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Phytoremediation properties of perennial legumes for the restoration of degraded set-aside lands

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ABSTRACT

Military-induced land degradation in Ukraine has emerged as a critical challenge for Europe, with more than 10 million hectares of land have been affected by hostilities, landmines, and chemical contamination caused by explosions. This study (2020–2025) evaluated the phytoremediation and agroecological restoration potential of *Lotus corniculatus* L. and *Galega orientalis* Lam. cultivated on degraded and abandoned Greyic Phaeozems in Ukraine. The six-year cultivation cycle of *Galega orientalis* resulted in a net increase in soil humus content of 0.22%, an increased soil pH from 5.0 to 5.4, and reduced hydrolytic acidity to 4.7 meq/100 g soil. In addition, *Galega orientalis* promoted the accumulation of alkali-hydrolyzable nitrogen (151 mg kg^{-1}) and available phosphorus (420 mg kg^{-1}), while improving dry macroaggregation and increasing the proportion of agronomically valuable aggregates to 97.5%. In contrast, *Lotus corniculatus* enhanced exchangeable potassium content (77 mg kg^{-1}) and exhibited superior heavy metal remediation efficiency. Over the six-year period, the concentrations of bioavailable heavy metals decreased by 3.2–5.0 times, reaching minimum values of 1.8 mg kg^{-1} for Pb, 0.1 mg kg^{-1} for Cd, 2.0 mg kg^{-1} for Cu, and 1.8 mg kg^{-1} for Zn. *Lotus corniculatus* also demonstrated exceptional aggregate-binding capacity, increasing water-stable aggregates to 93.5% and raising the soil structural coefficient to 24.5. The findings indicate that differentiated phytoremediation strategies should be applied to degraded and post-war degraded lands. *Lotus corniculatus* is recommended for areas with high erosion risk requiring rapid detoxification and soil stabilization, whereas *Galega orientalis* is more suitable for marginal lands requiring intensive humification and nutrient enrichment.

Keywords: soil reclamation, military-induced land degradation, perennial legumes, soil aggregate stability, heavy metal detoxification, land conservation.

INTRODUCTION

Land degradation and soil erosion represent major environmental and economic challenges that significantly reduce the quality of ecosystem services and agricultural productivity worldwide. Across Europe, intensive anthropogenic pressure, unsustainable agricultural practices, and industrial pollution have resulted in the progressive deterioration of soil resources and the withdrawal of extensive areas of marginal lands from agricultural use (Abney et al., 2017; Aziz and Mustafa, 2024).

According to the Joint Research Centre of the European Commission and the report *The State of Soils in Europe*, a substantial proportion of agricultural soils in the European Union are affected by different forms of degradation (JRC, 2024). To prevent further deterioration, millions of hectares have been included in land conservation programs that involve set-aside management, grassland establishment, afforestation, and ecosystem restoration within European environmental initiatives such as Natura 2000. It is projected that by 2030, approximately 5.6 million hectares of agricultural land in Europe may be abandoned due to combined environmental and socioeconomic factors (Perpiña Castillo et al., 2018).

Besides the traditional forms of soil degradation associated with water and wind erosion, salinization, and deterioration of peatlands, Europe is currently facing a new challenge caused by military activities in Ukraine. Large-scale hostilities, mine contamination, and the chemical impact of explosions have generated unprecedented damage to soil resources. According to recent estimates, more than 10 million hectares of land in Ukraine have been affected, making this one of the largest areas of anthropogenic soil destruction in Europe since the Second World War (Joint Research Centre, 2024; Solovei et al., 2026).

Many agricultural areas located in eastern and southern regions of Ukraine have been removed from production and require long-term ecological rehabilitation. Although passive natural succession contributes to ecosystem recovery, severely degraded soils often require decades to regain their ecological functions (European Environment Agency, 2024; Evgrafova et al., 2024). Consequently, the development of active, environmentally friendly, and cost-effective restoration technologies has become one of the key priorities of modern ecological engineering and sustainable land management.

Among nature-based solutions, phytoremediation has attracted considerable attention as an environmentally safe approach to restoring degraded soils. This technology utilizes the biological potential of plants to stabilize pollutants, improve soil properties, and accelerate ecosystem recovery processes (Gavrilescu, 2022; Ali et al., 2020).

Perennial legumes are of particular interest decause of their ability to establish symbiotic relationships with nitrogen-fixing bacteria, produce extensive root systems, and accumulate substantial amounts of organic matter. Species such as bird's-foot trefoil (*Lotus corniculatus* L.) and fodder galega (*Galega orientalis* Lam.) are characterized by long-term persistence and can remain productive for more than ten years, thereby reducing restoration costs and increasing ecological sustainability (Ignaczak and Symanowicz, 2022).

Previous studies have demonstrated that perennial legumes contribute to soil nitrogen enrichment, improve aggregate stability, stimulate microbial activity, and enhance organic carbon sequestration (Stagnari et al., 2017; Masson-Boivin and Sachs, 2018; Vukicevich et al., 2016). However, information regarding the long-term use of *Lotus corniculatus* and *Galega orientalis* for the restoration of degraded set-aside soils remains limited. In particular, comparative data describing their phytoremediation efficiency and their influence on soil fertility under prolonged conservation conditions are still insufficient.

Therefore, the aim of this study was to evaluate the phytoremediation potential of *Lotus corniculatus* L. and *Galega orientalis* Lam. as perennial legumes and to determine their influence on the structural and biochemical recovery of degraded Greyic Phaeozems under long-term conservation conditions. The obtained results provide a scientific basis for developing effective ecological engineering strategies aimed at restoring degraded agricultural lands and improving ecosystem resilience in post-war Ukraine.

MATERIALS AND METHODS

Field experiments were conducted during 2020–2025 at the experimental site of the Agronomichne Research Farm, Vinnytsia National Agrarian University, located in Vinnytsia district, Vinnytsia region, Ukraine (49°12′15″ N, 28°22′40″ E). The soil of the experimental area was classified as Greyic Phaeozem according to the World Reference Base for Soil Resources (WRB) and was locally characterized as degraded due to long-term erosion processes.

The study area belongs to the Forest-Steppe zone of Ukraine and is characterized by a temperate continental climate. During the experimental period, annual precipitation ranged from 450 to 550 mm, while the mean annual air temperature varied between 8.5 and 9.5 °C. The experiments were established on degraded agricultural lands that had been withdrawn from intensive cultivation three years before the beginning of the study because of severe water erosion and depletion of soil fertility.

Prior to sowing, soil samples were collected from the 0–20 cm deep to determine the initial physicochemical characteristics of the degraded soil. Laboratory analyses were performed at the South-West Interregional Centre of the State Institution "Institute for Soil Protection of Ukraine". The initial soil characteristics were as follows: humus content – 2.0%; alkali-hydrolyzable nitrogen – 133 mg kg^{-1}; available phosphorus – 390 mg kg^{-1}; exchangeable potassium – 64 mg kg^{-1}; hydrolytic acidity – 5.3 meq 100 g^{-1} soil; soil pH (H_2O) – 5.0.

The experiment was arranged as a randomized complete block design (RCBD) with four replications. The total plot area was 25 m², with an accounting area of 20 m².

Three experimental treatments were evaluated:
- Control – natural regeneration without active sowing;
- *Lotus corniculatus* L. (cv. Ajax);
- *Galega orientalis* Lam. (cv. Kavkazskyi Branets).

Before sowing, the soil surface was prepared by shallow disk tillage to create favorable conditions for seed incorporation. Sowing was carried out in April 2021 using a conventional mechanical seeder. Seeding rates adjusted to 100% seed viability were 12 kg ha^{-1} for *Lotus corniculatus* and 30 kg ha^{-1} for *Galega orientalis*.

Throughout the entire six-year conservation period, no mineral fertilizers, pesticides, or irrigation were applied to assess the intrinsic phytoremediation potential of the studied perennial legume species. Soil samples were collected during the second, fourth, and sixth years of vegetation at the end of the growing season (late September). Composite samples from the 0–20 cm soil layer were formed using the envelope method from five randomly selected points within each plot.

After collection, samples were air-dried, homogenized, and sieved through a 2 mm mesh. Soil organic matter (humus) content was determined using the Tyurin method. Alkali-hydrolyzable nitrogen was measured according to the modified Kjeldahl method. Available phosphorus and exchangeable potassium were determined using the Chirikov extraction method followed by spectrophotometric and flame photometric analyses, respectively. Soil pH was measured potentiometrically in a soil-to-water suspension ratio of 1:5. Hydrolytic acidity was determined by the Kappen method. Mobile fractions of Pb, Cd, Cu, and Zn were quantified using atomic absorption spectrophotometry. Soil aggregate composition and water stability were assessed by the Yoder wet-sieving method. All experimental data were subjected to statistical analysis. Results are presented as mean values obtained from four replications.

RESULTS AND DISCUSSION

The long-term cultivation of perennial legumes exerted a pronounced restorative effect on degraded Greyic Phaeozems. During the six-year conservation period, both investigated species promoted the accumulation of soil organic matter and improved soil acidity parameters (Figure 1).

Initially, the humus content of the degraded soil was 2.0% in all experimental treatments (Figure 1a). Continuous biological restoration resulted in a gradual increase in soil organic matter. Under *Lotus corniculatus*, humus content increased to 2.01% in the second year and reached 2.13% by the end of the experiment. However, *Galega orientalis* exhibited a greater capacity for carbon accumulation, increasing humus content to 2.22% after six years, which corresponded to a net increase of 0.22% compared with the initial level.

The enhanced humification observed under *Galega orientalis* can be explained by its extensive root biomass and substantial annual litter input. Similar results have been reported for perennial legumes capable of maintaining continuous carbon inputs into the rhizosphere and stimulating microbial-mediated stabilization of soil organic matter (Vukicevich et al., 2016; Masson-Boivin and Sachs, 2018).

Soil acidity parameters also improved during the restoration process. The initial soil pH of 5.0 indicated acidic conditions typical of degraded Greyic Phaeozems (Figure 1b). Under *Lotus corniculatus*, soil pH gradually increased to 5.3 by the sixth year, whereas *Galega orientalis* accelerated the neutralization process and increased soil pH to 5.4.

Conversely, hydrolytic acidity consistently decreased throughout the experiment (Figure 1c). The lowest value (4.7 meq 100 g^{-1} soil) was recorded under *Galega orientalis* after six years of cultivation. Such changes are likely associated with enhanced biological cycling of calcium and magnesium and with the alkaline nature of legume root exudates.

The cultivation of perennial legumes significantly improved the nutrient regime of degraded soils by increasing the availability of essential macronutrients (Figure 2).

Both species enhanced alkali-hydrolyzable nitrogen content due to their symbiotic association with nitrogen-fixing rhizobia. Under the cover of *Lotus corniculatus*, the nitrogen concentration increased from 133 to 148 mg kg^{-1}, whereas *Galega orientalis* reached the highest value of 151 mg kg^{-1} by the end of the study.

A similar tendency was observed for available phosphorus. The initial phosphorus content

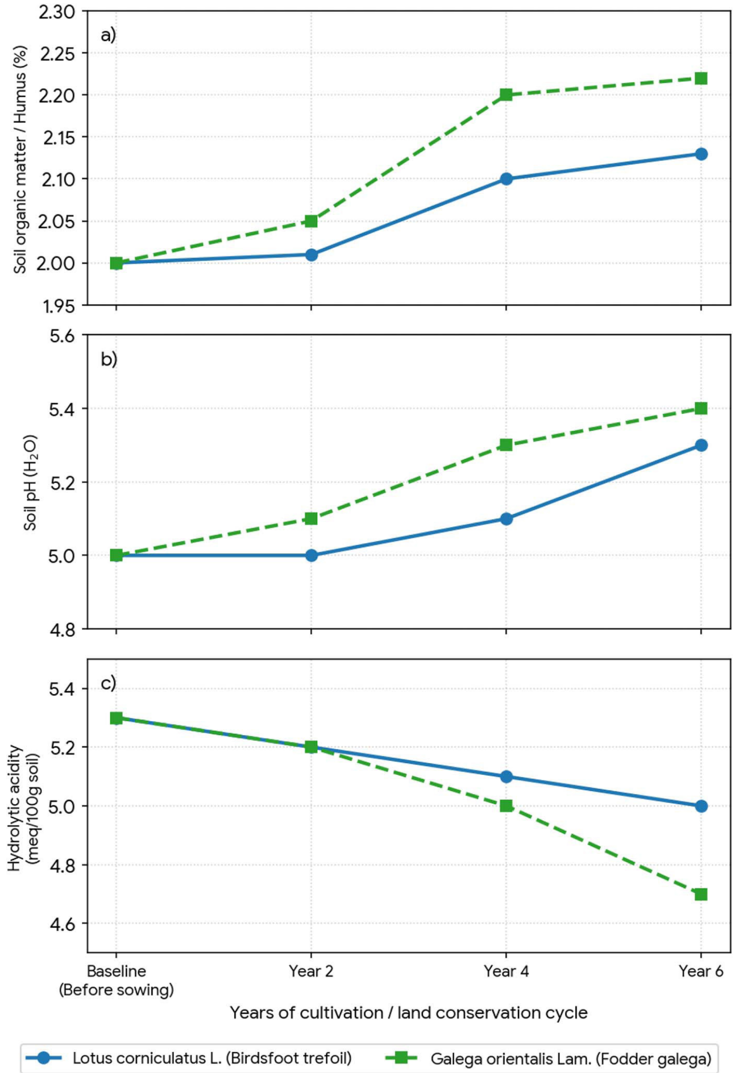

Figure 1. Dynamics of agrochemical properties of degraded Greyic Phaeozems during a 6-year conservation cycle under perennial legumes: a) soil organic matter / humus content; b) active acidity (pH); c) hydrolytic acidity

amounted to 390 mg kg^{-1}. Long-term cultivation of *Galega orientalis* resulted in a maximum concentration of 420 mg kg^{-1}, exceeding the values recorded under *Lotus corniculatus*. This effect can be attributed to the release of organic acids by plant roots, which enhance phosphorus mobilization from less available soil fractions.

Exchangeable potassium also increased throughout the restoration period. The highest potassium content was observed under *Galega orientalis* (80 mg kg^{-1}), while *Lotus corniculatus* provided a stable increase up to 77 mg kg^{-1}. Deep root systems of perennial legumes facilitate nutrient redistribution from lower soil horizons to the topsoil through biological cycling.

The superior nutrient accumulation observed under *Galega orientalis* is likely associated with its greater root biomass production and higher annual input of plant residues. Continuous incorporation of root-derived carbon stimulates microbial activity and enhances nutrient cycling processes in the rhizosphere. Similar relationships between perennial legumes and improved soil fertility have been reported by Stagnari et al. (2017) and Masson-Boivin and Sachs (2018).

In addition to improving soil fertility, long-term cultivation of perennial legumes demonstrated a pronounced phytoremediation effect by reducing the concentrations of bioavailable heavy metals in degraded Greyic Phaeozems (Figure 3).

The concentration of mobile lead (Pb) gradually decreased over the six-year restoration period. The initial Pb content of 5.9 mg kg^{-1} was reduced under both perennial legumes; however, *Lotus*

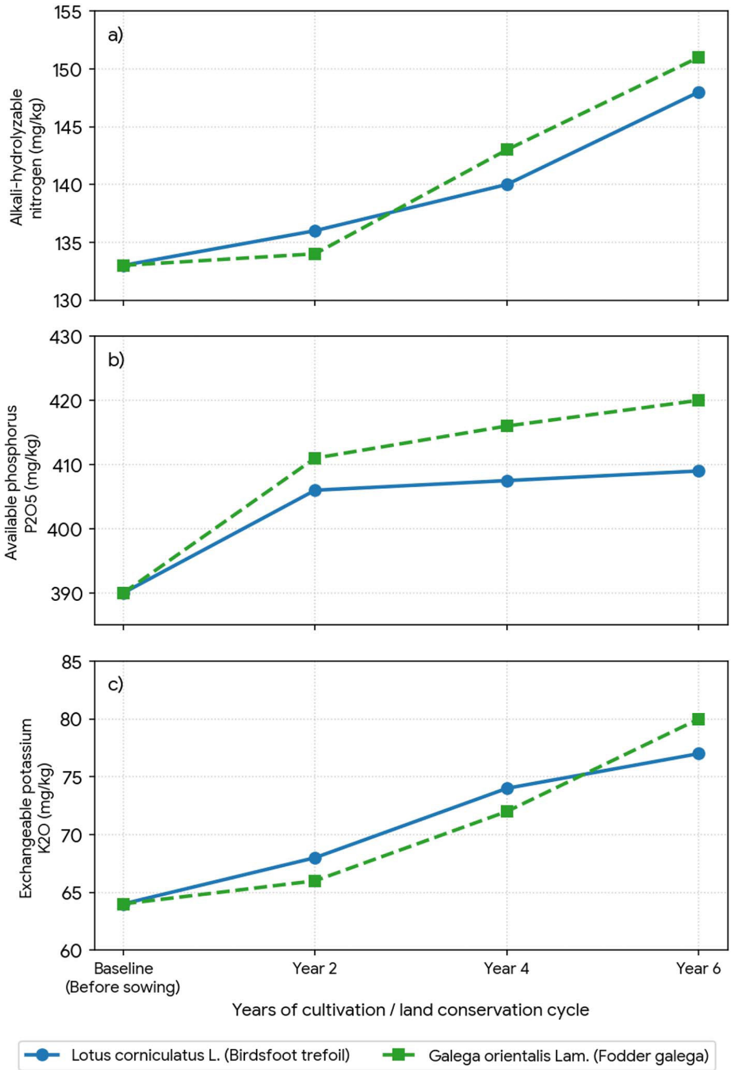

Figure 2. Dynamics of available macronutrient content (N, P, K) in degraded Greyic Phaeozems under long-term phytoremediation blocks: a) alkali-hydrolyzable nitrogen; b) available phosphorus; c) exchangeable potassium

corniculatus exhibited a more rapid remediation response. By the end of the experiment, the concentration of mobile lead decreased to 1.8 mg kg^{-1} under *Lotus corniculatus*, whereas *Galega orientalis* reduced Pb content to 2.0 mg kg^{-1}.A similar pattern was observed for cadmium contamination (Figure 3b). Starting from an initial concentration of 0.6 mg kg^{-1}, *Lotus corniculatus* reduced cadmium content to 0.1 mg kg^{-1} after six years, while *Galega orientalis* decreased it to 0.3 mg kg^{-1}. The superior performance of *Lotus corniculatus* may be associated with its highly branched fibrous root system, which provides a larger contact surface with the contaminated soil layer and enhances rhizosphere-mediated immobilization processes.

The remediation dynamics of copper and zinc further confirmed the higher detoxification efficiency of *Lotus corniculatus*. The concentration of mobile copper decreased from 6.8 to 2.0 mg kg^{-1}, whereas zinc concentration declined from 9.1 to 1.8 mg kg^{-1}. Although *Galega orientalis* also contributed to reducing heavy metal mobility, the rate of remediation was less pronounced.

These findings indicate that *Lotus corniculatus* possesses considerable potential for phytostabilization and detoxification of degraded soils contaminated with heavy metals. Similar mechanisms involving root exudates, metal complexation, and rhizosphere interactions have been described in previous phytoremediation studies (Ali et al., 2020; Mihăilescu et al., 2024). Overall, the concentrations of bioavailable heavy metals decreased by 3.2–5.0 times during the restoration period, demonstrating

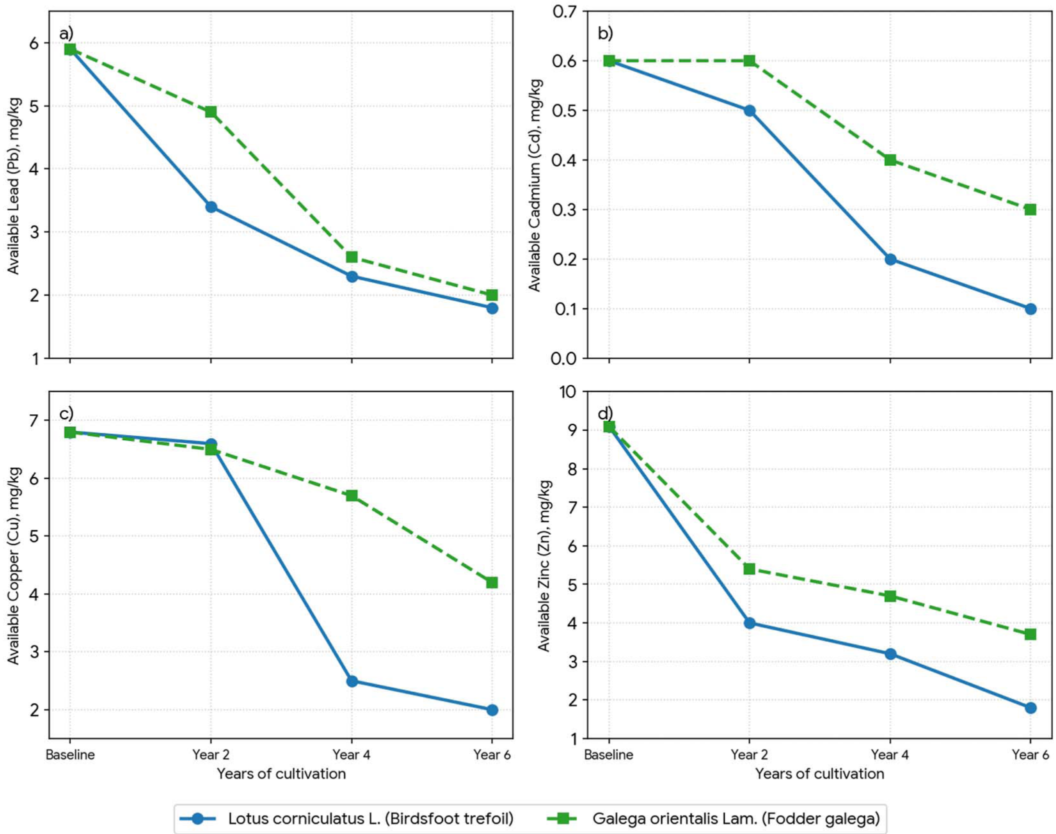

Figure 3. Heavy metal remediation dynamics (mobile forms) in degraded Greyic Phaeozems over a 6-year operational cycle under perennial legumes: a) Lead (Pb); b) Cadmium (Cd); c) Copper (Cu); d) Zinc (Zn)

the effectiveness of perennial legumes as nature-based solutions for post-war land rehabilitation.In addition to chemical remediation, perennial legumes also induced profound improvements in soil physical properties and aggregate stability (Figure 4).

Dry sieving analysis revealed a considerable increase in the proportion of agronomically valuable aggregates (0.25–10 mm). The initial value of 73.1% increased under both treatments, reaching 95.3% under *Lotus corniculatus* and 97.5% under *Galega orientalis* after six years. The superior aggregate formation observed under *Galega orientalis* can be attributed to its extensive root biomass and continuous input of organic residues.The structural coefficient (Kstr) also increased markedly during the experiment. Although *Galega orientalis* produced a greater proportion of macroaggregates, *Lotus corniculatus* generated a higher structural coefficient, reaching a maximum value of 24.5 by the sixth year.The most remarkable differences between the species were observed in the water stability of the aggregates. Initially, only 50.3% of the aggregates were water stable. Under *Lotus corniculatus*, this parameter rapidly increased to 88.7% within two years and reached 93.5% by the end of the study. In contrast, *Galega orientalis* showed a more gradual improvement, achieving 84.7% after six years.

The exceptional water-stability performance of *Lotus corniculatus* may be explained by the development of an extensive fibrous root system and by the production of rhizosphere exudates and glomalin-related compounds that act as natural binding agents. These substances promote aggregate stabilization and enhance soil resistance to water erosion.Conversely, *Galega orientalis* contributed primarily to long-term macroaggregate formation through continuous accumulation of organic matter and gradual modification of soil microbial communities. Therefore, although both species improved soil physical quality, they operated through different restoration mechanisms.

The obtained results suggest that *Lotus corniculatus* is particularly suitable for areas requiring rapid erosion control and soil stabilization, whereas *Galega orientalis* is more effective for long-term enhancement of soil fertility and aggregate development.

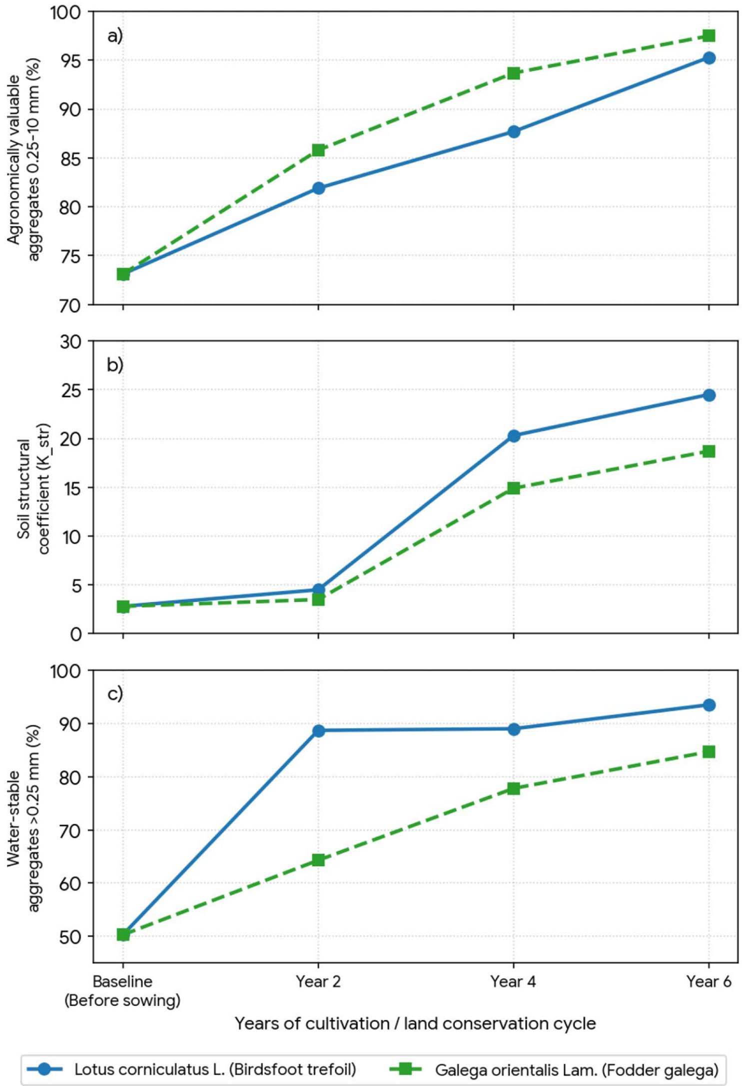

Figure 4. Dynamics of agrophysical soil properties of degraded Greyic Phaeozems during a 6-year conservation cycle under perennial legumes: a) content of agronomically valuable aggregates (0.25–10 mm); b) soil structural coefficient (K_{str}); c) content of water-stable aggregates (>0.25 mm)

CONCLUSIONS

The Long-term biological restoration of degraded Greyic Phaeozems through the cultivation of perennial legumes has proven to be an effective and sustainable ecological engineering strategy for accelerating soil recovery processes and may serve as an environmentally sound alternative to passive natural regeneration.Among the investigated species, *Galega orientalis* demonstrated superior performance in soil fertility restoration. During the six-year conservation period, it promoted organic matter accumulation, increased soil pH, reduced hydrolytic acidity, and enhanced the availability of essential nutrients, particularly alkali-hydrolyzable nitrogen and available phosphorus.

In contrast, *Lotus corniculatus* exhibited higher phytoremediation efficiency with respect to heavy metal detoxification. The concentrations of bioavailable Pb, Cd, Cu, and Zn decreased by 3.2–5.0 times, indicating a substantial reduction in soil contamination. Furthermore, *Lotus corniculatus* significantly improved aggregate water stability and achieved the highest structural coefficient, thereby increasing soil resistance to erosion.Both perennial legumes contributed to the reconstruction of soil physical architecture and the enhancement of ecosystem functions; however, their mechanisms of action differed. *Galega orientalis* primarily promoted long-term humification and nutrient enrichment, whereas *Lotus corniculatus* provided rapid stabilization and detoxification of degraded soils.Therefore, a differentiated restoration strategy is recommended for degraded and post-war degraded agricultural lands. *Lotus corniculatus* should be preferred in areas exposed to severe erosion and heavy metal contamination, while *Galega orientalis* is more suitable for marginal lands requiring intensive restoration of soil fertility and organic matter accumulation.

Overall, perennial legumes can be considered effective nature-based solutions for the rehabilitation of degraded agricultural ecosystems and for improving the ecological resilience of post-war landscapes in Ukraine.

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