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Influence of prolonged agrogenic transformation on soil structure and physicochemical properties of Ukrainian Albic Stagnic Luvisols: a case study from western Ukraine

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Abstract

Albic Luvisol occupy large areas in Ukraine, have low natural fertility and high acidity. Effective use of such soils is possible in the agricultural system only after improving their fertility. This involves constant management of reclamation and technological measures in accordance with the long-term dynamics of soil processes. A long-term experiment was started in 1965 with different rates and ratios of mineral, and organic fertilizers as well as lime. The purpose of the study is to establish the influence of systematic application of different fertilization schemes and periodic liming on the change in the structural-aggregate composition and physico-chemical properties of Albic Stagnic Luvisol under different crop rotations. Studies have shown that the long-term use of different fertilization systems and periodic liming on Albic Stagnic Luvisol both in the 4th and 9th crop rotation caused a significant predominance of very fine (VF – 0.25–1.0 mm) soil aggregates over coarse ones (CO – 5–10 mm). Under the combined organo-mineral system of fertilization and periodic liming of 1.0 n $CaCO_3$ (according to hydrolytic acidity), at the end of the 9th crop rotation, the content of large components is almost eight times higher than the content of very fine and medium ones (VM – 0.25–3.0 mm). The content 0.25–1.0 mm fraction along the profile increases significantly with increasing of depth in the control (without fertilizers) and with only mineral fertilization. This indicates deterioration of the waterproofing of the soil profile. Research results showed that the transformation of forest ecosystems into agricultural ecosystems improved the acid-base properties of Albic Stagnic Luvisol. The reaction of the soil became slightly acidic (pH 5.18–5.51) with the average multi-year application of a single norm of mineral fertilizers ($N_{65}P_{68}K_{68}$), the norm of 10 t ha^{-1} of cow manure against the background of the norm of 1.0 n $CaCO_3$ pH_{KCl}. Hydrolytic acidity, beside the control, ranges from low to medium with maximum values in the middle part of the soil profile. We investigated the accumulation of humus only in the upper layers of the soil in the control and on various fertilization systems. The lower horizons contain less than 1% humus.

1. Introduction

Albic Stagnic Luvisols occupy a large area in the western part of Ukraine. They are characterised by low natural fertility and high acidity of the soil solution. Efficient use of such soils in the farming system is only possible by improving their fertility. Unbalanced intensive and technogenic soil management practices may result in irreversible soil fertility losses and degradation. Therefore, the spontaneous processes of transformational soil development and formation of soil fertility should be countered by a scientifically based system of managing these processes. This entails continuously adjusting reclamation and technological measures in response to climate change, soil processes, regimes, and the physiological needs of plants. This approach will help counteract spontaneous processes of soil development and fertility formation through a scientifically based system of soil fertility management (Nosko, 2013; Truskavetskyi et al., 2020). To solve this problem, it is important to comprehensively compare the development of agrogenic-transformed and relatively natural soils, as well as to interpret data from previous studies (Repsiene and Karcauskiene, 2016; Truskavetskyi and Tsapko, 2016; Volungevicius et al., 2016; Brezinščak and Bogunović, 2021).

One of the priority challenges for modern soil science is to preserve the multifunctionality of soil ecosystems, thus contributing to the optimization of crop nutrition (Volungevicius et al. 2018). Modern management of soil resources in agroecosystems is characterized by a linear principle, while the processes occurring in natural systems are characterized by cyclicity. Elimination of cyclicity by agrogenic factors disrupts the cyclical nature of soil development. This causes problems in maintaining soil fertility.

The range of studies related to agrogenic soil transformation is very wide (Novikova and Konyushkova, 2013; Masilionytë and Maikđtënienë, 2016; Povilaitis et al., 2018). However, these studies focused primarily on changes in properties in the upper humus horizons (0–30–45 cm). It was assumed that the changes that occur at a depth of 100–150 cm are the result of long-term (50 years or more) tillage (Veenstra and Burras, 2015). Others have studied the effect of long-term mineral fertiliser on soil structure, arguing that the structure of low humus gley soils is more stable in acidic conditions, because its formation involves not calcium but aluminium and iron oxides (Šimanský and Jonczak, 2020). Still, others focused primarily on organic matter changes in the context of global CO_2 sequestration and soil fertility (Kaiser and Kalbitz, 2012; Roychowdhury et al., 2013; Haddix et al., 2016; Ovchinnikova, 2016). Some researchers have focused on the study of individual morphological features in the profile and related changes (Adewopo et al., 2014; Šimanský et al., 2016).

To assess the transformation of soil properties that occur in agro-ecosystems, it is important to understand how much soil has changed compared to the natural soil. Chendev et al. (2012) applied a similar approach in soil research, based on the example of the historical development of forest landscapes. They noted that long-term tillage in the first place greatly changed the morphology of the soil and its chemical and physical properties. Bai et al. (2013) also emphasize the importance of time duration.

Objective information about the state and changes of agroecosystems and their components under the influence of various anthropogenic loads can be obtained only in long-term stationary experiments.

Our research aimed to establish the effect of long-term use of various fertiliser systems and periodic liming on the change of structural and aggregate composition and physicochemical properties of Albic Stagnic Luvisol in such stationary experiments.

2. Materials and methods

2.1. Field experiment

The research was performed on a long-term stationary experiment established in 1965 (49°47’54.3” N 23°52’26.9” E) in the Department of Agrochemistry and Soil Science of the Institute of Agriculture of the Carpathian Region of the National Academy of Agrarian Sciences of Ukraine (NAAS). The experiment is included in the register of long-term stationary field experiments of NAAS (NAAS registration certificate No. 29). The soil type of the study site is classified according to WRB (2022) as Albic Stagnic Luvisol. The experiment has undergone five seven-field rotations (potatoes – spring barley with red clover sowing – red clover – winter wheat – sugar beets – corn for silage – winter wheat) since its establishment (1965–2001). Currently, research is conducted in a four-field crop rotation (corn for silage – spring barley with red clover sowing – red clover – winter wheat).

Investigation of soil structure and its physicochemical properties was conducted at the end of the 4th (1986–1994) and 9th (2012–2017) crop rotations under winter wheat. Three soil pits were dug for each of the researched treatments in the 1st field during the 9th crop rotation (Fig. 1). The field wasn’t specified in the 4th rotation (Voloshchuk et al., 1999).

2.2. Experimental design

The stationary experiment is placed on three fields, each has 18 plots in triplicate, so three crops of crop rotation are

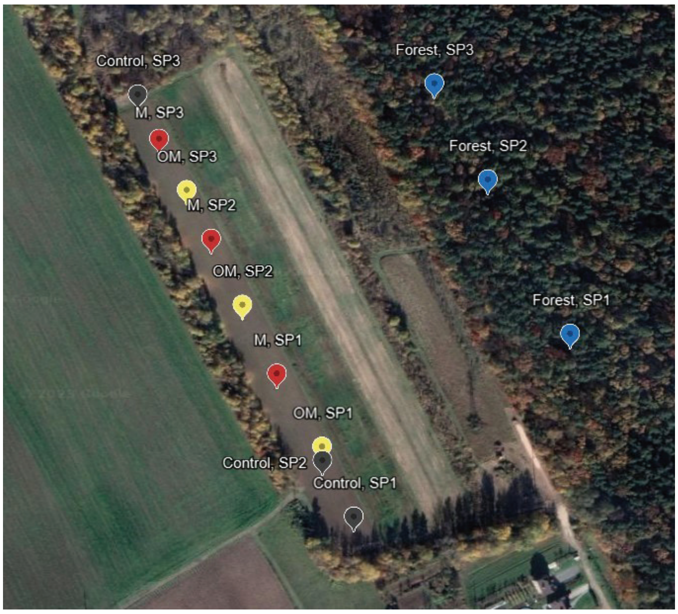

Fig. 1. Long-term experiment location (49°47’5” N 23°52’26” E) with soil profiles.

Note. Control – absolute control without fertilisers, OM – organo-mineral fertiliser system and M – mineral fertiliser system (Table 1); SP – soil profile. Map data: Google, Maxar Technologies.

grown simultaneously. The location of plots is single-tiered and consistent. The total area of the plot is 168 m^2, accounting area is 100 m^2. Agricultural cultivation techniques, tillage, and crop care are generally accepted for the conditions of the Western Forest-Steppe zone of Ukraine.

In seven-field rotation the following experimental design was used: C – absolute control without fertiliser (control), OM – organo-mineral fertiliser system (10 t of manure on ha of crop rotation area + $N_{70}P_{90}K_{90}$) on the background of periodic liming with 1.0 n $CaCO_3$ HA (6.0 t ha^{-1} of limestone flour), and M – mineral ($N_{140}P_{180}K_{180}$) fertiliser system. In four-field rotation following treatments were applied: C – absolute control without fertilisers (control), OM – organo-mineral fertiliser system (10 t of manure on ha of crop rotation area + $N_{65}P_{68}K_{68}$) on the background of periodic liming with 1.0 n $CaCO_3$ HA (6.0 t ha^{-1} of limestone flour) and M – mineral ($N_{65}P_{68}K_{68}$) fertiliser system (Table 1).

The experiment used semi-rotten cattle manure on straw litter, ammonium nitrate (34.5%), granular superphosphate (19.5%), potassium salt (40%), nitroammophos (NPK 16%) (when using nitroammophos, NPK content was balanced according to the levels of fertilisation with simple fertilisers). Manure in seven-field rotation at the rate of 10 and 20 t ha^{-1} of crop rotation area was applied under potatoes and sugar beets, in four-field – under corn. Phosphorus-potassium fertilisers were applied in autumn, and nitrogen – by pre-sowing cultivation. Liming in 1st–5th rotations according to the experimental scheme in a seven-field crop rotation was carried out under potatoes. In a four-field rotation liming was carried out under corn for silage with adjusted dose of fertiliser for crop rotation, without violating the content of treatments. As limestone materials, we used limestone flour (90% CaO). Starting from the 8th rotation (2008–2011), the second mowing of red clover was ploughed as fertiliser in all plots of the experiment.

Agrochemical characteristics of the arable layer of the soil before experiment establishment are as follows: humus content (according to Turin) 1.42%, pH_{KCl} 4.2, hydrolytic acidity (HA) (according to Kappen) 4.5, exchangeable acidity (according to Sokolov) – 0.6 cmol(+) kg^{-1} of soil, the content of mobile aluminium 60.0, mobile phosphorus (according to Kirsanov) and exchangeable potassium (according to Maslova) – 36.0 and 50.0 mg kg^{-1} of soil, respectively. Soil texture in the upper layer is silt (sand fraction (ϕ > 0.05 mm) content is 13.0–16.0%, the silt (ϕ 0.05–0.001 mm) content is 78.3–81.5% and the clay (ϕ < 0.001 mm) content is 3.6–5.2%).

To compare the transformation of soil properties under long-term anthropogenic impact to soil's natural state, additional soil profiles were made under the canopy in the forest (F) (49°47'53.4" N 23°52'36.7" E).

Soil classification was carried out according to the WRB (2022) rules. The Guidelines for Soil Description (FAO, 2006) were used for detailed morphological description and determination of soil particle size.

2.3. Experimental methods

Studies of the transformation of the structural and aggregate composition of Albic Stagnic Luvisol top layer under different systems of fertilisation and periodic liming were performed by the sieve method in Savvinov modification (DSTU 4744–2007), which consisted of two successive stages. In the first stage, 0.5–1.5 kg air-dried average soil sample is sifted through the 10, 7, 5, 3, 2, 1, 0.5, 0.25 mm sieves (dry sieving), resulting in soil decomposition to macro-aggregates of different sizes. One fraction of macro-aggregates is collected on each sieve. Macro-aggregates content is calculated as a percentage of the soil sample mass. In our case, for analysis were selected coarse 5–10 mm aggregates (CO), and very fine to medium 0.25–3.0 mm aggregates (VM) (FAO, 2006). In the second stage, all fractions of micro-aggregates from soil dry sieving were soaked and again sifted through sieves in water (wet sieving) to separate water-resistant macro-aggregates of coarse 5–10 mm (CO) and very fine (VF) 0.25–1.0 mm faction (FAO, 2006).

For the determination of physicochemical properties of the studied treatments, samples were taken from each genetic horizon and prepared for analysis following DSTU 4287: 2004 and DSTU ISO 11464:2007. Soil pH_{KCl} was determined by the potentiometric method in 1 M KCl (extraction ratio 1:2.5) according to DSTU ISO 10390:2001. HA was measured by Kappen method modified by CINAO (DSTU 7537:2014) using 1 M sodium acetate solution adjusted to pH 8.2 in the ratio of 1:2.5. The suspensions were shaken at room temperature for one hour and then filtrated. The filtrates were titrated with 0.1 M NaOH solution in presence of a phenolphthalein indicator. Mobile aluminium

Table 1
Characteristic of experimental treatments (4th and 9th crop rotations)

Fertilizer system		Crop rotation	Applied to 1 hectare of crop rotation area		
			rate of lime	rate of lime	NPK, kg of the active substance
C	Without fertilizers (control)	4th, 9th	0	0	0
OM	Organo-mineral with liming	4th	1.0 norm according to hydrolytic acidity (6.0 t/ha)	10	$N_{70}P_{90}K_{90}$
		9th	1.0 norm according to hydrolytic acidity (6.0 t/ha)	10	$N_{65}P_{68}K_{68}$
M	Mineral	4th	0	0	$N_{140}P_{180}K_{180}$
		9th	0	0	$N_{65}P_{68}K_{68}$

(Al^{3+}) determination was conducted according to Sokolov (GOST 26485–85) by extraction with 1 M KCl (1:2.5). Samples were shaken for 1 h then filtered, selected aliquots were boiled for 5 minutes and were using phenolphthalein as an indicator. Then, other samples were taken from the filtrate, boiled for 5 min and titrated with 0.02 M NaOH after the addition of 3 ml of 3.5% NaF. The concentration of mobile Al^{3+} was determined by the difference between these titrations. The sum of exchangeable bases (SEB) was measured according to GOST 27821-88, using 0.1 M HCl solution in the ratio of 1:5. The suspensions were shaken at room temperature for one hour, left for 24 h and then filtrated. The filtrates were titrated with 0.1 M NaOH solution in presence of a phenolphthalein indicator. Humus content was determined by spectrophotometric measurement at 590 nm after dichromatic oxidation according to Turin method modified by Nikitin (DSTU 4289:2004).

2.4. Statistical analysis

The significance of the differences between the means was determined Tukey's test. Differences between the samples were considered statistically significant at $P<0.05$. The data was analysed in OriginPro 2019b. The data in the tables are presented as an arithmetic mean with standard deviation (x ± SD).

3. Results

3.1. Soil structure

Analysis of the structural and aggregate composition of soil after dry sieving showed that in control without fertilisers (C) content of CO 5–10 mm and VM 0.25–3.0 mm aggregates is almost the same in 4th crop rotation (42.5% and 45.2%). At first sight, it indicates a high degree of soil structurality. At the end of 9th rotation, the number of coarse aggregates (65.6%) far exceeds the number of very fine to medium (25.8%) and are close to the soil under the forest. The results of wet sieving show a significant predominance of VF 0.25–1.0 mm aggregates over CO 5–10 mm fraction during the 4th rotation (44.8 and 12.0%, respectively) with almost the same ratio in the soil at the end of 9th rotation (27.8% and 26.6%, respectively). Down the soil profile, the content of a very fine fraction in the subsoil horizon noticeably increases, which indicates a deterioration of the water-resistance of the soil structure (Table 2).

The content of large 5–10 mm and very fine to medium 0.25–3.0 mm aggregates after dry sieving at the end of the 4th rotation is also almost the same (48.1% and 42.5%, respectively) in the organo-mineral fertilising system and periodic liming with 1.0 n $CaCO_3$ HA (OM). Under a similar system at the end of the 9th rotation, the content of 5–10 mm aggregates in the arable horizon is almost eight times higher than VM 0.25–3.0 mm aggregates and is 81.1% and 11.3%, respectively. The results of wet sieving are almost completely correlated with the control. There is a significant predominance of the very fine 0.25–1.0 mm fraction (52.8%) over coarse 5–10 mm fraction (15.6%) in the 4th rotation, and almost the same ratio in the soil of the 9th crop rotation (23.0% and 25.8%, respectively).

The results of dry sieving in 4th rotation showed that long-term and systematic application of the mineral fertilisers (M) as well as complete lack of their application (C), ensures almost the same content of CO 5–10 mm and VM 0.25–3.0 mm aggregates (43.1% and 42.4%). The content of the water-resistant fraction in both rotations shows a significant predominance of very fine aggregates over coarse.

In the structural composition under the canopy in the forest there is a decrease in water-resistance of aggregates in the soil (the 0.25–1.0 mm fraction content is 32.0–7.2%). It should be noted that there is a significant predominance of coarse 5–10 mm water-resistant aggregates over very fine units, which indicates better water-resistance of the structure compared to long-term fertilisation and periodic liming.

Table 2
Structural and aggregate composition of Albic Stagnic Luvisol under different systems of fertilisation and liming (x ± SD)

Crop rotation	Treatment	Aggregate size, %			
		Coarse (CO), 5–10 mm		very fine to medium (VM), 0.25–3.0 mm	very fine (VF), 0.25–1.0 mm
		type of sieving			
		dry	wet	dry	wet
IV	C	42.5 ± 5.4^{a}	12.0 ± 2.6^{a}	45.2 ± 5.8^{a}	44.8 ± 4.3^{a}
	OM	48.1 ± 5.7^{a}	15.6 ± 1.5^{a}	42.5 ± 4.5^{a}	52.8 ± 6.2^{a}
	M	43.1 ± 3.2^{a}	16.0 ± 2.6^{a}	42.4 ± 3.8^{a}	52.0 ± 5.4^{a}
	F	46.2 ± 2.3^{a}	17.6 ± 1.7^{a}	36.0 ± 2.3^{a}	32.0 ± 2.2^{b}
IX	C	65.6 ± 2.1^{a}	26.6 ± 2.2^{a}	25.8 ± 2.3^{a}	27.8 ± 3.3^{a}
	OM	81.1 ± 2.4^{b}	25.8 ± 1.5^{a}	11.3 ± 3.3^{b}	23.0 ± 0.9^{b}
	M	88.2 ± 0.8^{c}	22.8 ± 1.2^{a}	25.1 ± 1.2^{a}	27.6 ± 0.3^{ab}
	F	63.7 ± 1.0^{a}	35.0 ± 2.1^{b}	26.0 ± 1.4^{a}	7.2 ± 0.8^{c}

Note. Values labelled with the same letter within one crop rotation are not significantly different from each other according to the results of comparison using the Tukey test ($P<0.05$)

3.2. Physicochemical properties of soils

Analysis of the physicochemical properties of the studied soils showed that in control (C) the reaction of the soil solution at the end of the 4th crop rotation throughout the profile is strongly acidic (pH_{KCl} ranges from 3.90 to 4.47). At the end of the 9th rotation, pH_{KCl} is slightly higher and amounts to 4.13–4.47 under the same treatment, but the reaction of the soil solution remained strongly acidic (Table 3, 4). In both rotations, HA acidity tends to decrease down the profile with maximum values in the 0–0.30 cm. Its values are slightly higher in the 4th rotation (2.28–6.04 $cmol^{(+)}$ kg^{-1} of soil) than in the 9th crop rotation (1.40–5.11 $cmol^{(+)}$ kg^{-1} of soil), which indicates a very strongly acidic reaction in earlier rotation in contrast to just acidic reactions in later (Table 3).

The sum of exchangeable bases in control in both rotations can be described as very low and low with some increase down the profile. Its values range from 1.0 to 8.6 $cmol^{(+)}$ kg^{-1} of soil. They reach 10.4 $cmol^{(+)}$ kg^{-1} of soil only in 0.60–0.90 layer in the 9th rotation, which is characterized by an average amount (Table 4). The content of mobile aluminium in control in both rotations decreases down the profile, but at the end of the 4th rotation, it is slightly higher compared to the 9th rotation due to higher soil acidity. The humus content in the upper horizon of both rotations is low (1.44–1.48%). The horizons below have very small amount of humus (humus content does not exceed 1%).

The reaction of the soil solution of upper horizons under long-term application of one norm of mineral fertilisers and 10 t ha^{-1} of manure with the background of 1.0 n $CaCO_3$ (OM) is weakly acidic (pH_{KCl} – 5.18–5.51) in both rotations. However, with this system of fertilisation and liming at the end of the 4th rotation, the pH_{KCl} sharply decreases in the soil profile to strongly acidic. At the end of 9th rotation, it gradually shifts to medium-acid. In both rotations, HA ranges from low to medium with maximum values in the middle part of the profile, in contrast to the control.

The sum of exchangeable bases under application of $N_{70}P_{90}K_{90}$ + 10 t ha^{-1} of manure + $CaCO_3$ (1.0 n Ha) varies from very low in the upper part of the profile to low in slightly illuviated parent rock (3.2–10.0 $cmol^{(+)}$ kg^{-1} of soil) at the end of the 4th crop rotation. At the end of the 9th rotation under a similar system of fertilisation and liming, the sum of exchangeable bases is much higher and is estimated as low and medium (8.5–16.3 $cmol^{(+)}$ kg^{-1} of soil), but its profile distribution is similar to the profile distribution at the end of 4th crop rotation.

Table 3
Physicochemical properties of genetic horizons Albic Stagnic Luvisol under different systems of fertilisation and liming at the end of the 4th crop rotation

Soil layer, m	Treatment	pH_{KCl}	Ha	SAB	Al^{3+} mg kg^{-1} of soil	Humus %
			$cmol^{(+)}$ kg^{-1}			
0–0.30	C	3.99±0.13^{a}	6.04±0.12^{a}	1.6±0.3^{a}	157.8±22.3^{a}	1.44±0.08^{a}
	OM	5.51±0.09^{b}	2.19±0.12^{b}	5.0±0.3^{b}	1.4±0.7^{b}	1.73±0.08^{b}
	M	3.73±0.17^{a}	6.06±0.11^{a}	1.2±0.3^{a}	149.8±9.0^{a}	1.55±0.06^{a}
	F	3.85±0.04^{a}	9.26±0.10^{c}	3.48±0.1^{c}	303.1±7.0^{c}	1.88±0.04^{c}
0.30–0.60	C	4.40±0.03^{a}	4.39±0.09^{a}	1.0±0.3^{a}	123.3±15.1^{a}	0.88±0.04^{a}
	OM	4.50±0.10^{a}	3.29±0.18^{b}	3.2±0.1^{b}	16.7±3.9^{b}	0.97±0.04^{a}
	M	4.10±0.09^{b}	4.32±0.07^{a}	0.8±0.1^{a}	122.2±11.3^{a}	0.85±0.01^{a}
	F	3.93±0.06^{b}	5.72±0.06^{c}	2.46±0.1^{c}	215.8±9.0^{c}	0.93±0.07^{a}
0.60–0.90	C	3.90±0.10^{ac}	4.18±0.18^{a}	7.4±0.4^{a}	122.1±9.5^{a}	0.48±0.03^{a}
	OM	4.27±0.13^{b}	3.40±0.09^{b}	6.9±0.1^{a}	44.5±4.3^{b}	0.79±0.05^{b}
	M	4.20±0.05^{a}	3.68±0.07^{b}	1.2±0.4^{b}	92.5±7.2^{a}	0.71±0.05^{b}
	F	3.90±0.06^{c}	5.32±0.07^{c}	2.28±0.1^{c}	197.6±10.9^{c}	0.53±0.04^{a}
0.90–1.20	C	4.22±0.11^{ab}	2.36±0.19^{a}	7.4±0.1^{a}	23.6±3.5^{a}	0.35±0.05^{a}
	OM	4.40±0.02^{a}	2.08±0.08^{a}	7.6±0.2^{a}	14.2±2.1^{a}	0.76±0.02^{b}
	M	4.17±0.14^{ab}	4.69±0.18^{b}	6.4±0.2^{b}	133.9±22.4^{b}	0.77±0.04^{b}
	F	4.00±0.06^{b}	4.13±0.04^{c}	1.22±0.1^{c}	105.8±8.4^{b}	0.46±0.04^{a}
1.20–1.50	C	4.47±0.09^{a}	2.28±0.07^{a}	8.6±0.3^{a}	25.0±5.2^{a}	ND
	OM	4.45±0.01^{a}	2.53±0.12^{a}	10.0±0.5^{b}	22.6±2.9^{a}	0.68±0.04^{a}
	M	4.00±0.07^{b}	3.57±0.08^{b}	6.4±0.2^{c}	96.8±4.7^{b}	0.39±0.03^{b}
	F	4.12±0.05^{b}	3.36±0.04^{b}	0.91±0.1^{d}	76.7±6.4^{b}	ND

Note. Values labelled with the same letter within one soil layer are not significantly different from each other according to the results of comparison using the Tukey test ($P<0.05$); ND – not detected.

Table 4
Physicochemical properties of genetic horizons Albic Stagnic Luvisol under different fertilising and liming systems at the end of 9th crop rotation

Soil layer, m	Treatment	pH_{KCl}	Ha	SAB	Al^{3+} mg kg^{-1} of soil	Humus %
			cmol$^{(+)}$ kg^{-1}			
0–0.30	C	4.22±0.14^{a}	5.11±0.59^{a}	3.0±0.1^{a}	110.3±15.3^{a}	1.48±0.04^{a}
	OM	5.18±0.10^{b}	2.77±0.22^{b}	10.6±0.5^{b}	26.1±1.4^{b}	1.90±0.05^{b}
	M	4.03±0.07^{a}	5.11±0.92^{a}	3.0±0.5^{a}	75.2±5.1^{c}	1.57±0.03^{a}
	F	3.72±0.12^{c}	9.73±0.08^{c}	1.1±0.2^{a}	210.6±1.7^{d}	2.07±0.08^{b}
0.30–0.60	C	4.31±0.09^{a}	3.58±0.42^{a}	5.2±0.5^{a}	65.3±1.9^{a}	0.48±0.03^{a}
	OM	4.90±0.12^{b}	3.11±0.05^{a}	8.5±0.2^{b}	71.1±9.3^{a}	0.83±0.15^{b}
	M	4.17±0.04^{a}	4.54±0.06^{b}	1.5±0.1^{c}	126.5±3.8^{b}	0.63±0.06^{a}
	F	3.86±0.04^{c}	6.49±0.01^{c}	0.9±0.2^{c}	183.0±0.9^{c}	1.23±0.06^{c}
0.60–0.90	C	4.13±0.18^{a}	4.20±0.17^{ac}	10.4±1.2^{a}	91.8±0.2^{a}	0.28±0.02^{a}
	OM	4.78±0.21^{b}	3.46±0.21^{a}	9.0±1.9^{a}	79.7±1.6^{a}	0.64±0.10^{bc}
	M	4.00±0.02^{ac}	5.25±0.06^{b}	5.7±0.2^{b}	148.1±3.0^{b}	0.37±0.03^{ac}
	F	3.78±0.02^{c}	4.51±0.04^{bc}	1.0±0.1^{c}	90.1±1.3^{a}	0.53±0.07^{c}
0.90–1.20	C	4.22±0.08^{a}	3.23±0.10^{a}	6.9±0.1^{a}	68.4±1.7^{a}	0.28±0.01^{a}
	OM	4.90±0.13^{b}	3.15±0.04^{a}	11.9±0.8^{b}	43.2±5.8^{b}	0.55±0.06^{b}
	M	4.07±0.10^{ac}	2.97±0.02^{a}	8.0±1.3^{a}	66.2±2.8^{a}	0.26±0.02^{a}
	F	3.83±0.01^{c}	4.60±1.14^{b}	6.8±0.2^{a}	77.7±3.4^{a}	0.33±0.05^{a}
1.20–1.50	C	4.47±0.03^{a}	1.40±0.04^{a}	6.0±0.7^{a}	27.5±2.0^{a}	0.47±0.02^{a}
	OM	4.85±0.06^{b}	2.98±0.01^{b}	16.3±1.2^{b}	32.4±4.2^{a}	0.51±0.00^{a}
	M	4.04±0.05^{c}	2.97±0.10^{b}	13.8±0.3^{c}	54.5±6.1^{b}	0.21±0.01^{b}
	F	3.83±0.05^{c}	3.79±0.04^{b}	11.2±0.4^{d}	53.7±0.1^{b}	0.29±0.07^{b}

Note. Values labelled with the same letter within one soil layer are not significantly different from each other according to the results of comparison using the Tukey test (P<0.05).

The content of mobile aluminium in both rotations under the organo-mineral fertilising system and liming is significantly lower than in the control. The highest values are observed in the middle part of the profile, lower – in the upper and lower part. A decrease in the content of aluminium with the introduction of lime is probably due to the binding of its labile fractions. Long-term liming reduced the total non-crystalline Al, the organo-Al complexes of different stability as well as the exchangeable Al in the arable layer (Kryževičius et al., 2019).

The humus content under the influence of the organo-mineral system of fertilisation and liming (OM) in the 0–30 cm layer increased to 1.73% at the end of the 4th rotation and to 1.90% at the end of the 9th rotation compared to the 1.44–1.48% in control. Layers below have very small amount of humus (<1%).

Studies have shown that at the end of the 4th rotation by the application of mineral fertilisers in the soil at a dose of $N_{140}P_{180}K_{180}$ (M), the reaction of the soil solution throughout the profile is strongly acidic (pH_{KCl} ranges from 3.73 to 4.20). The same situation is observed with long-term application of the mineral fertilisers at a dose of $N_{65}P_{68}K_{68}$ at the end of the 9th rotation (pH_{KCl} values range from 4.00 to 4.17), which corresponds to a strongly acidic pH reaction. In both rotations, HA decreases down the profile. However, in the upper horizon at the end of the 4th rotation, the Ha is very high (6.06 cmol$^{(+)}$ kg^{-1}), down the profile – medium and high. In the upper layers at the end of 9th rotation, the content of HA is high (5.11 cmol$^{(+)}$ kg^{-1}), below it changes from low to high.

The sum of exchangeable bases in both rotations can be described as very low in the upper (0–60 cm) part of the profile (0.8–1.5 cmol$^{(+)}$ kg^{-1}), and low and medium – in the lower (1.2–13.8 cmol$^{(+)}$ kg^{-1}).

The content of mobile aluminium in the soil and its profile distribution at the end of the 4th rotation under mineral fertilization system is not significantly different from the control (92.5–149.8 mg kg^{-1}) except for lower horizons, where the stronger influence of mineral fertilizer on mobile forms of aluminium is traced. Slightly lower values are observed at the end of the 9th crop rotation (54.5–148.1 mg kg^{-1}), probably due to a decrease in the dose of mineral fertilizers.

There is no significant difference between soil humus content under mineral fertilisation from the control. In both rotations, humus content in the upper horizon (0–30 cm) is low (1.44–1.57%), and down the soil profile, genetic horizons have very small amount of humus (<1%) (Table 3, 4).

Comparing the reaction of the soil solution under the canopy in the forest, it can be stated that the change of forest coenoses by agrocoenoses had a positive effect on the acid-base properties of these soils. Thus, the reaction of the soil solution in the soil under the canopy in the forest throughout the profile is strongly acidic (pH_{KCl} – 3.72–4.12).

Similar dynamics can be observed in the profile distribution of HA. This value decreases in the forest soil. HA in the upper horizon is very high (9.26–9.73 $cmol^{(+)}\ kg^{-1}$), down to the soil-forming parental material it gradually changes to medium (3.36–3.79 $cmol^{(+)}\ kg^{-1}$).

The sum of exchangeable bases in the soils under the forest at the end of 9th crop rotation is very low (0.9–1.1 $cmol^{(+)}\ kg^{-1}$) in the upper horizons and low and medium (6.8–11.2 $cmol^{(+)}\ kg^{-1}$) below.

The content of mobile aluminium correlates with the acidity of soils, so it is natural that in the soil under the forest its content is higher (303.1 mg kg^{-1} at the end of the 4th crop rotation and 210.6 mg kg^{-1} at the end of the 9th crop rotation). There is a sharp decrease in its content with depth.

In terms of humus content, upper layer of forest soil is low-humus (1.88–2.07%), and the lower horizons have very small amount of humus (<1%).

4. Discussion

Under conditions of global warming, the focus is on the effect of long-term fertilization in the farming system to ensure sustainable management of soil fertility. It is long-term research that makes it possible to build prognostic models of soil behaviour under climate change conditions and will allow using optimal rates of fertilizers, as well as adjusting them in accordance with the trend of the evolution of various indicators of soil quality over a certain period (Tănase et al., 2022).

The results obtained by Olifir et al. (2020) in a long-term study provide opportunities to assess the systemic impact of various agricultural technologies on soil fertility, biotic processes, the state of the soil environment, as well as to find out the peculiarities of the circulation of substances and energy flows. In general, this will make it possible to theoretically substantiate directions for the formation of sustainable and ecologically safe functioning of agroecosystems under the conditions of global warming.

Dynamic anthropogenic soil changes affect the ecosystem services they provide (Robinson, et al., 2012). That is why understanding the main processes in the soil environment under different levels of fertilizer application, especially over long periods, is the basis for the development of measures to manage soil processes (Mayer et al., 2023).

Studies have shown that the dynamics of soil organic carbon (SOC) content should be constantly monitored to minimize the anthropogenic pressure on soils, which causes changes in the content of organic matter, as they are related to the intensity of land use. Therefore, Volungevičius et al. (2019) recommend strictly following crop rotation and combining organic fertilizers with mineral fertilizers when using Luvisol in agriculture.

In fact, our research shows that the long-term use of the organo-mineral fertilization system has the greatest positive effect on physical properties, contributes to the improvement of the physico-chemical and agrochemical properties of the soil compared to the mineral system and the control without fertilizers.

Similar results were also obtained in the research of Hoang (2023) where it was shown that 96 years of use of mineral and organic fertilizers had a clear effect on the chemical and sorption properties of the soil. The effect of fertilization was best expressed in the top layer of the soil. NPK mineral fertilizer led to acidification of the entire soil profile, which was expressed by an increase in exchangeable acidity and total potential acidity.

The obtained results of Siewruk and Szulc (2023), demonstrate a tendency to transport phosphorus, calcium and magnesium through the soil profile. The conducted studies show that the application of mineral fertilizers increases the nutrient saturation of soils at the studied depths, and deep-rooted crops should be used in crop rotation, which can effectively use the subsoil as a source of nutrients and contribute to the reduction of nutrient leaching.

Experiments by Mayer et al. (2023) confirm the importance of organo-mineral transformations for stabilization of soil organic matter (SOM), especially in the context of the current trend of climate change. Maintaining the dynamic nature of SOM through stable application of organic fertilizers and promoting soil biotic activity should be the foundation of sustainable agriculture under climatic fluctuations.

Researchers Meng et al (2020) have attempted to improve Albic soils and increase crop yields primarily by increasing the amount of organic matter in the A- horizon and deeper over the past thirty years. The study showed that mixing horizon A, representing Albic soil, with horizon B improved the physicochemical properties of Albic soil, which has a low humus content in the upper soil horizon and high infiltration resistance.

The obtained results (Bulyhin et al., 2022) made it possible to form a gradation scale for assessing the state of the water-resistant structure and the degree of manifestation of the consequences of the intensive use of chernozems of the Left Bank Forest Steppe with different fertilization and tillage. It was established that according to the speed of changes in the soil due to the formation of a certain degree of water resistance, chernozem-like soils occupy the following sequence: gray forest low-humus heavy loamy light clay on carbonate loess-like clay < typical chernozem low-humus heavy loamy light clay on loess-like clay < meadow-black earth low-humus carbonate heavy loamy soil on loess-like clay < typical medium humus heavy clay chernozem in the forest (Bulyhin et al., 2022).

In our research conducted under the conditions of a classical long-term stationary experiment, the influence of long-term use of various fertilization systems on changes in the structural-aggregate composition and physico-chemical properties of Albic Stagnic Luvisol was shown. Our further research will be aimed at studying the influence of different fertilization systems, periodic liming and climate changes on functional resistance to acidity, evolutionary patterns of changes in properties to provide information on sustainable management of the fertility of acidic Albic Stagnic Luvisol.

5. Conclusions

1. The fertility of Albic Stagnic Luvisols in western Ukraine is limited by periods of waterlogging and excess acidity.
2. To preserve and protect them, a long-term fertilization of 1.0 n $CaCO_3$, 10 t ha^{-1} of manure and one norm of mineral fertilisers ($N_{65}P_{68}K_{68}$). This organo-mineral fertilizing system has the greatest positive effect on the structural and aggregate condition of the soil, contributing to the improvement of its physical and chemical properties.
3. Long-term application of mineral fertilising system causes deterioration of physical and physicochemical parameters of Albic Stagnic Luvisol.

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