UDC 631.618:631.48 https://doi.org/10.31867/2523-4544/0297

EFFECT OF LONG-TERM PHYTOREMEDIATION ON THE SOIL GENESIS POTENTIAL OF THE TECHNOZEMS OF THE POKROV RESEARCH STATION

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Topicality. *In Ukraine, reclaiming the vast areas of mined lands is critical for improving the environment, human health, and agricultural production. Land reclamation is particularly relevant due to large-scale manganese mining in the Nikopol district of Dnipropetrovsk region.* ***Purpose.*** *Our research is aimed to create land use technologies that maximize soil fertility and agricultural productivity while minimizing the time, cost and negative environmental effects of the remediation.* ***Methods.*** *The experiment was placed on loess-like red-brown loam (quaternary). The species mixture included Onobrychis arenaria (Kit.) DC, Medicago sativa L., Melilotus albus Medik., Agropyron pectiniforme Roem. et Schult., Bromopsis inermis (Leyss.) Holub. Avena sativa with Vicia sativa were the cover crops of this species mixture.* ***Results.*** *A legume-grass mixture used for hay or forage is the most appropriate transition to profitable field-crop production on the bare, drastically disturbed soil that remains after mining operations. The most appropriate composition (in mln. seed per hectare) of legume-grass mixture during sowing included about 1.8 mln. seeds/ha of Onobrychis arenaria (Kit.) DC, Medicago sativa L. and Melilotus albus Medik., 0.6 mln. seeds/ha of Agropyron pectiniforme Roem. et Schult. and 0.5 mln. seeds/ha of Bromopsis inermis (Leyss.) Holub. This system produced high quality hay yields of 2.4 to 4.9 t/ha even without topsoil replacement. The percentage of harvested legume biomass decreased from 85 to 5 %, humus content – from the initial 0.32 % to 1.52 % at 0–5 cm, and to 1.24 % at 0–20 cm, depending on cultivation variants and the time period after planting. It was found that macronutrient content increased by 2.4–4 times. Bulk density of substrate at depth of 0–40 cm varied from 1.24–1.33 g/cm^3.* ***Conclusion.*** *In the Southern Steppe of Ukraine, it was found that the long-term (over 50 years) intensive phytoremediation, primarily with perennial legume-grass agrocenosis, contributed to increasing the nutrient content of technosols and optimising their physical and biological properties.*

Key words: *land reclamation, mining overburden, phytoremediation, young soils, legume-grass mixtures, loess-like loam, red-brown and grey-green clays¸ chernozem*

Introduction. In Ukraine, reclaiming the vast areas of mined lands is critical for improving the environment, human health, and agricultural production [1–3]. Mined lands produce excessive amounts of dust, which causes respiratory problems for residents of nearby areas. Such lands also lower the water table level, and reduce crop yields for quite some distance from the mine. This land can be returned to agricultural production (Fig.1).

Fig. 1. Pokrov (Ordzhonikidze) mine site. Overburden removal, land reclamation research field.

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Land reclamation is particularly relevant due to large-scale manganese mining (about 75.0 % of manganese-ore) in the Nikopol district of Dnipropetrovsk region.

There are 9,000 hectares of mined land in the region, but reclamation of most of them has been ineffective. Another 11,000 ha or more exists without soil replacement (mainly as a result of mining more than 50 years ago), and an estimated additional 150,000 ha or more in Nikopol district suffers significant adverse effects from the non-restored mined land [4–5]. In addition to mineral mines, there are thousands of smaller quarries in different parts of Ukraine where construction materials are quarried.

The Nikopol area is a very productive agricultural region, as it has very fertile soils, sufficient water resources for irrigation, and enough warmth, sunshine and growing season length for excellent yields.

Both the hypothetical and practical aspects of agronomic renovation of mined lands were initiated in Ukraine by Dnipro State Agrarian and Economic University (DSAEU) under the guidance of the professors Ivan Uzbek, Mykola Kharytonov. Recommendations, which were based on the research of the Pokrov Mining and Processing Complex, were implemented by all mining enterprises in the Nikopol district [6]. However, earlier mining operations did not preserve the integrity of the topsoil and underlying soil horizons. Therefore, even after levelling, the resulting soil is actually mixed-overburden substrata. Vegetation is poor and the wind carries large amounts of dust over long distances. This dust does not contain hazardous levels of heavy metals or other toxic substances in the Nikopol district, but is detected in some other mining areas [7].

The current research priority is to determine the species composition of the legume-grass mixture for the most effective soil improvement aimed at supporting profitable production of wheat, maize and other field crops.

The Department of General Agriculture and Soil Science of DSAEU has proposed six universal and special models of remediated soils:

Model 1 (Fig. 2) is the simplest. The lithozem model consists of the substrate type that is most fertile and most favorable for crops, except of replacement surface-stratum chernozem. It is based on phytoremediation against the background of crop rotations that involve the alternation of legume crops with legume-grass mixtures. The most common substrate is loess (Quaternary) (Fig. 2), a mixture of red-brown loam and clay (Neogene-Quaternary period origin, N_2S/Q), or grey-green clay (Neogene, N_1Srm_2+3). The content of macro- and microelements in these substrates is sufficient to produce high yields of alfalfa and sainfoin hay. High grain yields can only be achieved through the application of phosphorus, potash and especially nitrogen fertilisers [4].

Model 2 and Model 3 are two-layer models (Fig. 2). These models are based on a fertile substrate under a layer of chernozem 0.5 m depth (Model 2) or 0.70–1.0 m depth (Model 3). Model 2 is more commonly used. It can be used to grow the full range of crops used in the Steppe and Forest-Steppe ecological zones. The production technology after soil replacement differs from the technology for normal (undisturbed) soil only in that it requires alfalfa or sainfoin to be grown for 5 years at the beginning of exploitation. The yields are equal for both these soils and for low-eroded chernozem [4].

Model 3 provides an additional 10–30 % yield, presumably due to better nutrient and moisture supplies. However, this model includes the additional costs of transporting, placing and levelling additional chernozem. All the costs of land reclamation are paid by the mining companies.

Model 4 (Fig. 2) is used for orchards. Chernozem is embedded in holes or trenches in a fertile substrate. The chernozem is laid in holes or trenches into the fertile substrate. Experiments with fruit crops (apple, pear, plum, apricot trees, etc.) and berries crops (red currant, black currant, grapes) have been successful. For example, over 18 years, the average apple yield ranged from 11 to 15 tonnes per hectare, depending on the variety. The required amount of chernozem per tree is about one cubic metre.

Model 5 (Fig. 2) consist of 3 layers. The deepest layer is a phytotoxic or unfavorable substrate for crop growth (coal-bearing substrates with a high content of pyrite, saline substrates). The second layers acts as a protective shield and consist of loess (0.5 m). The third is the layer of fertile chernozem (0.3–0.8 m). Testing winter wheat, depending on the chernozem depth of 0.3 m, 0.5 m and 0.7–0.8 m,

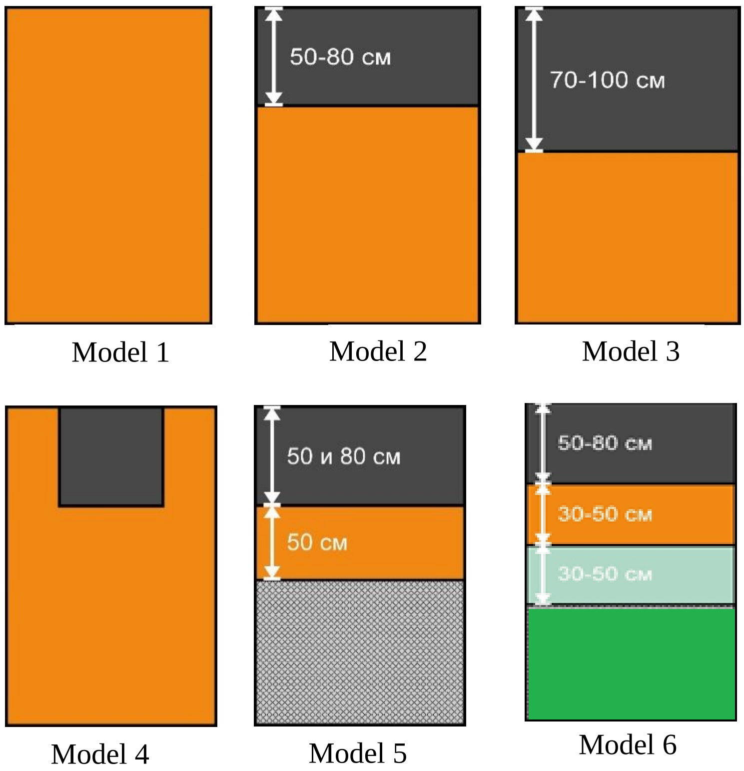

Figure 2. Models of technozems:

- chernozem;
- loess-like loam;
- red-brown clay;
- sand;
- gray-green clay.

resulted in increase in yield by 1.8, 2.6 and 3.4 t/ha, and produced yield of 28.3 and 33.7 t/ha, and 32.1 t/ha, respectively.

Model 6 (Fig. 7) consists of 4 layers: the top layer is 0.5–0.8 m of chernozem, followed by 0.3–0.5 m of loess loam, 0.3–0.5 m of waterproof layer, and a non-saline substrate. Higher crop yields are obtained through improved soil fertility and an additional 43–62 mm of available moisture per year [2, 7].

After the initial replacement of the substrate, there is a significant soil subsidence for at least 5–7 years, which prevents normal crop maintenance. Therefore, after the surface levelling of the subsoil, it is necessary to wait out at least 12–17 years before adding chernozem on top. Therefore, there is great practical and agro-economic motivation to make agricultural production possible on replaced substrates using phytoremediation without replacement of the chernozem [4].

Analyses of periodic soil samples over time have documented the nature and extent of changes that occurred in the first 25 years of plant cultivation [8]. The initial humus content increased from the 0.3 % to 1.5 % at depth of 0–5 cm, and to 1.12 % – at 0–20 cm. Total nitrogen content increased by 4–9 times, mobile phosphorus content increased by 2.6–3.4 times, and macronutrient content by 2.3–5.2 times. Considerable improvement of physical properties was observed. Bulk density of substrate at depth of 0–40 cm varies from 1.23–1.32 g/cm^3. Loess salinity decreased from 0.34 % to 0.15 % at depth of 0–60 cm. After 40 years of phytoremediation, the yield of dry matter of a legume-grass mixture was 15.2–22.8 % higher than after 10–14 years [9].

As mentioned earlier, legume-grass mixtures should be sown only after legumes. Mixture of *Onobrychis arenaria (Kit.) DC, Medicago sativa L., Melilotus albus Medik., Agropyron pectiniforme Roem. et Schult., Bromopsis inermis (Leyss.) Holub*. is suitable, but other-species are also promising [2]. There are some factors limiting the effectiveness of these species on overburden substrates. One of these factors is a significant decrease in the productivity of the mixture after 4–5 years of cultivation due to the autotoxicity of alfalfa [10]. Reducing alfalfa crops significantly reduces the nitrogen supply, as alfalfa is the main nitrogen supplier, although sainfoin also contributes. The second factor is the aggressive colonisation by grasses in the mixture, as the fertility of the substrate increases due to the growth of legumes. After 3-4 years, the growth of legumes reduces not only through the autotoxicity of alfalfa, but also through competition with grasses for light, water, phosphorus, etc. We should find ways to increase the life time of the mixture and reduce the number of years and cycles required to start growing field crops [11]. When the legumes are almost degenerating, the productivity of the mixture should be increased by grasses. The main environmental factor limiting the growth of non-legume crops on replaced overburden is a lack of nitrogen. Therefore, after legumes stop providing nitrogen to the soil, it is necessary to introduce nitrogen fertiliser under the legume-grass mixture. In this article, we present the results of studies of the effect of the composition (in million seeds per hectare) of legumes and grasses components during sowing of the mixture on the characteristics of artificial phytocenosis.

Materials and Methods. The experiment was conducted at the Pokrov Reclamation Research Center of DSAEU, located at 47º39' N, 34º08' E, with an elevation of 60 m. Average January and July ambient temperatures for this location are –2.8˚C and 21,7˚C respectively, with absolute minimum and maximum temperatures of -34.1˚C and 37.3˚C. The average frost-free period is 163–191 days. Annual precipitation averaged 448 mm for the last 40 years, with an average of 247 mm in the period from April to September. April – September precipitation varied from 285 mm to 357 mm in individual years.

During the first part of April annually from 2004 to 2008, and after 2011–2021, the legume-grass mixture was sown immediately after the cover crop followed by 18 months of clean fallow on loess loam. We selected this substrate because it is the most fertile type of subsoil available, and it is the main source material for soils in our region. Loess-like deposits are mainly pale-yellow loam or red-brown loam, but occasionally clay loam. Depth of this substrate is about 0.5–7.4 m. Properties of loess-like deposits and the major steppe soil (deep, rich, black steppe soils – chernozem) are presented in Table 1.

The proportions of different species in the legume-grass mixture are as follows (apportioned by million germinable seeds per ha and as % based on total germinable seeds per hectare in the mixture):

Variant 1 (legume mixture): *Onobrychis arenaria* (Kit.) DC ~2.0 + *Medicago sativa* L. ~2.0 + *Melilotus albus* Medik. ~2.3;

Variant 2 (80 % legumes: 20 % grasses): *Onobrychis arenaria* (Kit.) DC ~1.9 + *Medicago sativa* L. ~1.9 + *Melilotus albus* Medik. ~1.9 + *Agropyron pectiniforme* Roem. et Schult. ~0.6 + *Bromopsis inermis* (Leyss.) Holub. ~05;

Variant 3 (65 % legumes: 35 % grasses): *Onobrychis arenaria* (Kit.) DC ~1.6 + *Medicago sativa* L. ~1.6 + *Melilotus albus* Medik. ~1.6 + *Agropyron pectiniforme* Roem. et Schult. ~1.1 + *Bromopsis inermis* (Leyss.) Holub. ~1.1;

Variant 4 (50 % legumes : 50 % grasses): *Onobrychis arenaria* (Kit.) DC ~1.2 + *Medicago sativa* L. ~1.2 + *Melilotus albus* Medik. ~1.2 + *Agropyron pectiniforme* Roem. et Schult. ~1.7 + *Bromopsis inermis* (Leyss.) Holub. ~1.7;

Variant 5 (grass mixture): *Agropyron pectiniforme* Roem. et Schult. ~3.5 + *Bromopsis inermis* (Leyss.) Holub. ~3.5.

The mixtures was planted into a cover crop mixture of *Ovena sativa* (1.8 mln seeds/ha) and *Vicia sativa* (0.4 mln seeds/ha). The cover crop was planted immediately before sowing the plant mixture. The cover crop was planted with 15 cm row spacing. When cover crop grew to approximately 45–65 cm tall with approximately 75.0 % ground cover, it was removed before at the flower-bud

Table 1. Edaphic properties of technozems and steppe chernozem

Soil / substrate	Density[1], g/cm^3	Content, %[2]				pH	$CaCO_3$, %	CEC, meq/100g	Content, mg/kg of soil[3]		
		Humus	Total N	Hygroscopic moisture	Mechanical elements <0.01 mm				Total P	NO_3^- after composting[4]	Exchangeable K
Typical chernozem	1.13 ±0.03[5]	5.43 ±0.11	0.26 ±0.07	8.94 ±0.22	52.5 ±1.3	6.77 ±0.12	14.5 ±0.18	40.2 ±1.15	83.5 ±1.08	192 ±2.23	157 ±1.87
Ordinary chernozem	1.17 ±0.06	4.52 ±0.17	0.18 ±0.03	8.21 ±0.18	54.7 ±1.8	7.12 ±0.14	11.3 ±0.14	47.5 ±1.22	74.5 ±2.13	168 ±3.12	133 ±1.64
South chernozem	1.04 ±0.04	3.22 ±0.12	0.15 ±0.03	8.13 ±0.14	59.3 ±1.7	6.9 ±0.13	12.7 ±0.12	34.3 ±1.28	67.8 ±2.17	141 ±3.31	128 ±2.12
Loess-like loam	1.35 ±0.14	0.21 ±0.12	0.03 ±0.03	2.14±0.45	53.1±1.8	6.8 ±1.12	13.81 ±2.11	28.3 ±2.88	14.1 ±1.25	8.2 ±1.03	103 ±2.28
Red-brown clay	1.28 ±0.18	0.23 ±0.08	0.03±0.02	9.52- ±2.21	70.85±3.42	7.5 ±0.87	10.84 ±2.34	27.1 ±2.95	8.8 ±1.34	5.2 ±1.76	241 ±3.37
Grey-green clay	1.33 ±0.21	0.16 ±0.07	0.03±0.01	9.13 ±1.63	70.92±4.13	7.5 ±0.92	12.61 ±2.19	28.6 ±2.91	7.2 ±1.28	5.6 ±1.93	547 ±3.21

Comments: [1] *– for density of chernozem plough-layer,* [2] *– for chernozem in surface horizon,* [3] *– for chernozem in surface horizon,*
[4] *– NO_3 content after 14 days of chemically assisted composting at 25^o C, ±* [5] *– variation of indicators*

formation of *Vicia sativa* in mid-June.

The experiment was repeated 5 times on plots of 34 m^2 each (1.70 m x 20.0 m) arranged in a split block with timing as the main block and the ratio of different species as sub-blocks. During the first year, only the cover crop yield was recorded. Yield of legume-grass mixture was evaluated at the beginning of the second year.

The hay was harvested in the flower-bud formation stage of legumes. Data was collected on four 1 m^2 samples per plot, with the remainder of each plot cut with a reciprocal mower. The data collected included total biomass (wet and dry), botanical composition, structure of the harvest, plant height and number of stems per m^2.

Results and Discussion. With time, the share of legumes in the harvest biomass decreased gradually (Table 2), reducing the phytomeliorative effect of the plant community on the substrate. In the fifth year, the share of legumes in biomass was 17.8 % compared to 58.2 % in the second year of cultivation. The decrease resulted from the elimination of *Melilotus albus* after the third year of cultivation, as well as the reduction of *Medicago sativa* growth due to autotoxicity and competition with other grass. *Agropyron pectiniforme* and *Bromus inermis* were more competitive than the legumes, probably in part due to the available nitrogen provided by the sustained growth of the legumes [2, 4].

Nitrogen application resulted in greater biomass yield (Table 2), with the increase ranging from 22.2 to 34.1 kg/ha N in the year of application. Perhaps the most desirable N rate is 44 kg/ha in both the 5th and the 6th year, but when the sum of years 5 and 6 is considered, the highest increase in dry matter content per kg of N (62.3 kg N) was actually in year 5 only. Statistically significant increases of hay yield beyond 62.3 kg were not obtained in individual years, presumably because other factors limited the yield. Although the yield with 92.4 kg N significantly exceeded that with 60.5 kg N when 5th and 6th years were combined, using more than 58.6 kg N/ha - is not justified by the small increase in yield. Because of the suppressive effect of nitrogen fertilization on the legumes, we concluded that nitrogen should not be applied earlier than the 5th year. Previous research showed that nitrogen in the form of ammonium nitrate gave the biggest effect [4]. Therefore, we concluded that an early-spring application of ammonium nitrate should begin in the 5th year. Further research is necessary to determine whether application in both the 5th and 6th years is superior to a single larger application in the 5th year.

After nitrogen application, the share of

Table 2. Change productivity and ratio of components in the perennial agrophytocenosis depending on technozem constructions and time from the beginning of their agricultural development

Time from the moment of agricultural development*	Indexes	Technozems			
		chernozem	loess-like loam	red-brown clay	grey-green clay
10–12 years (1981–1983)	yield, t/ha	4.35±0.08	3.91±0.07	3.34±0.07	4.14±0.08
	share of legumes, %	44.1	71.4	79.8	75.6
	share of cereals, %	48.2	23.3	17.5	20.3
	share of other species, %	7.7	5.3	2.7	4.1
25–27 years (1996–1998)	yield, t/ha	4.52±0.09	4.21±0.08	3.47±0.07	4.22±0.08
	share of legumes, %	42.3	63.6	66.7	63.3
	share of cereals, %	52.1	33.3	30.4	32.1
	share of other species, %	5.6	3.1	2.9	4.6
40–52 years (2011–2021)	yield, t/ha	4.46±0.09	4.41±0.08	4.05±0.08	4.63±0.09
	share of legumes, %	47.7	55.9	61.3	54.4
	share of cereals, %	44.8	40.8	35.5	42.4
	share of other species, %	7.5	3.3	3.2	3.2

***** Comments. For 1981–1983, data from the facility of M. T. Masiuk (1984); S. F. Petrenko (1984); for 1996–1998 – V. O. Zabaluev (2005).

legume biomass in the mixture decreased. This was most dramatic in 5th year, when legumes dropped from 17.6 % (0.43 t/ha) without nitrogen to 6.13 % (0.34 t/ha) after incorporation of N_{90}. Comparatively, the grasses increased from 77.0 % (1.8 t/ha) to 91.5 % (4.6 t/ha). *Bromus inermis* accounts for a significant share of the increase, due to its high mobility and ability to occupy free ecological niches. There was a strong decline in legumes from 5th year to 6th year even without nitrogen, but the decline was much more with 60.3 and 90.5 kg N applied in 5th year only, and even greater with N applications both years.

Conclusions. In the Southern Steppe of Ukraine, cost-effective land reclamation has established that the long-term (over 50 years) impact of intensive phytoremediation, primarily perennial leguminous and cereal agrocenosis, has contributed to increasing the nutrient content of technozems, optimizing their physical and biological properties. For lithogenic technozems (not covered with fertile soil layer), over a 50-year development period, the saturation of crop rotations with complex phytoremedial legume-cereal agrocenosis (*Medicago sativa* L. + *Onobrychis arenaria* (Kit.) DC + *Agropyron desertorum* Schult. + *Bromopsis inermis* (Leyss.) ensures an increase in humus content by 2.9–6.8 times, optimises physical soil properties, increases biological activity.

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УДК 631.618:631.48

Мицик О. О., Гаврюшенко О. О., Шевченко С. М., Гуленко О. І. ***Вплив тривалої фітомеліораційної дії на потенціал грунтогенезу техноземів покровського дослідного стаціонару.***

Grain Crops. 2023. 7 (2). 350–357.

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Актуальність. *Рекультивація величезних площ порушених земель, які залишилися спустошеними, є критично важливою в Україні для покращення навколишнього середовища, здоров’я людей та* *сільськогосподарського виробництва. Особливо актуальною є потреба у рекультивації Нікопольського району Дніпропетровської області, оскільки тут великий видобуток марганцю.* ***Метою*** *нашого дослідження було створення такої технології землекористування, яка б сприяла відновленню родючості ґрунтів та продуктивності сільського господарського використання при мінімізації часу, вартості та негативних екологічних наслідків проведення рекультивації.* ***Матеріали і методи.*** *Дослідні ділянки розміщували на різноякісних конструкціях з лесоподібних, червоно-бурих суглинків. Вирощувана суміш видів включала Onobrychis arenaria* (Kit.) DC, *Medicago sativa* L., *Melilotus albus* Medik., *Agropyron pectiniforme* Roem. et Schult., *Bromopsis inermis* (Leyss.) Holub. *Ця видова суміш була розміщена під покровом таких культур: Avena sativa з Vicia sativa.* ***Результати.*** *Злаково-бобова суміш, яка використовується на сіно або корм, є найдоцільнішим переходом до рентабельного вирощування польових культур з порушеного ґрунту, що залишився після гірничих робіт. Найбільш прийнятний агрофітоценоз (у млн. насінин на гектар) бобових і злакових компонентів при сівбі становив близько 1,8 млн. насіння/га Onobrychis arenaria* (Kit.) DC, *Medicago sativa* L. *та Melilotus albus* Medik., *0,6 млн. насіння/га Agropyron pectiniforme* Roem. et Schult. *та 0,5 млн. насіння/га Bromopsis inermis* (Leyss.) Holub. *Від 2,4 до 4,9 т/га високоякісного сіна за цією схемою можна одержувати навіть без нанесення верхнього родючого шару ґрунту. Відсоток урожайної біомаси, отриманої від бобових, зменшувався з роками після сівби з 85 до 5 % залежно від варіантів вирощування та тривалості після сівби. Вміст гумусу збільшився з початкових 0,32 % до 1,5 % в 0–5 см, і до 1,2 % в 0–20 см. Вміст макроелементів збільшився в 2,4–4 рази. Щільність складення субстрату в 0–40 см коливається від 1,24–1,33 г/см^3.* ***Висновки.*** *В умовах Південного Степу України на рекультивованих землях встановлено, що довготривалий (понад 50 років) вплив інтенсивної фітомеліорації, насамперед багаторічними бобово-злаковими агроценозами, сприяв збільшенню в техноземах поживних речовин, оптимізації фізичних і біологічних властивостей.*

Ключові слова: *рекультивація, гірнича розкривна порода, агрофітомеліорація, молоді ґрунти, злаково-бобові сумішки, лесоподібний суглинок, червоно-бурі та сіро-зелені глини¸ чорнозем*