination	*Tilia cordata, Quercus robur*	Field experiment	Both species maintained growth, but whole-plant accumulation of As, Hg, In, Mn, Mo, Pb, Ti and Zn was higher in T. cordata. After three years, T. cordata accumulated 68.7 mg As, 158 mg Mn and 157 mg Zn per plant.	Remediation performance develops over successive growing seasons and must be evaluated as the interaction between tissue content, biomass production, and duration of exposure.	Budzyńska, Rudnicki et al., 2024
As-contaminated soil near mining sludge deposits	*Tilia cordata, Quercus robur*	Naturally established plants	Soil As concentration decreased by up to 71.8%. *T. cordata* was more effective during the early years, whereas *Q. robur* became more effective in year 5; TF remained <1, indicating dominant root retention.	Species ranking is time-dependent. Multi-year assessment can lead to a different conclusion than short-term screening and shows the importance of biomass development and long-term contaminant retention.	Budzyńska, Niedzielski et al., 2024

FROM SPECIES SELECTION TO ECOSYSTEM RESTORATION

Post-industrial areas encompass various forms of anthropogenic transformation of the Earth's surface, including areas associated with extractive and processing industries as well as waste storage. Particularly prominent landscape features include spoil heaps and waste dumps

resulting from mining activities, which, due to their size, origin, extensively altered vegetation cover, and unnatural topography, substantially transform the landscape (Kistowski, 2008; Lamparska-Wieland & Waga, 2003). At the same time, many post-industrial areas are characterized by severe soil and vegetation disturbance or their complete removal, consequently resulting in a substantial reduction in biological activity. Their recolonization may occur spontaneously as a result of natural succession or may be supported by deliberate human interventions, including reclamation.

Natural succession is a directional process in which the colonization of an area by successive groups of organisms leads to gradual changes in habitat conditions (Czerepko, 2008; Faliński, 1988). Primary succession occurs in areas previously devoid of developed biological life, whereas secondary succession takes place in locations where the former ecosystem has been destroyed or severely transformed, including as a result of human activity (Adamowski & Bomanowska, 2011; Faliński, 1988). During the initial stages, pioneer species emerge. These species are characterized by broad tolerance to climatic and soil conditions, a high light requirement, rapid juvenile growth, early and abundant fruiting, and the ability to reproduce vegetatively (Faliński, 1990). Their presence gradually modifies the habitat, creating conditions suitable for species characteristic of later stages of succession, which are better adapted to competition than to severe environmental stress (Connell & Slatyer, 1977)

In temperate climates, the final, stable stage of succession is represented by a forest community. Forests and woodland communities constitute the potential natural vegetation over more than 99% of Poland's land area (Matuszkiewicz, 2008). The development of woody vegetation can therefore be regarded as one of the key stages in the restoration of the ecological functions of post-industrial areas. However, the rate of tree colonization varies and depends on habitat type. The first woody plants may appear within the first ten years of succession; however, post-mining areas are among the habitats colonized by woody vegetation at the latest stages (Prach et al., 2001; Prach & Pyšek, 1994). In the process of spontaneous succession on post-industrial sites silver birch occurs particularly frequently (Prach & Pyšek, 1994, 2001; Woźniak et al., 2003). Poplars and willows, which also represent a group of pioneer species, colonize many other pioneer habitats, including river valleys, abandoned fields, windthrow areas, and burned areas (Adamowski & Bomanowska, 2011; de Chantal & Granström, 2007; Jagodziński et al. 2014; Faliński, 1988, 1997; Myking et al., 2011).

Species selection and the properties of degraded habitats

The long duration of natural succession is one of the main reasons for undertaking reclamation measures. Their aim is to accelerate the recovery of areas transformed by human activities. The most common reclamation approaches include recreational, agricultural, and forestry uses. However, the choice between leaving an area to spontaneous succession and implementing technical reclamation remains a widely discussed issue in research on the management of post-industrial areas. (Krzaklewski et al., 2016) indicates that natural successional processes can be used to develop desired plant communities, including forest stands, by appropriately directing the course of succession. At the same time, the high costs of comprehensive technical reclamation limit the feasibility of its widespread application. Technical measures should primarily be aimed at ensuring the stability of the reclaimed site, for example by reinforcing unstable slopes (Bradshaw, 2000).

In the case of contaminated and degraded areas, species selection should not, however, be based solely on their ability to survive under harsh conditions. Their potential to modify the habitat and initiate further ecosystem changes should also be taken into account. Pioneer

species can stabilize the substrate, increase the input of organic matter, influence nutrient cycling, and create conditions conducive to the development of subsequent groups of plants. Therefore, species selection should consider the type and degree of degradation, the physicochemical properties of the substrate, the availability of water and nutrients, light conditions, and, in the case of contaminated areas, also the type, mobility, and bioavailability of contaminants.

In the reclamation of post-industrial land, the conventional typology of forest habitats may be an insufficient tool for assessing habitat potential and making silvicultural decisions. The soil is often undeveloped, poorly developed, or severely altered, while the absence of an existing forest stand prevents its site index from being used as an indicator of habitat quality. Moreover, the floristic composition of pioneer phytocoenoses may have little correspondence with the diagnostic species used in conventional forest habitat classification. Under such conditions, direct assessment of substrate properties and observation of the natural course of succession become particularly important.

The importance of pioneer species

Pioneer species are particularly well suited to areas characterized by high light availability and heterogeneous access to water and nutrients. Due to their biological and ecological characteristics, they should play an important role in the reclamation of post-mining land (Dutta & Agrawal, 2001). Species frequently used in reclamation include *Pinus sylvestris*, *Betula pendula*, and *Alnus glutinosa*. Scots pine is one of the most commonly used species; however, abiotic and biotic risks associated with monocultures indicate the need for greater use of broadleaved species. *A. glutinosa* and *B. pendula* may be of particular importance due to their rapid growth and ability to improve the availability of N and P in the substrate. Broadleaved species also exert a greater influence on soil biological properties than conifers, while soils in broadleaved forests are generally more fertile than those in coniferous forests (Józefowska et al., 2016; Rahmonov et al., 2020). As the forest stand develops, light conditions also change, which may limit the regeneration and growth of light-demanding species (Mudrák et al., 2010).

The importance of pioneer species is also related to their resource-use strategies. Light availability is one of the key factors determining the composition and structure of plant communities (Gravel et al., 2010; Zavala et al., 2011). Species characteristic of early successional stages generally exhibit rapid growth and efficient acquisition of available resources. Their root systems are often adapted to rapid uptake of water and nutrients, and early-successional species are generally more deeply rooted than species characteristic of later successional stages (Casper & Jackson, 1997; Chen & Brassard, 2013; Hernández et al., 2010; Schenk, 2006). They also exhibit greater potential for nutrient acquisition (Chen & Brassard, 2013; Comas et al., 2002). These characteristics may be particularly important in degraded areas, where the availability of water and nutrients is limited and highly heterogeneous in space.

The root system is also important for substrate stabilization and the development of the soil environment. Roots, together with microorganisms and ectomycorrhizal fungi, participate in the transformation of biotic and abiotic components. *Betula pendula*, *Alnus glutinosa*, and *Pinus sylvestris* exhibited high levels of mycorrhizal colonization during growth on spoil heaps, exceeding 95% and reaching nearly 100% in the case of Scots pine (Ostonen et al., 2006). This indicates that, when selecting species for reclamation, their ability to establish functional interactions with soil microorganisms should also be taken into account.

Species improving soil properties

In the process of restoring degraded environments, particular importance may be attributed to species that not only tolerate adverse conditions but also actively contribute to their modification. Examples include *Alnus glutinosa* and *Robinia pseudoacacia*, which are capable of fixing atmospheric nitrogen through symbiotic associations with nodule-forming bacteria (Danso et al., 1995). In the case of black locust, the annual N_2 fixation capacity, depending on site conditions and stand age, ranges from 30 kg·ha^{-1} in a four-year-old stand to 274 kg·ha^{-1} in stands aged 5–18 years (Danso et al., 1995). These species may therefore contribute to increasing nitrogen availability and the gradual development of the humus layer.

Black locust is also characterized by considerable plasticity in its root system, which can develop different architectures depending on site conditions (Degomez & Wagner, 2001). This trait may enhance its ability to stabilize the substrate and function under highly heterogeneous environmental conditions. Consequently, the occurrence of *Alnus glutinosa* or *Robinia pseudoacacia* during natural succession may promote the development of upper soil horizons on degraded post-mining sites.

Example of post-mining areas

A particular example of environments in which the relationship between species selection and the course of ecosystem restoration can be observed is provided by post-mining spoil heaps. The substrate of external spoil heaps, composed of overburden excavated during coal mining, differs substantially in its biological, chemical, and physical properties from the soils of natural forest ecosystems (Fettweis et al. 2005; Jagodziński et al., 2014). It is characterized, among other features, by low organic matter content, low porosity and water-holding capacity, and often high toxicity (Helingerová et al., 2010; Shrestha & Lal, 2011). Spoil heaps can therefore be regarded as large-scale systems in which the course of natural succession can be observed (Urbanová et al., 2014).

The observed species composition is consistent with earlier recommendations concerning the management of areas affected by industrial activity. As early as the 1950s, based on studies conducted in the Upper Silesian Industrial District, an increase in the proportion of birch, pedunculate, sessile, and red oak, lime, and beech at the expense of Scots pine and Norway spruce was recommended (Latocha, 1989). In subsequent decades, particular emphasis was placed on native tree and shrub species (Latocha, 1989; *Zasady Techniczno−hodowlane Obowiązujące w Państwowym Gospodarstwie Leśnym*, 1953). In the 1970s, the reconstruction of forest stands on post-industrial areas involved, among others, pedunculate oak, sessile oak and red oak, aspen and other poplar species, downy and silver birch, beech, hornbeam, maples, alder, and black locust (Latocha & Hawryś, 1976).

Silver birch is a species characterized by a broad ecological amplitude and resistance to industrial emissions, whereas black and grey alder are classified as pollution-tolerant species with phytomeliorative properties (Latocha, 1989). Alders, birches, aspen, goat willow, and black locust are classified as species forming the preparatory stand phase on post-mining spoil heaps (Zubikowska-Skawinowa, 1965). During the transitional phase, some poplar cultivars, European larch, and red oak can be used alongside pioneer species (Strzelecki & Sobczak, 1972). Black locust was also considered by Morawski (Morawski, 1968) to be highly suitable for afforestation of spoil heaps associated with hard-coal mining. The main woody species reported in the literature as important for spontaneous succession, reclamation, and subsequent reconstruction of vegetation on degraded and post-mining sites are summarized in Table 3. The

table highlights their role in habitat development, successional stage, and characteristics relevant to their use under degraded site conditions.

Table 3. The role of woody species in the reclamation and natural succession of degraded and post-mining sites

Tabela 3. Uloga drvenastih vrsta u rekultivaciji i prirodnoj sukcesiji degradiranih i rudarskim aktivnostima narušenih područja

Tree species	Role / significance on degraded sites	Successional stage / application	Key characteristics	Reference
Acer spp.	Used in stand reconstruction; sycamore maple occurred on the Turów spoil heap	Later stages / stand reconstruction	Supplementing stand species composition	Latocha & Hawryś,1976
Acer pseudoplatanus	Recorded on older parts of the Turów spoil heap	Later stages of succession / stand reconstruction	Occurrence in more developed stands	Latocha & Hawryś, 1976
Alnus glutinosa	One of the most important reclamation species; its proportion increased in young stands on the Turów spoil heap and it was dominant in some stands Main group of pioneer trees in succession on degraded sites	Pioneer species; preparatory stand; initiation of site improvement Early stages of succession	Resistance to pollution; phytomeliorative properties; atmospheric nitrogen fixation; high degree of mycorrhizal colonization Broad ecological tolerance; rapid growth; ability to colonize open habitats	Latocha 1989; Latocha & Hawryś,1976; Zubikowska-Skawinowa, 1965; Danso et al., 1995; Ostonen et al., 2006 Prach & Pyšek 1994, 2001
Alnus incana	Pollution-tolerant species used in reclamation Main group of pioneer trees in succession on degraded sites	Pioneer species / preparatory stand Early stages of succession	Resistance to pollution; phytomeliorative properties Broad ecological tolerance; rapid growth; ability to colonize open habitats	Latocha, 1989; Zubikowska-Skawinowa, 1965 Faliński, 1990; Prach & Pyšek, 1994, 2001
Betula pendula	One of the most important species in spontaneous succession on post-industrial sites; colonizes post-mining areas Main group of pioneer trees in succession on degraded sites	Pioneer species; early stages of succession; preparatory stand Early stages of succession	Broad ecological amplitude; resistance to industrial emissions; rapid growth; very common in spontaneous succession; high degree of mycorrhizal colonization Broad ecological tolerance; rapid growth; ability to colonize open habitats	Prach $& Pyšek, 1994, 2001; Woźniak et al., 2003; Latocha, 1989; Ostonen et al., 2006 Faliński ,1990; Prach & Pyšek, 1994, 2001
Betula pubescens	Species used in the reclamation of post-	Pioneer species /	Tolerance of harsh conditions; used	Latocha & Hawryś, 1976; Zubikowska-

Tree species	Role / significance on degraded sites	Successional stage / application	Key characteristics	Reference
	industrial and post-mining areas Main group of pioneer trees in succession on degraded sites	preparatory stand Early stages of succession	together with *B. pendula* Broad ecological tolerance; rapid growth; ability to colonize open habitats	Skawinowa, 1965 Faliński, 1990; Prach & Pyšek, 1994, 2001
Carpinus betulus	Used in stand reconstruction	Later stages / stand reconstruction	Component of the target stand composition	Latocha & Hawryś, 1976
Fagus sylvatica	Indicated as a desirable species for stand reconstruction on industrial sites	Later stages	Species used to promote the restoration of more complex forest communities	Latocha & Hawryś, 1976; Latocha, 1989
Populus spp.	Important pioneer species; spontaneously colonize degraded sites Main group of pioneer trees in succession on degraded sites	Early stages of succession; preparatory stand and transitional phase	Rapid growth; colonization of open habitats; occur in river valleys, abandoned fields, windthrow areas, and burned areas Broad ecological tolerance; rapid growth; ability to colonize open habitats	Faliński, 1988; Jagodziński et al., 2014; Adamowski & Bomanowska, 2011; Myking et al., 2011; de Chantal & Granström, 2007; Zubikowska-Skawinowa, 1965; Strzelecki & Sobczak 1979 Faliński, 1990; Prach & Pyšek, 1994, 2001
Populus tremula	Pioneer species used in reclamation Main group of pioneer trees in succession on degraded sites	Early stages of succession / preparatory stand	Rapid growth and ability to colonize pioneer habitats Broad ecological tolerance; rapid growth; ability to colonize open habitats	Latocha & Hawryś, 1976; Zubikowska-Skawinowa ,1965 Faliński, 1990; Prach & Pyšek, 1994, 2001
Quercus petraea	Used in stand reconstruction on post-industrial sites	Later stages / stand reconstruction	Native species, used in stand reconstruction	Latocha & Hawryś,1976
Quercus robur	Species recommended for stand reconstruction and restoration on industrial sites	Later stages / stand reconstruction	Native species, indicated as desirable in reclamation	Latocha & Hawryś, 1976; Latocha 1989
Quercus rubra	Used in reclamation and stand reconstruction; occurred on the Turów spoil heap	Transitional phase / stand reconstruction	Adaptation to use on post-industrial sites	Latocha & Hawryś, 1976; Strzelecki & Sobczak, 1979; Latocha, 1989
Robinia pseudoacacia	Important colonizing and reclamation species; one of the dominant species on older parts of the Turów spoil heap	Pioneer species / preparatory stand	Rapid growth; high plasticity of the root system; atmospheric nitrogen fixation; potential to improve substrate fertility	DeGomez & Wagner 2001; Morawski, 1968; Latocha & Hawryś, 1976; Zubikowska-Skawinowa, 1965
Salix caprea	Species recommended for the	Preparatory stand	Pioneer species, suitable for	Zubikowska-Skawinowa, 1965;

Tree species	Role / significance on degraded sites	Successional stage / application	Key characteristics	Reference
	reclamation of post-mining spoil heaps Main group of pioneer trees in succession on degraded sites	Early stages of succession	colonizing degraded areas Broad ecological tolerance; rapid growth; ability to colonize open habitats	Faliński, 1990; Prach & Pyšek, 1994, 2001
Salix spp.	Pioneer species colonizing heavily transformed habitats Main group of pioneer trees in succession on degraded sites	Early stages of succession / preparatory stand	Rapid growth; colonization of pioneer habitats Broad ecological tolerance; rapid growth; ability to colonize open habitats	Faliński, 1988; Jagodziński et al., 2014; Adamowski & Bomanowska, 2011; Myking et al., 2011; de Chantal & Granström, 2007; Zubikowska-Skawinowa, 1965 Faliński, 1990; Prach & Pyšek, 1994, 2001
Tilia spp.	Indicated in recommendations to increase the proportion of broadleaved species	Later stages / stand reconstruction	Native species, component of more complex forest communities	Latocha, 1989; Latocha & Hawryś, 1976
Larix decidua	Species used in the reclamation of post-mining areas	Transitional phase	Suitable for introduction after the pioneer phase	Latocha & Hawryś, 1976; Strzelecki & Sobczak, 1979
Picea abies	In historical recommendations, its proportion was to be reduced in favor of broadleaved species	Not indicated as a preferred reclamation species in the cited recommendations	Reduced proportion compared with broadleaved species	Latocha, 1989
Pinus nigra	Occurred on older parts of the Turów spoil heap	Later stages / stand component	Recorded as a component of older stands	Latocha & Hawryś, 1976
Pinus sylvestris	Species occurring on spoil heaps and used in reclamation, but its significance is assessed in the context of the limitations of monocultures	Succession / reclamation	Tolerance of site conditions; very high degree of mycorrhizal colonization on spoil heaps	Ostonen et al., 2006; Latocha, 1989

From reclamation to ecosystem restoration

Experience gained from post-mining areas can be applied more broadly to other contaminated and degraded sites; however, it should be borne in mind that there is no universal set of species suitable for all such sites. An individual spoil heap may constitute a unique experimental setting, for which the appropriate management approach requires detailed investigation (Strzelecki & Sobczak, 1972). Before making decisions regarding species selection, it is necessary to assess the surrounding conditions, soil type, physicochemical properties of the substrate, and processes occurring in the transformed environment. In the case of contaminated

sites, the type of contaminants, their mobility, and their availability to plants must additionally be taken into account.

Artificial regeneration should be adapted to the mosaic character of the substrate and its spatial variation in site conditions (Harabiš et al., 2013). At the same time, natural succession can serve as an important tool supporting the reclamation process. Combining spontaneous succession with artificial afforestation adapted to site conditions may enhance ecosystem stability and accelerate naturalization processes (Sroka et al., 2018), while also having beneficial effects on plant diversity, soil properties, and ecosystem stability (Vachova et al., 2021).

Consequently, species selection on contaminated and degraded sites should be regarded as the first stage of a long-term ecosystem restoration process rather than as a one-time reclamation measure. A species suitable for this process should not only tolerate the existing conditions but also be capable of growth and reproduction, substrate stabilization, influencing nutrient cycling and soil development, and creating conditions conducive to subsequent stages of succession. In contaminated areas, an additional criterion should be the ability to reduce contaminant mobility, or to promote their accumulation or stabilization, depending on the remediation objectives.

Such an approach makes it possible to integrate species selection, natural succession, phytoremediation, and the restoration of ecosystem functions. The objective should therefore not be merely to introduce trees into a degraded area, but rather to create conditions under which vegetation can gradually assume stabilizing and regenerative functions, ultimately leading to the development of a more complex and self-sustaining ecosystem.

CONCLUSIONS

Chemical degradation of soils should be regarded as a complex disturbance of the soil–plant–microorganism system, involving contaminant mobility, bioavailability, chemical speciation and interactions among elements, rather than solely their total concentrations.

Woody plants are valuable tools for long-term environmental monitoring. Dendromonitoring enables assessment of spatial and temporal changes in soil contamination and may provide information extending beyond conventional soil sampling.

Dendroremediation depends on tree species, contaminant type, soil and substrate properties, pH, tree age and exposure duration. Its effectiveness should therefore be assessed using not only contaminant concentrations or BCF and TF indices, but also biomass production, plant survival, whole-plant accumulation and temporal changes.

From a phytostabilisation perspective, contaminant retention in the root zone may be advantageous; high concentrations in roots should not automatically indicate ineffective remediation.

Species selection for chemically degraded sites should consider both tolerance to adverse conditions and the ability to improve habitat properties and facilitate subsequent vegetation development. Direct assessment of soil and substrate is particularly important on highly transformed post-industrial and post-mining sites, where conventional forest habitat classification may be insufficient.

Pioneer species can initiate ecosystem development by contributing to soil formation, improving microclimatic conditions and facilitating subsequent vegetation establishment. Natural succession and artificial afforestation should therefore be regarded as complementary approaches.

Overall, dendromonitoring, dendroremediation and ecosystem restoration form interconnected components of long-term management of chemically degraded soils. Restoration should aim beyond contaminant reduction or tree establishment towards the recovery of ecosystem functions, ecological stability and long-term self-sustaining ecosystems.

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