DOI: 10.32636/01308521.2026-(79)-1-2

Review
UDC 631.421:303.436.3

SCIENTIFIC LEGACY AND RESEARCH CONTRIBUTIONS OF THE LONG-TERM FIELD EXPERIMENT AT THE INSTITUTE OF AGRICULTURE OF CARPATHIAN REGION OF THE NAAS

Y. Olifir, T. Partyka, O. Havryshko, N. Kozak

Institute of Agriculture
of Carpathian Region of NAAS
Hrushevskoho Street, 5, Obroshyne village, Lviv district, Lviv region, 81115

About authors:

Yurii OLIFIR
ORCID: 0000-0002-7920-1854

Tetiana PARTYKA
ORCID: 0000-0001-7912-5292

Oleh HAVRYSHKO
ORCID: 0000-0002-5458-0691

Nadiia KOZAK
ORCID: 0000-0002-2809-2432

For corresponding:
Yurii OLIFIR
e-mail: olifir.yura@gmail.com

Funding information:
Ministry of Education and Science of Ukraine

Received:
January 23, 2026
Accepted:
March 11, 2026
Published:
March 31, 2026

This paper presents the history, experimental design, and main scientific results obtained during the 60-year operation of the long-term field experiment at the Institute of Agriculture of Carpathian Region of NAAS. The experiment was established in 1965 to investigate the long-term effects of organic, mineral, and lime fertilizers in crop rotation on the fertility of acidic, light-grey forestal surface-gleyed soils corresponding to the Albic Pantostagnic Luvisol (WRB 2022). The experimental design includes different fertilization systems combined with periodic liming, enabling the assessment of long-term changes in soil agrochemical, physicochemical, and biological properties, as well as crop productivity. Results obtained over 12 crop rotation cycles demonstrate that the organo-mineral fertilization system ($N_{65}P_{68}K_{68}$ combined with 10 t ha^{-1} of manure and periodic liming) provides the highest crop rotation productivity and contributes to the stabilization of soil acidity, improvement of nutrient regimes, and accumulation of soil organic matter. In contrast, prolonged sole mineral fertilization on low-buffered acidic soils leads to progressive soil acidification, increased mobile aluminium content, and deterioration of humus quality. The experiment represents a unique scientific infrastructure for monitoring soil transformation processes under long-term agricultural use and provides an important information basis for the development of sustainable soil fertility management strategies in changing climatic conditions.

Keywords: long-term field experiment, soil fertility, fertilization systems, liming, Albic Pantostagnic Luvisol, soil acidity, crop rotation, soil organic matter.

Наукова спадщина та результати довготривалого польового досліду Інституту сільського господарства Карпатського регіону НААН

Інститут сільського господарства Карпатського регіону НААН
вул. Грушевського, 5, с. Оброшине Львівський р-н, Львівська обл., 81115

Про авторів:
Юрій ОЛІФІР,
кандидат сільськогосподарських наук
ORCID: 0000-0002-7920-1854

Тетяна ПАРТИКА,
кандидат біологічних наук
ORCID: 0000-0001-7912-5292

Олег ГАВРИШКО,
кандидат сільськогосподарських наук
ORCID: 0000-0002-5458-0691

Надія КОЗАК,
доктор філософії
ORCID: 0000-0002-2809-2432

Для листування:
Юрій ОЛІФІР
e-mail: olifir.yura@gmail.com

Інформація про фінансування:
Міністерство освіти і науки України

Отримано:
23 січня 2026 р.
Погоджено до друку:
11 березня 2026 р.
Опубліковано:
31 березня 2026 р.

У статті висвітлено історію створення, експериментальну схему та основні наукові результати, отримані протягом 60-річного функціонування довготривалого польового досліду Інституту сільського господарства Карпатського регіону НААН. Дослід закладено у 1965 р. з метою вивчення довготривалого впливу органічних, мінеральних і вапнякових добрив у сівозміні на родючість кислих ясно-сірих лісових поверхнево оглеєних ґрунтів, які за міжнародною класифікацією WRB (2022) відповідають Albic Pantostagnic Luvisol. Схема досліду передбачає різні системи удобрення у поєднанні з періодичним вапнуванням, що дає змогу оцінити багаторічну динаміку агрохімічних, фізико-хімічних і біологічних властивостей ґрунту, а також продуктивність культур сівозміни. Узагальнення результатів дванадцяти ротацій сівозміни показало, що найбільш ефективною є органо-мінеральна система удобрення ($N_{65}P_{68}K_{68}$ у поєднанні з внесенням 10 т/га гною на гектар сівозмінної площі та періодичним вапнуванням), яка забезпечує найвищу продуктивність сівозміни, стабілізацію кислотності ґрунту, покращення поживного режиму та накопичення органічної речовини. Встановлено, що тривале застосування лише мінеральних добрив на низькобуферних кислих ґрунтах спричинює їх подальше підкислення, підвищення вмісту рухомого алюмінію та погіршення якісного складу гумусу. Довготривалий польовий дослід є унікальною науковою інфраструктурою для моніторингу трансформації ґрунтів за умов тривалого агровикористання та формує наукову основу для розроблення сталих систем управління родючістю ґрунтів в умовах змін клімату.

Ключові слова: довготривалий польовий дослід, родючість ґрунту, системи удобрення, вапнування, Albic Pantostagnic Luvisol, кислотність ґрунту, сівозміна, органічна речовина ґрунту.

Introduction. The most representative research method for studying the theoretical and practical foundations of soil fertility preservation, increasing crop yields, and improving product quality is the long-term field experiment [1]. These experiments occupy a unique position in agricultural research, since many soil processes respond to management changes only after years or decades, making short-term studies insufficient for detecting meaningful trends [8, 17].

According to the Long-Term Field Experiments Overview Map (LTE-Map), more than 600 long-term agricultural experiments are currently documented worldwide, several of which have been maintained for more than a century. Among the most well-known examples are the Rothamsted experiments in the United Kingdom (established in 1843), the Morrow Plots in the United States (1876), the rye experiment in Halle (Germany, 1878), and the Askov experiment in Denmark (1894). These experimental infrastructures provide unique long-term datasets that allow researchers to analyse cumulative management effects, evaluate soil fertility dynamics, and assess the sustainability of agricultural systems over time [12, 13].

The particular value of long-term stationary field experiments as information sources lies in their capacity to accumulate scientific data over several decades. Combined with contemporary observations, this longitudinal perspective enables the objective identification of natural patterns in the functioning of soil systems at both regional and global levels [4]. At the same time, the long-term nature of such experiments provides opportunities to introduce necessary adjustments in response to emerging scientific challenges and societal needs, thereby improving the efficiency of research and the reliability of results.

Due to the delayed responses of many soil parameters to changes in management practices, these parameters are crucial for understanding the long-term effects of agricultural management on soil productivity and soil health [8]. This is particularly relevant for acidic soils, where the consequences of liming and fertilization on soil organic matter dynamics and aluminium mobility may not become apparent for one or more crop rotation cycles [9, 14].

Long-term field experiments are typically conducted to study the effects of cropping systems (crop rotations, mineral and organic fertilization, tillage practices, and post-harvest residue management) on crop yields, product quality, and soil properties [19]. Long-term fertilization experiments serve as an indispensable platform for understanding complex interactions among soil, plants, climate, and management practices, as well as for determining how these interactions influence yield stability over time [15, 20]. In particular, the combination of organic and mineral fertilizers has consistently demonstrated advantages over sole mineral fertilization in maintaining soil organic carbon, improving microbial activity, and sustaining long-term productivity [20, 22].

The scientific value of long-term experiments lies not only in their duration but also in the consistency of their experimental design. The repeated application of defined management practices under stable conditions enables the identification of cumulative effects and gradual transformations in soil systems that remain undetectable in short-term trials [16]. Such experiments therefore provide an essential basis for evaluating long-term productivity stability, soil quality evolution, and ecological consequences of agricultural management [11].

At the current stage of development of Ukraine's agricultural sector, long-term stationary agrotechnical experiments investigating crop rotations, soil tillage technologies, and fertilization systems have become particularly important. They make it possible to study the systematic effects of different agricultural technologies on soil fertility, biological processes, and environmental conditions, and to determine nutrient cycling and the direction of energy flows, thereby providing a theoretical basis for the sustainable and environmentally safe development of agroecosystems under different soil and climatic conditions [7].

However, the time scale itself is not the main criterion for defining an experiment as long-term. An equally important criterion is the continuity of a repeated cycle of defined management practices. These practices may include crop rotations, soil improvement measures, nutrient application, or climate-related factors aimed at studying or confirming their long-term effects [16]. Moreover, long-term experiments are increasingly expected to serve as platforms for monitoring the effects of climate change on soil processes and agricultural productivity, which requires flexible experimental designs capable of accommodating new research questions without compromising the integrity of the original treatments [8, 17].

In Ukraine, according to the register of certified stationary experiments compiled by the National Academy of Agrarian Sciences of Ukraine (NAAS) in 2014, only 4 out of 89 experiments had a duration exceeding 60 years. According to the international classification, such experiments are referred to as ultra-long-term or classical experiments. In all countries, long-term field experiments represent an exceptional scientific value and are considered inviolable; no one has the right to modify or terminate them without a decision of the relevant state authorities [6].

Long-term experimental infrastructures are particularly important for agricultural systems undergoing structural and economic transformation. In transition economies, agricultural management decisions are often guided by short-term productivity indicators, which may obscure gradual soil degradation processes such as acidification, nutrient imbalance, and structural decline. Long-term monitoring experiments, therefore, provide critical evidence for identifying such processes and for developing sustainable soil management strategies under changing economic and climatic conditions.

The value of well-designed and well-executed long-term experiments increases over time, as does their cost. However, their economic efficiency improves when they serve multiple research objectives and are conducted on well-characterised sites, enabling results to be extrapolated as widely as possible [12]. This is facilitated by the inclusion of such experiments in international networks, which promotes standardisation of methodologies and broader comparative analyses across diverse pedoclimatic conditions.

Research has shown that long-term field experiments are valuable for identifying ways to protect European soils and for developing scientifically grounded alternative management approaches for the future [11]. However, such experiments should place greater emphasis on biological indicators of soil quality, greenhouse gas emissions, and the buffering capacity of soils against acidification to better assess trade-offs and synergies among different management practices [9, 11].

Therefore, the aim of this study was to synthesise the results from the long-term stationary field experiment conducted by the Institute of Agriculture of Carpathian Region of NAAS and to analyse the cumulative effects of different fertilization and liming systems on soil properties and agroecosystem productivity. The objectives were: (i) to identify long-term trends in the transformation of light-grey forestal surface-gleyed soil properties and crop productivity under contrasting fertilization systems; and (ii) to evaluate the implications of these long-term changes for sustainable soil management and adaptation of agricultural production to current climate change.

Materials and methods. The long-term stationary field experiment (49°47'54.3"N, 23°52'26.9"E) was established in 1965 at the Department of Agrochemistry and Soil Science of the Institute of Agriculture of Carpathian Region of NAAS by Adam Humeniuk, PhD in Agricultural Sciences. The experiment entitled "Effect of long-term application of organic, mineral and limestone fertilizers in crop rotation on the fertility of light grey forest surface-gleyed soils, crop yield and quality" was designed to evaluate the effectiveness of different liming rates and fertilization systems in crop rotation on acidic light grey forest surface-gleyed soil.

According to the results of inventories conducted in 2005 and 2014, the long-term field experiment was included in the Register of Long-Term Stationary Field Experiments of the National Academy of Agrarian Sciences of Ukraine (NAAS) (registration certificate No. 29) [6].

In 2023, the experiment was also included in the Global Long-Term Agricultural Experiments Network (GLTEN), which comprises experimental sites across six continents that represent diverse climatic conditions, environments, cropping systems, and agricultural management practices [10].

The soil at the experimental site is classified as light grey forest surface-gleyed soil formed on loess-like deposits, which according to the World Reference Base for Soil Resources (WRB, 2022) corresponds to Albic Pantostagnic Luvisol [21].

The region's climate is humid continental, with warm summers. The average annual air temperature is +7.5 °C. The sum of active temperatures above 10 °C ranges from 2400 to 2800 °C, ensuring 160–175 days of active vegetation. Mean annual precipitation is 767 mm, of which 300–380 mm falls during the warm season. The hydrothermal coefficient ranges from 1.3 to 1.6, indicating adequate moisture supply for crop production [5].

According to particle-size distribution analysis, the plough layer of the light grey forest soil is classified as coarse silt light loam. The initial agrochemical characteristics of the soil prior to the establishment of the experiment were as follows: humus content (Tyurin method) 1.42 %, soil pH (KCl) 4.2, hydrolytic acidity (Kappen method) 4.5 cmol(+) kg^{-1} soil, exchangeable acidity (Sokolov method) 0.6 cmol(+) kg^{-1} soil, mobile aluminium content 60.0 mg kg^{-1}, available phosphorus (Kirsanov method) 36.0 mg kg^{-1}, and exchangeable potassium (Maslova method) 50.0 mg kg^{-1}. These characteristics indicate the low natural fertility of the soil (Table 1).

1. Initial agrochemical properties of the plough layer (0–20 cm) and particle-size distribution of light-grey forestal soil before the establishment of the long-term field experiment (1965)

Agrochemical properties of the plough layer (0–20 cm)					
Humus, %	pH (KCl)	Hydrolytic acidity, cmol(+) kg^{-1} soil	Mobile aluminium	Available phosphorus	Exchangeable potassium
			mg 100 g^{-1} soil		
1.42 1.39–1.45	4.2 4.0–4.4	4.5 4.1–4.9	6.0 5.8–6.2	3.6 3.01–4.19	5.0 4.2–5.8

Particle-size distribution of the soil profile				
Sampling depth, cm	Particle size (mm), %			
	Sand	Silt	Clay	Physical clay
	> 0.25–0.05	0.05–0.001	< 0.001	< 0.01
0–22	13.0	81.5	5.2	20.7
22–32	16.0	78.3	3.6	20.4
40–50	19.5	66.6	13.1	26.3
53–63	13.9	72.9	12.4	27.7
85–95	12.8	73.8	12.1	28.0
110–120	19.9	62.9	15.6	32.1
135–145	13.9	72.5	11.9	29.1

Note. The numerator indicates mean values, and the denominator indicates the range of variation.

Experimental layout

Since its establishment, the long-term field experiment has been conducted on three fields. Each field comprises 18 treatment variants arranged in three replications, resulting in 54 plots per field. Crop rotations are introduced sequentially, with one field entering the next stage of the rotation each year. Due to the experimental layout, the crop rotation started in 1965, 1966, and 1967 on the first, second, and third fields, respectively. The total plot size is 28 × 6 m (168 m²), with a harvest area of 25 × 4 m (100 m²). The plots are arranged in a single-tier sequential layout.

At the beginning of the experiment, a seven-field crop rotation was established: potato – spring barley undersown with red clover – red clover – winter wheat – sugar beet – maize for green mass – winter wheat (Table 2).

2. Experimental design of the long-term field experiment during rotations I–V

Treatment No.	Lime rate (based on hydrolytic acidity)	Potato	Spring barley + red clover	Red clover	Winter wheat	Sugar beet	Maize for silage	Winter wheat
1	No fertilizers (control)							
2	1.0	–	–	–	–	–	–	–
3	–	FYM 40 t ha⁻¹	–	–	–	FYM 30 t ha⁻¹	–	–
4	1.0	FYM 40 t ha⁻¹	–	–	–	FYM 30 t ha⁻¹	–	–
5	–	FYM 40 t ha⁻¹ + $N_{90}P_{60}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$	FYM 30 t ha⁻¹ + $N_{150}P_{120}K_{180}$	$N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$
6	0.5	FYM 40 t ha⁻¹ + $N_{90}P_{60}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$	FYM 30 t ha⁻¹ + $N_{150}P_{120}K_{180}$	$N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$
7	1.0	FYM 40 t ha⁻¹ + $N_{90}P_{60}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$	FYM 30 t ha⁻¹ + $N_{150}P_{120}K_{180}$	$N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$
8	1.0*	FYM 40 t ha⁻¹ + $N_{90}P_{60}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$	FYM 30 t ha⁻¹ + $N_{150}P_{120}K_{180}$	$N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$
9	1.0	FYM 40 t ha⁻¹ + $N_{45}P_{30}K_{45}$	$N_{30}P_{45}K_{45}$	–	$N_{30}P_{45}K_{45}$	FYM 30 t ha⁻¹ + $N_{90}P_{60}K_{90}$	$N_{60}P_{45}K_{45}$	$N_{30}P_{45}K_{45}$
10	No fertilizers (control)							
11	–	FYM 40 t ha⁻¹ + $N_{135}P_{90}K_{135}$	$N_{105}P_{135}K_{135}$	–	$N_{105}P_{135}K_{135}$	FYM 30 t ha⁻¹ + $N_{225}P_{180}K_{270}$	$N_{180}P_{135}K_{135}$	$N_{105}P_{135}K_{135}$
12	1.0	FYM 40 t ha⁻¹ + $N_{135}P_{90}K_{135}$	$N_{105}P_{135}K_{135}$	–	$N_{105}P_{135}K_{135}$	FYM 30 t ha⁻¹ + $N_{225}P_{180}K_{270}$	$N_{180}P_{135}K_{135}$	$N_{105}P_{135}K_{135}$
13	1.5	FYM 40 t ha⁻¹ + $N_{135}P_{90}K_{135}$	$N_{105}P_{135}K_{135}$	–	$N_{105}P_{135}K_{135}$	FYM 30 t ha⁻¹ + $N_{225}P_{180}K_{270}$	$N_{180}P_{135}K_{135}$	$N_{105}P_{135}K_{135}$
14	1.5	FYM 40 t ha⁻¹ + $N_{180}P_{120}K_{180}$	$N_{140}P_{180}K_{180}$	–	$N_{140}P_{180}K_{180}$	FYM 30 t ha⁻¹ + $N_{300}P_{240}K_{360}$	$N_{240}P_{180}K_{180}$	$N_{140}P_{180}K_{180}$
15	–	$N_{180}P_{120}K_{180}$	$N_{140}P_{180}K_{180}$	–	$N_{140}P_{180}K_{180}$	$N_{300}P_{240}K_{360}$	$N_{240}P_{180}K_{180}$	$N_{140}P_{180}K_{180}$
16	1.0	$N_{180}P_{120}K_{180}$	$N_{140}P_{180}K_{180}$	–	$N_{140}P_{180}K_{180}$	$N_{300}P_{240}K_{360}$	$N_{240}P_{180}K_{180}$	$N_{140}P_{180}K_{180}$
17	1.5	$N_{180}P_{120}K_{180}$	$N_{140}P_{180}K_{180}$	–	$N_{140}P_{180}K_{180}$	$N_{300}P_{240}K_{360}$	$N_{240}P_{180}K_{180}$	$N_{140}P_{180}K_{180}$
18	1.5	$N_{135}P_{90}K_{135}$	$N_{105}P_{135}K_{135}$	–	$N_{105}P_{135}K_{135}$	$N_{225}P_{180}K_{270}$	$N_{180}P_{135}K_{135}$	$N_{105}P_{135}K_{135}$

Note. Industrial waste of the Rozdil State Mining and Chemical Enterprise "Sirka".

After the completion of five seven-field rotations (rotations I–V), a partial reconstruction of the experiment was carried out before the beginning of rotation VI. This was necessitated by the accumulation of high levels of readily available phosphates and exchangeable potassium in the intensively fertilised treatments (12–18), a situation characteristic of agricultural practices across Ukraine during that period. As a result, the seven-field crop rotation was replaced by a four-field crop rotation: maize for green mass – spring barley undersown with red clover – red clover – winter wheat (Table 3).

During the following three four-field rotations (VI–VIII), the experiment focused on evaluating the residual effects of accumulated mobile phosphates and exchangeable potassium under moderate nitrogen fertilization, without altering the fertilization treatment structure. Before the start of rotation IX, liming was applied, and fertilizer application rates for individual crops within the rotation were adjusted according to the experimental design. Starting from rotation XI, maize has been grown for grain rather than green mass (Table 4).

The chronology of crop rotation cycles across the three experimental fields is presented in Table 5.

3. Experimental design of the long-term field experiment during rotations VI–VIII

Treatment No.	Lime rate based on hydrolytic acidity (residual effect of liming applied in previous rotations)	Applied per 1 ha of crop rotation area		Maize for silage	Spring barley + red clover	Red clover	Winter wheat
		FYM, t	NPK, kg a.i.				
1	No fertilizers (control)						
2	1.0	–	–	–	–	–	–
3	–	10	–	FYM 40 t ha^{-1}	–	–	–
4	1.0	10	–	FYM 40 t ha^{-1}	–	–	–
5	–	10	$N_{65}P_{68}K_{68}$	FYM 40 t ha^{-1} + $N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$
6	0.5	10	$N_{65}P_{68}K_{68}$	FYM 40 t ha^{-1} + $N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$
7	1.0	10	$N_{65}P_{68}K_{68}$	FYM 40 t ha^{-1} + $N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$
8	1.0	10	$N_{65}P_{68}K_{68}$	FYM 40 t ha^{-1} + $N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$
9	1.0	10	$N_{30}P_{34}K_{34}$	FYM 40 t ha^{-1} + $N_{60}P_{45}K_{45}$	$N_{30}P_{45}K_{45}$	–	$N_{30}P_{45}K_{45}$
10	No fertilizers (control)						
11	–	10	N_{30} (PK residual effect)	FYM 40 t ha^{-1} + N_{60}	N_{30}	–	N_{30}
12	1.0	10	N_{30} (PK residual effect)	FYM 40 t ha^{-1} + N_{60}	N_{30}	–	N_{30}
13	1.5	15	N_{30} (PK residual effect)	FYM 60 t ha^{-1} + N_{60}	N_{30}	–	N_{30}
14	1.5	10	N_{65} (PK residual effect)	FYM 40 t ha^{-1} + N_{120}	N_{70}	–	N_{70}
15	–	–	N_{65} (PK residual effect)	N_{120}	N_{70}	–	N_{70}
16	1.0	–	N_{65} (PK residual effect)	N_{120}	N_{70}	–	N_{70}
17	1.5	–	N_{65} (PK residual effect)	N_{120}	N_{70}	–	N_{70}
18	1.5	–	N_{30} (PK residual effect)	N_{60}	N_{30}	–	N_{30}

Note. Lime was not applied in rotations VI–VIII. The values indicate the residual effect of previous liming based on hydrolytic acidity.

4. Experimental design of the long-term field experiment during rotations IX–XII

Treatment No.	Lime rate (based on hydrolytic acidity (Ha) or acid–base buffering capacity (ABBC))	Applied per 1 ha of crop rotation area		Maize for grain	Spring barley + red clover	Red clover	Winter wheat
		FYM, t	NPK, kg a.i.				
1	No fertilizers (control)						
2	1.0 (Ha)	–	–	–	–	–	–
3	–	10	–	FYM 40 t ha^{-1}	–	–	–
4	1.0 (Ha)	10	–	FYM 40 t ha^{-1}	–	–	–
5	–	10	$N_{65}P_{68}K_{68}$	FYM 40 t ha^{-1} + $N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$
6	0.5 (Ha)	10	$N_{65}P_{68}K_{68}$	FYM 40 t ha^{-1} + $N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$
7	1.0 (Ha)	10	$N_{65}P_{68}K_{68}$	FYM 40 t ha^{-1} + $N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$
8	Optimum (ABBC)	10	$N_{65}P_{68}K_{68}$	FYM 40 t ha^{-1} + $N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$
9	1.0 (Ha)	10	$N_{30}P_{34}K_{34}$	FYM 40 t ha^{-1} + $N_{60}P_{45}K_{45}$	$N_{30}P_{45}K_{45}$	–	$N_{30}P_{45}K_{45}$
10	No fertilizers (control)						
11	–	10	$N_{105}P_{101}K_{101}$	FYM 40 t ha^{-1} + $N_{180}P_{135}K_{135}$	$N_{120}P_{135}K_{135}$	–	$N_{120}P_{135}K_{135}$
12	1.0 (Ha)	10	$N_{105}P_{101}K_{101}$	FYM 40 t ha^{-1} + $N_{180}P_{135}K_{135}$	$N_{120}P_{135}K_{135}$	–	$N_{120}P_{135}K_{135}$
13	1.5 (Ha)	15	$N_{30}P_{34}K_{34}$	FYM 60 t ha^{-1} + $N_{60}P_{45}K_{45}$	$N_{30}P_{45}K_{45}$	–	$N_{30}P_{45}K_{45}$
14	Optimum (ABBC)	10	$N_{53}P_{41}K_{53}$	FYM 40 t ha^{-1} + $N_{90}P_{45}K_{90}$	$N_{60}P_{60}K_{60}$	–	$N_{60}P_{60}K_{60}$
15	–	–	$N_{65}P_{68}K_{68}$	$N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$
16	1.0 (Ha)	–	$N_{65}P_{68}K_{68}$	$N_{120}P_{90}K_{90}$	$N_{70}P_{90}K_{90}$	–	$N_{70}P_{90}K_{90}$
17	1.5 (Ha)	–	$N_{105}P_{101}K_{101}$	$N_{180}P_{135}K_{135}$	$N_{120}P_{135}K_{135}$	–	$N_{120}P_{135}K_{135}$
18	Optimum (ABBC)	–	$N_{105}P_{101}K_{101}$	$N_{180}P_{135}K_{135}$	$N_{120}P_{135}K_{135}$	–	$N_{120}P_{135}K_{135}$

5. Chronology of crop rotation cycles in the long-term field experiment

Rotation	Field 1	Field 2	Field 3	Rotation type
1	2	3	4	5
I	1965–1971	1966–1972	1967–1973	seven-field
II	1972–1978	1973–1979	1974–1980	seven-field
III	1979–1985	1980–1986	1981–1987	seven-field
IV	1986–1992	1987–1993	1988–1994	seven-field
V	1993–1999	1994–2000	1995–2001	seven-field
VI	2000–2003	2001–2004	2002–2005	four-field

1	2	3	4	5
VII	2004–2007	2005–2008	2006–2009	four-field
VIII	2008–2011	2009–2012	2010–2013	four-field
IX	2012–2015	2013–2016	2014–2017	four-field
X	2016–2019	2017–2020	2018–2021	four-field
XI	2020–2023	2021–2024	2022–2025	four-field
XII	2024–2027	2025–2028	2026–2029	four-field

Fertilization treatments.

From the beginning of the experiment, the design included both combined and separate applications of liming and fertilizers. Liming treatments consisted of 0.5; 1.0; and 1.5 rates of $CaCO_3$, calculated based on hydrolytic acidity (Ha). Fertilization treatments included full, half, 1.5-fold, and double rates of mineral fertilizers (NPK), as well as 10 and 20 t ha^{-1} of farmyard manure per hectare of crop rotation area.

Liming was carried out at the beginning of each of the first five seven-field crop rotation cycles (rotations I–V) under potato, based on hydrolytic acidity values. Before the beginning of rotations IX and XII of the four-field crop rotation, liming was performed under maize according to the experimental scheme, with lime doses calculated based on hydrolytic acidity (Ha) and, in three treatments (8, 14 and 18), additionally based on acid–base buffering capacity (ABBC). Limestone flour containing 93.5 % $CaCO_3$ was used as the liming material.

Before the reconstruction of the experiment, farmyard manure (FYM) was applied twice within the crop rotation – under potato and sugar beet (rotations I–V). Starting from rotation VI, manure was applied once per rotation under maize at a rate of 40–60 t ha^{-1}. The experiment used semi-decomposed cattle manure with straw bedding. From rotation VIII onwards, the second red clover cut was incorporated into the soil as green manure in all experimental treatments.

Mineral fertilizers were applied annually at rates calculated for each crop in accordance with the experimental design. Phosphorus and potassium fertilizers were applied in autumn prior to primary tillage, whereas nitrogen fertilizers were split equally, with 50 % applied during pre-sowing cultivation and the remaining 50 % as top dressing during the growing season.

The mineral fertilizers used in the experiment included ammonium nitrate (34.4 % N), granulated superphosphate (19.5 % P_2O_5), and potassium salt (40 % K_2O). In more recent rotation cycles, nitroammophoska (17 % NPK) and kalimag (28 % K_2O + MgO) have also been applied.

Soil tillage and crop management practices were carried out in accordance with the standard agronomic recommendations for the Western Forest-Steppe zone of Ukraine.

Soil sampling and laboratory analyses.

Within the long-term field experiment, monitoring of changes in the main soil fertility indicators, including acid–base, physicochemical, and agrochemical properties, of the light grey forest surface-gleyed soil is conducted under the long-term application of different fertilization systems. Soil samples are collected at the end of each crop rotation cycle. Composite soil samples are taken separately from the plough layer (0–20 cm) and the subsurface layer (20–35 cm) in each field and prepared for laboratory analysis according to DSTU ISO 11464:2001.

Agrochemical and physicochemical soil properties were determined using the following standardised analytical methods: soil pH in KCl extract – potentiometric method (DSTU ISO 10390:2001); hydrolytic acidity – Kappen method (DSTU 7537:2014); exchangeable acidity and mobile aluminium – Sokolov method; soil organic matter (humus) content – Tyurin method as modified by Nikitin (DSTU 4289:2004); sum of exchangeable bases – Kappen–Hilkovitz method; calcium and magnesium – complexometric (trilonometric) method;

readily hydrolysable nitrogen – Cornfield method (DSTU 7863:2015); available phosphorus and exchangeable potassium – Chyrykov method using 0.5 M CH_3COOH extractant (DSTU 4115:2002).

Statistical analysis

Statistical analysis of the experimental data was initially performed using the methodology of B. A. Dospehov, and subsequently with Microsoft Excel and Statistica 10.0 software. Currently, data processing is performed using OriginPro 2019 software. All treatment means were compared using analysis of variance (ANOVA), and differences were considered statistically significant at $P \leq 0.05$.

Results and discussion. The results from the 60-year operation of the long-term field experiment reflect the evolution of soil properties and crop productivity under different fertilization and liming systems. For clarity, the major findings are presented according to the main stages of the experiment corresponding to successive crop rotation cycles. These stages reflect the evolution of research objectives over the long-term experiment and their integration into international research infrastructures, such as the Global Long-Term Agricultural Experiments Network (GLTEN).

1. Establishment and early research phase (1965–2001)

During the first and second rotations of the long-term field experiment, the effects of different lime application rates, forms, and frequencies were investigated under contrasting fertilization systems. The studies were conducted against a background of farmyard manure application (40 t ha^{-1} under potato and 30 t ha^{-1} under sugar beet) combined with two relatively low rates of mineral fertilizers.

In subsequent phases of the experiment, research focused on evaluating the effects of long-term systematic liming under different fertilization systems on the stabilization of soil fertility in acidic light grey forest soils.

During this period, the optimal rate and placement of liming materials in a seven-field cereal–row crop rotation were determined. Lime was applied once per rotation under potatoes, identified as the most suitable crop for lime incorporation within the rotation. In addition, the effectiveness of lime-containing industrial waste from the Rozdil Mining and Chemical Enterprise "Sirka" (containing approximately 81.0 % CaO) was evaluated.

The results showed that these lime-containing industrial by-products were comparable in effectiveness to limestone flour when applied at equivalent $CaCO_3$ rates, and in some cases even surpassed it. These findings confirm that on acidic soils, chemical amelioration through liming should precede other agronomic measures, particularly the application of mineral fertilizers. These results were later synthesised in the monograph "Liming of Soils" [3].

The experimental design during rotations III–V included liming under potato at rates of 0.5; 1.0 and 1.5 times the lime requirement calculated based on hydrolytic acidity. Organic fertilizers were applied twice within the rotation: under potato (40 and 80 t ha^{-1}) and sugar beet (30 and 60 t ha^{-1}). Mineral fertilizers were applied annually to all crops except red clover at half, full, 1.5-fold, and double rates.

Based on a synthesis of research results from 5 seven-field crop rotations, the long-term effects of different fertilization and liming systems on soil agrochemical properties, nutrient regimes, crop yields, and crop quality were identified. It was established that stable, biologically valuable crop yields can be achieved, combined with improvements in soil fertility indicators, under an organo-mineral fertilization system with $N_{122}P_{116}K_{135}$ and 10 t ha^{-1} of manure per hectare of crop rotation area, with liming at 1.0 Ha (hydrolytic acidity). By contrast, sole mineral fertilization proved to be economically, environmentally, and bioenergetically inefficient, leading to a gradual decline in soil fertility.

2. Experimental reconstruction and residual nutrient effects (2000–2013)

Under the transitional economic conditions of that period, a key research priority was to establish a stable, predictable level of effective soil fertility through the resource-efficient use of fertilizers and ameliorants. This required the development of diagnostic approaches capable of ensuring environmental stability and regulating soil processes under long-term agricultural use.

Starting from rotation VI (2000), a partial reconstruction of several treatments was carried out. The reconstruction aimed to investigate the effectiveness and duration of residual liming effects, as well as the fate of phosphorus and potassium accumulated under previous intensive fertilization, under a moderate nitrogen application regime.

The seven-field rotation was replaced by a four-field rotation, removing potato and sugar beet from intensive cultivation and terminating high levels of mineral fertilizer application (Table 3). The crop rotation was modified to: maize for silage – spring barley undersown with red clover – red clover – winter wheat. This was particularly important because soils that had previously undergone intensive agrochemical inputs with high lime rates (1.0 and 1.5 $CaCO_3$ based on Ha) had accumulated considerable residual phosphates, exchangeable potassium, and calcium – raising concerns about potential contamination of surface waters with nitrates, phosphates, and calcium.

Research during rotation VI examined the influence of 40 years of different fertilization systems and liming, as well as residual effects of high mineral fertilizer rates, on the soil nutrient regime, fractional composition of soil phosphates, potassium group composition, humus content, and acid–base properties, together with their effects on crop yield and quality.

The results demonstrated a pronounced long-term residual effect of phosphorus fertilizers, leading to the transformation of residual P into iron and aluminium phosphate forms characteristic of this soil type. Their content ranged from 445 to 479 mg kg^{-1}, approximately twice the amount of calcium-bound phosphates. In contrast, the residual effect of soluble potassium fertilizers was relatively limited, consistent with the soil's low potassium-buffering capacity.

The optimal management strategy identified during this period involved $N_{65}P_{68}K_{68}$ combined with 10 t ha^{-1} of farmyard manure per hectare of crop rotation area and liming at 1.0 $CaCO_3$ equivalent based on Ha. Under these conditions, the highest crop rotation productivity was achieved, reaching 6.78 t ha^{-1} in grain units.

Research during rotation VII investigated the agroecological effects of long-term fertilizer and lime applications on soil profile structure, transformation of soil properties, and the accumulation and distribution of total and mobile forms of heavy metals within genetic soil horizons. The humus status, microbiological properties, and physicochemical characteristics of the soil were also examined in relation to crop yield and productivity.

Results showed that long-term sole mineral fertilization (> 40 years) led to increased soil acidity, elevated mobile aluminium concentrations, and exceedance of the maximum permissible concentration of mobile copper. These processes contributed to the loss of ecological and regenerative soil functions and to the stimulation of degradation processes.

Conversely, the systematic application of an organo-mineral fertilization system combined with periodic liming (1.0 $CaCO_3$ based on Ha) increased humus content and improved its qualitative composition, creating favourable conditions for humification microorganisms. Crop rotation productivity under this system reached 4.02–4.50 t ha^{-1} in grain units.

Theoretical principles of soil ecological quality in cultivated grey forest ecosystems were developed within the framework of long-term monitoring. These studies demonstrated the leading role of the active fraction of soil organic matter as an energy–plastic buffer ensuring nutrient regime stability and edaphic comfort. Indicators of soil ecological quality were proposed based on acid–base buffering reactions, redox potential, and electrical conductivity of soil suspensions [2].

3. Soil ecological processes and buffering capacity (2012–2021)

After eight crop rotation cycles, the combined application of mineral fertilizers, manure, and lime proved to be the most effective strategy for maintaining and improving the fertility of light grey forest surface-gleyed soils. This approach neutralises soil acidity, eliminates phytotoxic mobile aluminium, increases base saturation, and promotes humus accumulation, thereby forming an optimal nutrient regime for crops.

Under the leaching water regime typical of light grey forest soils, increased soil acidity was identified as the main limiting factor for crop productivity. Organic fertilization partially mitigated soil solution acidity, raising pH to 4.61; liming alone increased it to 4.73; combined lime and manure application raised pH to 5.07. Organo-mineral systems showed a smaller ameliorative effect on acidity, which diminished further with increasing mineral fertilizer doses.

Studies of soil CO_2 emissions (rotation IX) showed that high lime rates calculated according to Ha (6–9 t ha^{-1} $CaCO_3$) on low-buffered light grey forest soils are associated not only with substantial economic costs but also with environmental risks arising from additional mineralisation of soil organic matter. Lime rates calculated according to acid–base buffering capacity (ABBC; 2.5 t ha^{-1} $CaCO_3$) achieved comparable effects on labile organic compound content at significantly lower material inputs.

Research during rotation X demonstrated that redox potential (Eh) can serve as a highly sensitive indicator for assessing the intensity of transformation of soil properties and functional regimes under different levels of agricultural pressure. This parameter enables a quantitative assessment of deviations from the natural redox equilibrium and supports the justification of optimal fertilizer and lime rates to maintain balanced biogeochemical cycles.

The organo-mineral fertilization system combined with ABBC-based liming most effectively optimised soil CO_2 emission intensity by promoting oxidising and moderately oxidising conditions, increasing aerobic bacterial abundance, and enhancing overall biological activity. In contrast, sole mineral fertilization or unfertilised management resulted in lower productivity, increased CO_2 losses from mobile humus mineralisation, intensified reducing conditions, decreased biological and protease activity, and increased fungal microflora abundance.

4. Functional soil stability under long-term anthropogenic pressure (2020–2025)

Research during rotation XI focused on the functional stability of acidic light grey forest soils under long-term anthropogenic pressure and changing climatic conditions. Studies examined the mechanisms of aluminium toxicity resistance and the content, forms, and quantitative ratios of iron and manganese compounds in relation to redox potential. Particular attention was paid to mobile iron compounds, since the Fe^{3+}/Fe^{2+} ratio and redox potential (Eh) are sensitive indicators of oxidation–reduction processes in Albic Pantostagnic Luvisol. It was shown that the gross Fe content and the content of its mobile forms generally remained within the optimal range for plant growth; however, under long-term mineral fertilization without liming, especially during periods of excessive soil moisture, reducing conditions intensified and iron could shift into potentially toxic ferrous forms.

Mobile aluminium (Al) content in light grey forest soils was closely related to soil acidity (pH_{KCl} and hydrolytic acidity), fertilization system, residual effects, and crop rotation. Under intensive sole mineral fertilization during the first five seven-field rotations, mobile Al content reached 92.0–132.0 mg kg^{-1}. Replacing the seven-field with a four-field rotation reduced mobile Al by the end of rotation X to 68.4 mg kg^{-1} (mineral fertilization) and 58.5 mg kg^{-1} (control). Combined with Ha-based liming, mobile Al decreased to 6.7 mg kg^{-1}, and to 10.8 mg kg^{-1} when ABBC-based liming was applied [18].

Studies of soil physical properties showed that maintaining fertility in these soils, which is limited by periodic waterlogging and high acidity, requires long-term systematic application of 1.0 $CaCO_3$, 10 t ha^{-1} of manure, and $N_{65}P_{68}K_{68}$. The organo-mineral system had the most positive effect on the structural–aggregate state and physicochemical soil properties, while sole mineral fertilization caused deterioration approaching the level of the unfertilised control.

A short-term exploratory study of soil enzymatic activity during rotation XI revealed patterns of mineralisation and immobilisation under different management systems, depending on the intensity of anthropogenic pressure.

5. Current research stage: soil organic matter fractions and climate adaptation (2024–present)

Long-term field experiments constitute an important research infrastructure for understanding the long-term effects of climate variability and agricultural management practices on soil functioning. Although designed to operate under relatively stable experimental conditions, climate change is expected to alter environmental conditions at experimental sites substantially, and these changes must be considered in both the interpretation of results and the redesign of experimental setups [8].

Currently, fundamental research within rotation XII focuses on evolutionary changes in light grey forest soils under long-term agricultural pressures, including the dynamics of particulate organic matter (POM) as a function of the duration of anthropogenic use. Applied studies address the transformation of soil physical and agrophysical properties under long-term anthropogenic loads.

The results of this long-term field experiment provide a generalised assessment of the effects of different fertilization systems on soil properties and crop productivity. Over the 60 years of the experiment, clear differences were observed in the direction and intensity of soil transformation depending on fertilization system and liming practices. In particular, the long-term application of mineral fertilizers without liming contributed to the progressive acidification of soil and deterioration of humus quality, whereas organic fertilization partially stabilised soil properties. The most favourable changes in soil fertility indicators and crop productivity were observed under the organo-mineral fertilization system combined with periodic liming. A summary of the long-term effects of the main fertilization systems on soil properties and agroecosystem productivity is presented in Table 6.

6. Generalized long-term effects of different fertilization systems on soil properties and crop productivity

Fertilization type	Fertilization system	Liming approach	Soil reaction	Mobile Al	Soil organic matter (SOM) dynamics	Crop productivity	Overall effect
1	2	3	4	5	6	7	8
Unfertilized system	Control (no fertilizers)	–	strongly acidic	high	low SOM content	low	gradual soil degradation
Mineral system	Mineral fertilization (NPK)	–	strongly acidic	high	deterioration of SOM quality	low, unstable	progressive acidification and fertility decline
Organic system	Organic fertilization (manure)	–	slightly buffered, remains acidic	moderate	increased SOM content	moderate	partial stabilization
Organo-mineral system	Manure + NPK	Liming based on hydrolytic acidity (Ha)	moderately acidic	low	SOM accumulation and improved humus quality	high	improved soil fertility

1	2	3	4	5	6	7	8
Organo-mineral system (buffer-based)	Manure + NPK	Liming based on acid–base buffering capacity (ABBC)	moderately acidic	low	stabilization of active SOM fractions, reduced CO_2 emission risk	high	resource-efficient and environmentally sound soil management

The extensive information base generated by this long-term experiment, combined with rigorous methodological standards, enables both objective assessment of the natural resource potential of light grey forest surface-gleyed soils and the preservation of this experimental system as a unique national research infrastructure. The experiment continues to serve as an important platform for systematic monitoring and as an invaluable source of theoretical knowledge and practical recommendations for maintaining and protecting soil fertility [1].

Conclusions. Over its 60-year history, the long-term field experiment of the Institute of Agriculture of Carpathian Region of NAAS has generated a unique dataset reflecting long-term transformations of soil properties and agroecosystem productivity under different fertilization and liming systems on light grey forest surface-gleyed soils (Albic Pantostagnic Luvisol). The experiment is included in the NAAS Register of Long-Term Stationary Field Experiments (certificate No. 29) and, since 2023, in the Global Long-Term Agricultural Experiments Network (GLTEN).

The most effective strategy for maintaining soil fertility was the combined application of mineral fertilizers, farmyard manure, and lime. The organo-mineral fertilization system ($N_{65}P_{68}K_{68}$ + 10 t ha^{-1} manure) combined with periodic liming based on hydrolytic acidity ensured the highest crop rotation productivity across successive four-field rotation cycles, averaging 6.15–6.78 t ha^{-1} across rotations VI–XII. Under the seven-field rotation (rotations I–V), the optimal organo-mineral system ($N_{122}P_{116}K_{135}$ + 10 t ha^{-1} manure, liming at 1.0 Ha) also provided the highest and most stable yields. In comparison, the unfertilized control and sole mineral fertilization systems yielded 4.02–4.50 t ha^{-1} grain units during rotation VII, reflecting the long-term productivity penalty of fertilization without liming on acidic soils.

Long-term sole mineral fertilization proved to be economically and environmentally inefficient on these low-buffering soils. It led to soil acidification, accumulation of mobile aluminium, deterioration of humus quality, and reduced crop productivity. Periodic liming was identified as a prerequisite for sustainable management of acidic light grey forest soils.

Liming rates calculated according to acid–base buffering capacity (ABBC) achieved comparable agrochemical effects to rates calculated according to hydrolytic acidity, while requiring lower material inputs and reducing the risk of accelerated organic matter mineralisation and CO_2 emissions.

The long-term experiment provides an important platform for monitoring soil processes under changing climatic conditions. Current research during rotation XII focuses on the dynamics of particulate organic matter and soil physical properties, contributing to the development of adaptive soil fertility management strategies for the Western Forest-Steppe and Pre-Carpathian regions of Ukraine.

Список використаної літератури

1. Габрієль А. Й., Оліфір Ю. М. Тривалий стаціонарний дослід Інституту сільського господарства Карпатського регіону в контексті його 50-річного функціонування. *Передгірне та гірське землеробство і тваринництво.* 2015. Вип. 58. С.

References

1. Habriel A. Y., Olifir Yu. M. Long-term stationary experiment of the Institute of Agriculture of Carpathian Region in the context of its 50-year functioning. *Peredhirne ta hirske zemlerobstvo i tvarynnytstvo*. 2015. Vol. 58. P. 30–40.

30–40.

2. Гамкало З. Г. Екологічна якість ґрунту : навчальний посібник. Львів, 2009. 410 с.

3. Гуменюк А. І. Вапнування ґрунтів. Київ : Урожай, 1968. 99 с.

4. Довгострокові стаціонарні польові досліди України: реєстр атестатів / За ред. П. І. Коваленка, В. І. Кисіля, М. В. Лісового. Харків : Друкарня. № 13. 2006. 119 с.

5. Львівська область: природні умови та ресурси : монографія / за заг. ред. д-ра геогр. наук, проф. М. М. Назарука. Львів : Видавництво Старого Лева, 2018. 592 с.

6. Стаціонарні польові досліди України / А. С. Заришняк та ін. Київ : Аграрна наука, 2014. 146 с.

7. Тараріко Ю. О. Формування сталих агроекосистем: теорія і практика. Київ : Аграрна наука, 2005. 508 с.

8. Climate change causes spatial shifts in the productivity of agricultural long-term field experiments / C. Dönmez et al. *European Journal of Agronomy*. 2024. Vol. 155. Art. 127121. DOI: https://doi.org/10.1016/j.eja.2024.127121.

9. Effects of liming on soil physical and chemical properties in Europe and North America: a review / R. Wenyika et al. *Agrosystems, Geosciences & Environment*. 2025. Vol. 8 (2). Art. e70175. DOI: https://doi.org/10.1002/agg2.70175.

10. Effect of long-term application of organic, mineral and limestone fertilizers in crop rotation on the fertility of light grey forest surface-gleyed soils, crop yield and quality. GLTEN Metadata Portal. URL: https://glten.org/experiments/413 (accessed: March 2026).

11. European long-term field experiments: knowledge gained about alternative management practices / T. Sandén et al. *Soil Use and Management*. 2018. Vol. 34. P. 167–176. DOI: https://doi.org/10.1111/sum.12421.

12. Johnston A. E., Poulton P. R. The importance of long-term experiments in agriculture: their management to ensure continued crop production and soil fertility; the Rothamsted experience. *European Journal of Soil Science*. 2018. Vol. 69. P. 113–125. DOI: https://doi.org/10.1111/ejss.12521.

13. Long-Term Field Experiments Overview Map: An Interactive Open-Access Metadata Platform to Enhance Networking and Data Reuse / C. Dönmez et al. *Computers and Electronics in Agriculture*. 2026. Vol. 245. Art. 111534. DOI: https://doi.org/10.1016/j.compag.2026.111534.

14. Soil organic matter dynamics in long-term temperate agroecosystems: rotation and nutrient addition effects / J. Li et al. *Canadian Journal of Soil Science*. 2018. Vol. 98 (2). P. 232–245. DOI: https://doi.org/10.1139/cjss-2017-0127.

15. Soil Quality Index as a Predictor of Maize–Wheat System Productivity Under Long-Term Nutrient Management / D. Suri et al. *Land*. 2026. Vol. 15 (1).

2. Hamkalo Z. Ecological quality of soils : textbook. Lviv, 2009. 410 p.

3. Humeniuk A. I. Liming of Soils. Kyiv : Urozhai, 1968. 99 p.

4. Long-Term Stationary Field Experiments of Ukraine : Register of Certificates / Za red. P. I. Kovalenka, V. I. Kysilia, M. V. Lisovoho. Kharkiv : Drukarnia. No. 13, 2006. 119 p.

5. Lviv region: natural conditions and resources: monograph / za zah. red. d-ra heohr. nauk, prof. M. M. Nazaruka. Lviv : Vydavnytstvo Staroho Leva, 2018. 592 p.

6. Stationary Field Experiments of Ukraine / A. S. Zaryshniak et al. Kyiv : Ahrarna nauka, 2014. 146 p.

7. Tarariko Yu. O. Formation of Sustainable Agroecosystems: Theory and Practice. Kyiv : Ahrarna nauka, 2005. 508 p.

8. Climate change causes spatial shifts in the productivity of agricultural long-term field experiments / C. Dönmez et al. *European Journal of Agronomy*. 2024. Vol. 155. Art. 127121. DOI: https://doi.org/10.1016/j.eja.2024.127121.

9. Effects of liming on soil physical and chemical properties in Europe and North America: a review / R. Wenyika et al. *Agrosystems, Geosciences & Environment*. 2025. Vol. 8 (2). Art. e70175. DOI: https://doi.org/10.1002/agg2.70175.

10. Effect of long-term application of organic, mineral and limestone fertilizers in crop rotation on the fertility of light grey forest surface-gleyed soils, crop yield and quality. GLTEN Metadata Portal. URL: https://glten.org/experiments/413 (accessed: March 2026).

11. European long-term field experiments: knowledge gained about alternative management practices / T. Sandén et al. *Soil Use and Management*. 2018. Vol. 34. P. 167–176. DOI: https://doi.org/10.1111/sum.12421.

12. Johnston A. E., Poulton P. R. The importance of long-term experiments in agriculture: their management to ensure continued crop production and soil fertility; the Rothamsted experience. *European Journal of Soil Science*. 2018. Vol. 69. P. 113–125. DOI: https://doi.org/10.1111/ejss.12521.

13. Long-Term Field Experiments Overview Map: An Interactive Open-Access Metadata Platform to Enhance Networking and Data Reuse / C. Dönmez et al. *Computers and Electronics in Agriculture*. 2026. Vol. 245. Art. 111534. DOI: https://doi.org/10.1016/j.compag.2026.111534.

14. Soil organic matter dynamics in long-term temperate agroecosystems: rotation and nutrient addition effects / J. Li et al. *Canadian Journal of Soil Science*. 2018. Vol. 98 (2). P. 232–245. DOI: https://doi.org/10.1139/cjss-2017-0127.

15. Soil Quality Index as a Predictor of Maize–Wheat System Productivity Under Long-Term Nutrient Management / D. Suri et al. *Land*. 2026. Vol.

Art. 183. DOI: https://doi.org/10.3390/land15010183.

16. Soil Quality Indicators in Agroecological Practices: Lessons From a Systematic Review of Long-Term Experiments / A. Maienza et al. *European Journal of Soil Science*. 2025. Vol. 76 (4). Art. e70138. DOI: https://doi.org/10.1111/ejss.70138.

17. The Broadbalk Wheat Experiment, Rothamsted, UK: Crop yields and soil changes during the last 50 years / P. R. Poulton et al. *Advances in Agronomy*. 2024. Vol. 184. P. 173–298. DOI: https://doi.org/10.1016/bs.agron.2023.11.003.

18. The content of mobile aluminium compounds depending on the long-term use of various fertilizing and liming systems of Albic Pantostagnic Luvisol / Y. Olifir et al. *Agronomy Research*. 2023. Vol. 21 (2). P. 869–882. DOI: https://doi.org/10.15159/AR.23.039.

19. The Effect of Different Fertilization Treatments on Wheat Root Depth and Length Density Distribution in a Long-Term Experiment / P. Svoboda et al. *Agronomy*. 2020. Vol. 10 (9). Art. 1355. DOI: https://doi.org/10.3390/agronomy10091355.

20. The Effect of Long-Term Crop Rotations for the Soil Carbon Sequestration Rate Potential and Cereal Yield / D. Svensson et al. *Agriculture*. 2024. Vol. 14 (3). Art. 483. DOI: https://doi.org/10.3390/agriculture14030483.

21. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th ed. / IUSS Working Group WRB. Vienna: International Union of Soil Sciences (IUSS), 2022. https://wrb.isric.org/files/WRB_fourth_edition_2022-12-18.pdf.

22. Xing Y., Xie Y., Wang X. Enhancing soil health through balanced fertilization: a pathway to sustainnable agriculture and food security. *Frontiers in Microbiology*. 2025. Vol. 16. Art. 1536524. DOI: https://doi.org/10.3389/fmicb.2025.1536524.

15 (1). Art. 183. DOI: https://doi.org/10.3390/land15010183.

16. Soil Quality Indicators in Agroecological Practices: Lessons From a Systematic Review of Long-Term Experiments / A. Maienza et al. *European Journal of Soil Science*. 2025. Vol. 76 (4). Art. e70138. DOI: https://doi.org/10.1111/ejss.70138.

17. The Broadbalk Wheat Experiment, Rothamsted, UK: Crop yields and soil changes during the last 50 years / P. R. Poulton et al. *Advances in Agronomy*. 2024. Vol. 184. P. 173–298. DOI: https://doi.org/10.1016/bs.agron.2023.11.003.

18. The content of mobile aluminium compounds depending on the long-term use of various fertilizing and liming systems of Albic Pantostagnic Luvisol / Y. Olifir et al. *Agronomy Research*. 2023. Vol. 21 (2). P. 869–882. DOI: https://doi.org/10.15159/AR.23.039.

19. The Effect of Different Fertilization Treatments on Wheat Root Depth and Length Density Distribution in a Long-Term Experiment / P. Svoboda et al. *Agronomy*. 2020. Vol. 10 (9). Art. 1355. DOI: https://doi.org/10.3390/agronomy10091355.

20. The Effect of Long-Term Crop Rotations for the Soil Carbon Sequestration Rate Potential and Cereal Yield / D. Svensson et al. *Agriculture*. 2024. Vol. 14 (3). Art. 483. DOI: https://doi.org/10.3390/agriculture14030483.

21. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th ed. / IUSS Working Group WRB. Vienna: International Union of Soil Sciences (IUSS), 2022. https://wrb.isric.org/files/WRB_fourth_edition_2022-12-18.pdf.

22. Xing Y., Xie Y., Wang X. Enhancing soil health through balanced fertilization: a pathway to sustainnable agriculture and food security. *Frontiers in Microbiology*. 2025. Vol. 16. Art. 1536524. DOI: https://doi.org/10.3389/fmicb.2025.1536524.