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Long-term rye monoculture on chernozem: stable yields with changing soil organic matter

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Abstract. Long-term field experiments are essential for understanding how monocultures reshape soils under climate change. We hypothesised that the buffering capacity of Ukrainian chernozem sustains low but persistent winter rye yields without external inputs, while gradually altering the quality of soil organic matter and the base-cation status. We tested this in a long dataset from Poltava (Ukraine): a 0.4-ha plot established in 1884 and managed uniformly (annual disking and ploughing to 22–25 cm, mid-September sowing, no fertilisers, herbicides or pesticides; varieties renewed). Hydrometeorological records, archived yields (1885–2024) and repeated soil surveys (1964–2024) were analysed; elemental composition was determined by ICP-MS; humus fractions by standard alkaline extraction; statistics in Statistica 12. Mean grain yield was 1.19 t ha^{-1} (straw 2.80 t ha^{-1}) with wide interannual variability (0.15–2.38 t ha^{-1}) but no significant long-term trend despite regional warming and modest precipitation decline. Topsoil humus (0–20 cm) decreased from 2.8% mid-century to 2.3% in 2024, and the humic: fulvic carbon ratio fell from 1.15 to 0.89, indicating a shift toward more mobile, less polymerised fractions. Soil reaction remained acid to slightly acid (pH(salt) 4.7–5.5) with hydrolytic acidity 2.4–3.8 meq 100 g^{-1}; available N, P and K fluctuated within stable ranges, but Ca and Mg declined. Weed communities changed markedly; pest pressure intermittently exceeded economic thresholds yet appeared buffered by natural antagonists. Continuous winter rye on chernozem maintains modest, persistent yields without fertiliser inputs, while organic matter quantity declines moderately and quality becomes more fulvic; concurrent base-cation depletion flags a risk to structural and ecological stability. The 140-year record provides a rare baseline for calibrating models and designing rotation, liming, and nutrient-return strategies for climate-resilient agro-ecosystems in Eastern Europe.

Keywords: chernozem, long-term field experiments, monoculture, winter rye, soil fertility.

1. Introduction

Long-term field experiments are a unique means to measure and understand changes in agriculture, soil chemistry and ecology. They lend insight into soil fertility, sustainability, crop productivity, and adaptation of agricultural systems to climate change. Their value only increases year-on-year but they cannot be replicated within a lifetime (Boincean et al., 2013; Powlson et al., 2014; Kokhan et al., 2014, 2019; Gangur et al., 2019) and there are only a few such studies that were initiated in the 19th century and which still continue (Table 1).

Table 1. Long-established field experiments

Experiment site	Country	Year of establishment
Rothamsted	England	1843
Grignon	France	1875
Morrow Plots, Illinois	USA	1876
Halle/Salle	Germany	1878
Poltava	Ukraine	1884
Sanborn Field, Missouri	USA	1888
Dakota	USA	1892
Askov	Denmark	1894
Auburn	USA	1896

The first study of continuous cropping systems was initiated at Rothamsted, in England, with trials of continuous winter wheat and other crops established between 1843 and 1856. Similar experiments on eternal rye were initiated at Poltava in 1884 (Kokhan et al., 2017) and in Halle (Germany) in 1885. Since 1912, trials of continuous winter wheat and rye have also been conducted in Ukraine at the V.M. Remeslo, Myronivka Institute of Wheat; and peas, winter wheat, sugar beet, and maize-for-grain have been studied in both rotation and monoculture systems at the Black Sea Experimental Field in the south of the country. In Skierniewice, Poland, long-term monitoring of soil properties and crop yields on a permanent research plot was established in 1923 by the Department of Agricultural Chemistry of the Agricultural University of Warsaw (Blake et al., 1999). The results of this almost 100-year-old static fertilizer experiment were presented by Stępień et al. (2019) in a chapter of a book published after an international agro-industrial scientific and practical forum in Lviv, Ukraine.

Experiments in different parts of the world enable the assessment of regional soil and climatic factors that influence the response of crops to agronomic practices. For instance, humus degradation has been studied in Ukrainian chernozems; long-term fertiliser efficiency on sandy soils in England; and experimental data have demonstrated the significance of crop rotation, the effectiveness fertilisers and soil erosion control in various places. The results can be further used for modelling and developing sustainable agronomic practices in the context of climate change (Kokhan et al., 2019) but results from one region cannot be directly extrapolated to another.

Different crops respond differently to continuous monoculture but, generally, yields decline compared to those in crop rotations (Shvartau et al. 2016; Kokhan et al., 2018; Samoylenko & Kokhan, 2020; Schevchenko et al., 2023, 2024; Ravitie-Uvarova et al., 2024). In some cases, this decline is brought about by the emergence of crop-specific pests and diseases; in others due to the continuous depletion of nutrients. Moreover, crop growth may be diminished by root exudates from the crops themselves, along with microbial activity; even limited tillage might inhibit oxygen-dependent processes and contribute to soil fatigue. In this research, we analyse climate change over the course of the long-term experiment on continuous winter rye at Poltava, and evaluate the yield performance in the light of corresponding changes in the content of nutrient elements and heavy metals in the soil.

2. Materials and Methods

The experiment on continuous winter rye at the Poltava experiment field was initiated in 1884 on a 0.4 ha plot of *dark gray podzolic heavy loam soil* (according to the Ukrainian soil classification). Throughout the last 140 years, agronomic practices have remained unchanged: annually, after harvest, the soil is loosended by a heavy disc harrow and, 7-10 days later by ploughing to a depth of 22-25 cm with simultaneous rolling; emergent weeds are controlled by harrowing; winter rye is sown in the second decade of September and rolled in; no fertiliser or chemical control measures for weeds, diseases, and pest, are applied. The experimental is conducted with one replicate (Fig. 1).

Over the entire historical period, ten varieties of winter rye have been grown. Until 1930, the seed rate was 90 kg/ha. From 1930 to 1972, the field was divided into two: one half followed the old sowing rate of 90 kg/ha, while the other used 150 kg/ha. The average yield over 43 years for the 90 kg/ha sowing rate was 1.11 t/ha, and for 150 kg/ha, it was 1.25 t/ha. Since 1972, the current sowing rate of 6 million viable seeds/ha has been imposed. The seed is renewed annually but varieties have been changed when the previous one was superseded. The following locally adapted varieties of rye were sown: Probshteynska (1885-1907), Poltavska (1908-10), Petkuska (1911-60), Kharkivska 194 (1961-64), Kharkivska 55 (1965-1982), Kharkivska 78 (1983-92), Kharkivska 88 (1993-1998), Kharkivska 95 (1999-2009), Khamarka (2010-2021), and Pamiat Khudoierko (2022-2024).

Hydrometeorological data were provided by the Poltava Regional Hydrometeorological Centre.

Figure 1. Views of the experimental field

The content of easily hydrolysable nitrogen (Kornfield), potassium and phosphorus (Chirikov), as well as the results of humus analysis, are presented for the period from 1964 to 2024, based on data from the M.I. Vavilov, Poltava State Agricultural Experimental Station. The elemental composition of the soil samples from the experiment was determined at the Institute of Plant Physiology and Genetics, National Academy of Sciences of Ukraine, using the ICP-MS method on an Agilent 7700x inductively coupled plasma mass spectrometer. The samples were dried at 105°C to a constant weight and ashed in ICP-grade nitric acid using Milestone Start D microwave sample preparation. The extract was diluted to 50 mL with grade 1 water (18 MΩ), prepared using the Scholar-UV NexUp 1000 water purification system (Human Corporation, Korea).

Data analysis was performed using Statsoft Statistica 12 software. Results are presented as the mean ($\bar{x}$) ± standard deviation (SD). Crop productivity was determined using mathematical statistics.

3. Results and Discussion

3.1. Weather and climate

Alongside significant technological advances, crop production has been affected by increasing average daily temperatures, irregular rainfall and more frequent extreme weather events. According to the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine, areas with significant moisture deficits increased by 7% between 1961-90 and 1991-2012, and now extend over 30% of the country. In contrast, regions with ample moisture decreased by 10%, now occupying only 22.5% of the country. At the same time, the increase in average daily temperatures has allowed a significant northward expansion of the cultivation of maize, soybeans, and sunflowers.

Analysis of the average annual temperature in Poltava, in the central region of Ukraine, revealed typical annual

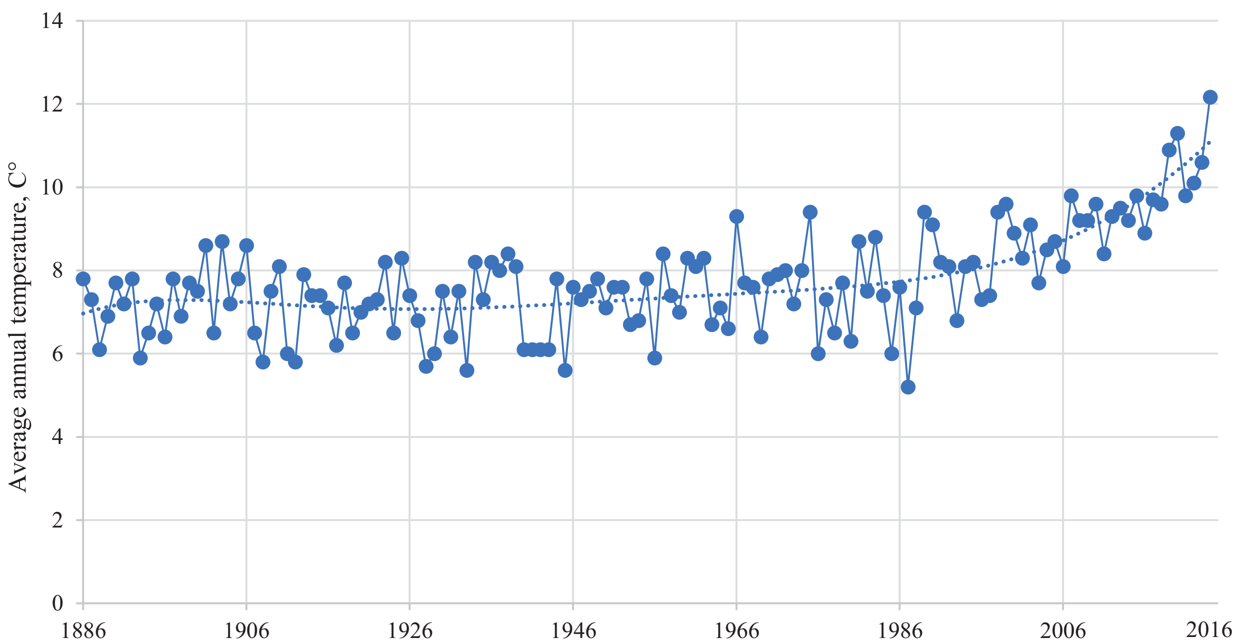

Figure 2. Average annual air temperature by year, °C

fluctuations (Fig. 2). For instance, in 1912 and 1928, low temperatures were recorded, 5.8°C and 5.7°C, respectively; while 2007, 2019, 2020 and 2024 registered record high temperatures of 9.8°C, 10.9°C, 11.3°C and 12.17°C, respectively.

During the first half of the 20th century, the average annual temperature remained fairly stable, fluctuating around 6-8°C. However, starting in the 1960s, more significant fluctuations were observed and, from the 1980s, temperatures rose steadily and this increase has accelerated. In the 1990s, the average annual temperature exceeded 9°C, and in the 2020s, it reached 10-12°C.

Precipitation over the past 140 years has also fluctuated and has decreased somewhat in the new millennium (Fig. 3).

Faybishenko et al. (2023) and Romashchenko et al. (2025) assessed the individual temperature and precipitation trends from 1901 to 2022 for each region of Ukraine, observing climate warming beginning in the 1940s and a hot phase setting in from 1979 to 1994 with an average annual air temperature increase of 0.45°C per decade. During the hot phase, precipitation has remained practically unchanged, increasing soil water deficit which, in turn, has decreased groundwater recharge, streamflow and crop yields. Projected increases in water deficit will move most of southern Ukraine into the arid zone, with an annual soil water deficit exceeding 550 mm in 2050 and surpassing 700 mm in 2100, which will have dire consequences for ecosystems and Society.

Such weather conditions exacerbate erosion, nutrient depletion and soil degradation, impacting pollination, water conservation and pest control. Agronomists try to combat them by introducing crop varieties and hybrids that are more resilient to drought and heat stress but, in order to m maintain high crop yields, especially in the southern steppes, it is essential to develop modern irrigation systems (Hapich et al., 2023; Onopriienko et al., 2024, 2025). Considering all the aspects, it becomes clear that climate change creates opportunities with an extended growing season and the expansion of thermal crop ranges in the north, while also presenting significant challenges with drought and soil erosion in the south. Poltava is sited half way between the southern region that faces increasing droughts and the northern region that will benefitting from longer, warmer growing seasons.

3.2.Yields of winter rye

Table 2 presents the grain and straw yields of winter rye over 140 years. The grain yield has averaged 1.19 t/ha, while the straw yield has been 2.80 t/ha. The highest productivity was recorded in 1887 (2.38 t/ha, cultivar Probstein), 1970 (2.28 t/ha, cultivar Kharkivske 55), and 1991 (2.26 t/ha, cultivar Kharkivske 78). The lowest grain yields were observed in 1954 (0.15 t/ha, cultivar Petkus) and 2016 (0.16 t/ha, cultivar Khamarka).

On average, over the 140 years of research, the grain yield amounted to 1.17 t/ha, and straw yield was 2.73t/ha. Although there have been big annual fluctuations throughout the entire experimental period, there has been no discernible long-term trend, except that yields have remained below average over the last three decades. The highest grain yield was observed in 1887, 1983 and 1982: 2.38, 2.26 and 2.24 t/ha, respectively. The lowest yields occurred in 1954, 2016 and 1924, with values of 0.15, 0.16 and 0.29 t/ha, respectively.

These data are comparable to those for unmanured continuous winter wheat on the Broadbalk Field at Rothamsted

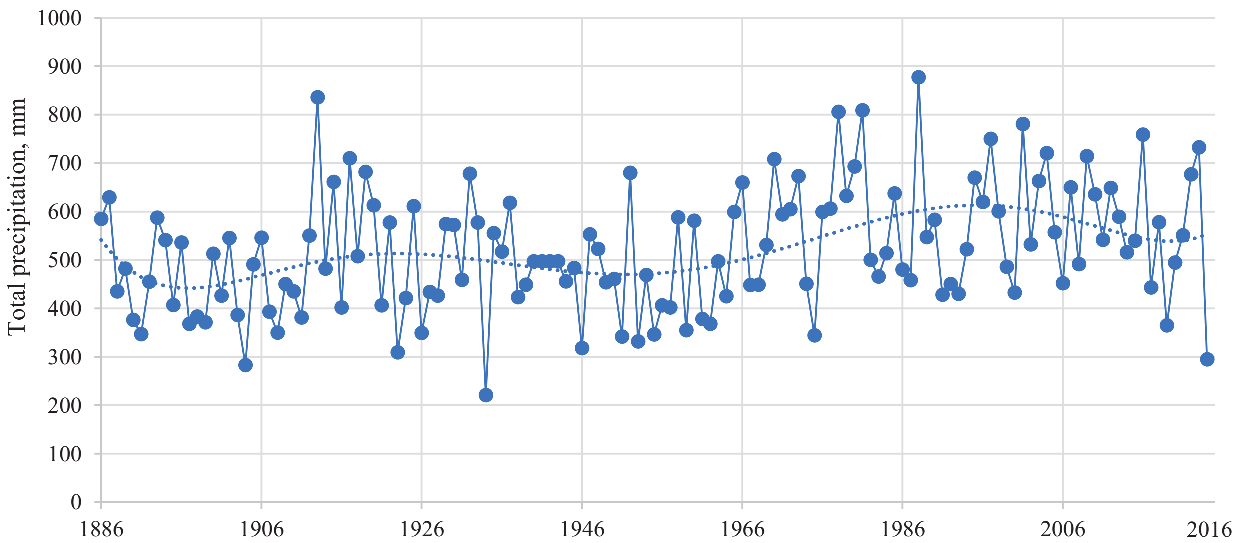

Figure 3. Annual precipitation, mm

Table 2. Grain and straw yield of winter rye under continuous cultivation, t/ha

Year	Yield, t/ha		Year	Yield, t/ha		Year	Yield, t/ha	
	grain	straw		grain	straw		grain	straw
1885	1.10	2.00	**1932**	0.86	2.77	**1979**	1.23	1.49
1886	1.04	1.69	**1933**	0.85	4.62	**1980**	1.47	1.76
1887	2.38	4.75	**1934**	1.54	2.53	**1981**	1.21	3.09
1888	1.95	3.35	**1935**	1.57	2.61	**1982**	2.24	5.06
1889	1.06	1.97	**1936**	0.89	3.07	**1983**	2.26	4.75
1890	1.43	2.38	**1937**	1.19	3.32	**1984**	2.04	6.43
1891	0.91	2.59	**1938**	1.10	2.72	**1985**	1.61	5.07
1892	0.65	1.20	**1939**	1.69	3.56	**1986**	1.02	2.62
1893	0.96	3.41	**1940**	0.83	2.41	**1987**	1.22	1.73
1894	0.82	2.36	**1941**	1.38	3.64	**1988**	1.90	6.56
1895	0.53	2.04	**1942**	0.26	0.50	**1989**	1.43	4.23
1896	0.54	1.08	**1943**	0.44	1.17	**1990**	1.55	6.51
1897	0.66	2.10	**1944**	0.75	3.09	**1991**	0.70	1.96
1898	0.91	2.92	**1945**	1.67	3.43	**1992**	2.03	6.29
1899	1.11	1.91	**1946**	0.92	1.75	**1993**	1.39	3.24
1900	0.59	1.62	**1947**	1.65	3.34	**1994**	1.22	2.02
1901	0.45	0.87	**1948**	1.31	3.07	**1995**	1.27	2.29
1902	1.25	4.74	**1949**	1.49	1.93	**1996**	1.08	2.05
1903	—	—	**1950**	1.67	2.79	**1997**	1.40	6.16
1904	2.15	5.62	**1951**	0.98	2.64	**1998**	0.56	1.85
1905	1.13	2.49	**1952**	0.96	2.67	**1999**	1.09	2.07
1906	0.35	1.32	**1953**	1.73	3.96	**2000**	0.50	1.62
1907	1.17	2.24	**1954**	0.15	0.69	**2001**	1.22	2.06
1908	1.31	2.40	**1955**	1.88	4.51	**2002**	1.19	1.94
1909	1.15	2.28	**1956**	1.82	1.35	**2003**	0.58	0.96
1910	1.66	3.86	**1957**	0.75	1.20	**2004**	1.79	2.91
1911	0.90	1.67	**1958**	1.89	3.03	**2005**	1.03	1.44
1912	1.08	2.67	**1959**	1.00	2.70	**2006**	0.34	1.53
1913	1.02	2.49	**1960**	0.97	1.00	**2007**	0.78	1.48
1914	1.50	4.25	**1961**	0.94	2.40	**2008**	0.46	1.15
1915	1.36	3.26	**1962**	0.98	1.33	**2009**	0.79	1.98
1916	1.38	3.39	**1963**	0.78	1.53	**2010**	0.89	1.40
1917	1.35	2.22	**1964**	1.02	2.22	**2011**	1.65	2.62
1918	0.96	2.27	**1965**	1.87	2.99	**2012**	1.90	4.06
1919	0.75	2.27	**1966**	1.32	4.14	**2013**	1.80	2.08
1920	1.02	1.92	**1967**	0.82	1.29	**2014**	1.07	2.03
1921	1.45	2.95	**1968**	0.70	2.15	**2015**	1.40	2.83
1922	1.70	3.67	**1969**	2.22	3.91	**2016**	0.15	1.95
1923	1.42	3.04	**1970**	0.59	1.20	**2017**	0.56	0.96
1924	0.29	1.75	**1971**	1.49	6.23	**2018**	0.80	1.28
1925	0.60	1.76	**1972**	1.79	8.68	**2019**	0.63	1.00
1926	1.29	3.18	**1973**	1.51	3.70	**2020**	0.65	1.04
1927	1.35	2.26	**1974**	2.28	6.45	**2021**	0.28	0.44
1928	0.64	1.91	**1975**	1.34	3.89	**2022**	2.00	3.20
1929	0.78	1.62	**1976**	1.47	2.79	**2023**	0.63	1.00
1930	1.83	3.66	**1977**	1.43	2.86	**2024**	0.50	0.80
1931	0.48	1.83	**1978**	2.18	4.59			
Least significant difference, t/ha (p = 0.05) for grain 0.06 for straw 0.08								

since 1844 (mostly in the range 1-1.5 t/ha) which have been supported by wet and dry deposition of nitrogen from the atmosphere (Powlson et al., 1986, Powlson et al., 2014; Mytsyk et al., 2024)

At Poltava, the lowest absolute productivity was in 1954 with the Petkus variety, yielding only 0.15 t/ha, while the highest among the minimum values was 1.15 t/ha in 1909 with the Poltava variety, which was grown for only three years (1908-1910). Among the maximum yields, the lowest was 1.02 t/ha in 1963 with the Kharkiv 194 variety, while the highest was in 1887 with the Probstein variety, yielding 2.38 t/ha but we have no evidence of any significant relationship between yield and variety.

3.3. Soil conditions and plant growth

We have investigated changes in the soil chemistry over the years. The assessment of humus content records, over 127 years, absolute humus loss in the 0-20cm soil layer of 0.55%, that is 20% of the initial humus content or 136.5t/ha. Specifically, in 1888, the humus content was 2.83%, declining to 2.63% in 1900, 2.30% in 1945, 2.15% in 1948; recovering to 2.20% in 1955, 2.44% in 1957, 2.56% in 1981, 2.54% in 1991 – decades of higher-than-average crop yields; and declining again to 2.47% in 2001, 2.08% in 2014, 2.30% in 2016, and 2.27% in 2024. However, the methods of analysis are not comparable. The 19th century methods may have overestimated humus content by 4-8% to as much as 9-12% compared with the Tyurin procedure which dates from the 1930s (Ushkarenko et al., 2008; Mazur et al., 2020) and which, itself, has been modified over the years. Moreover, the humus content changes during the growing season: soil samples collected at different times from the 0-20 cm soil layer in 2024 from designated plots registered a humus content of 2.27% in April, decreasing to 2.22% in July, but increasing again to 2.60% in September. In recent years, qualitative indicators of humus composition have also changed, particularly in the ratio of humic to fulvic acid carbon. In 1964, this ratio was 1.15 and 1.26 in the 0-20 and 20-40cm layer, respectively; decreasing to 0.93 and 1.16 in 1979, 0.93 and 0.99 in 2012, and 0.91 and 0.97 in 2024 (Table 3).

Soil reaction has remained relatively stable over the years (Table 4): pH of the salt extract fluctuating between 5.5 and 4.7 in the 0-10/20 cm layer and 4.6-4.8 in the 20-40 cm layer; and hydrolytic acidity fluctuating between 2.4 and 3.8 meq/100g of soil in the 0-10/20 cm layer and 3.4-3.8 meq/100g soil in the 20-40 cm layer.

Similarly, the contents of readily-available nutrients have varied within a relatively stable range. The amount of easily hydrolysable nitrogen has not significantly changed over the years: specifically, in 1964 and 1990, hydrolysable nitrogen in the 0-10 cm soil layer was 95 and 104 mg/kg, respectively; and in the 0-20 cm layer, remained at 88-98 mg/kg of soil in 2002, 2014 and 2024.

In 1964, the content of mobile phosphorus and exchangeable potassium (Chirikov) in the 0-10 cm soil layer was 131 and 123 mg/kg of soil, respectively. After 26 years, in 1990, these values remained almost unchanged at 132 and 138 mg/kg of soil. In 2002, the content of mobile phosphorus and exchangeable potassium in the 0-20 and 20-40 cm soil layers was 66 and 118 mg/kg, and 166 and 142 mg/kg, respectively; by 2024, the content of these nutrients amounted to 88 and 79 mg/kg in the 0-20 cm layer and 181 and 134 mg/kg in the 21-40 cm layer.

Analysis of changes in the content of other elements (Table 5) does reveal a significant decrease in calcium (Ca) and magnesium (Mg) which are critical for maintaining soil structure and fertility, also molybdenum (Mo) which could negatively impact future cultivation, especially of legumes.

Table 3. The humus composition in soil under continuous winter rye cultivation (x ± SD)

Indicator	Year							
	1964		1979		2012		2024	
	Soil layer, cm							
	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40
Humus content, %	2.35±0.06	1.76±0.04	2.26±0.06	1.84±0.05	2.33±0.06	1.81±0.05	2.27±0.06	1.78±0.05
Soil organic carbon	1.47±0.04	1.02±0.03	1.30±0.04	1.97±0.06	1.42±0.05	1.19±0.04	1.31±0.06	1.13±0.04
Carbon in 0.1 N H_2SO_4	0.066±0.006	0.056±0.005	0.095±0.009	0.072±0.007	0.088±0.007	0.069±0.006	0.084±0.007	0.066±0.006
Carbon in $N_4P_2O_3$ + NaOH	0.659±0.015	0.465±0.012	0.599±0.014	0.486±0.012	0.613±0.015	0.472±0.012	0.600±0.014	0.465±0.012
Humic acid carbon	0.353±0.011	0.258±0.010	0.288±0.011	0.261±0.010	0.307±0.011	0.234±0.011	0.295±0.012	0.228±0.011
Fulvic acid carbon	0.306±0.010	0.210±0.009	0.311±0.011	0.225±0.009	0.329±0.010	0.236±0.009	0.332±0.010	0.239±0.009
Humic to fulvic acid carbon ratio	1.15±0.03	1.26±0.04	0.93±0.02	1.16±0.03	0.93±0.02	0.99±0.03	0.89±0.02	0.95±0.03

Table 4. Agrochemical indicators of soil under continuous winter rye (x ± SD)

Soil layer, cm	Content on an absolutely dry soil basis, mg/kg			Total N, %	Total P_2O_5, mg/kg	pH (salt extract)	Hydrolytic acidity, meq/100 g
	easily hydro-lysable N	P_2O_5	K_2O				
1964							
0–10	95±5	131±7	123±7	-	-	5.5±0.3	2.4±0.1
1981							
0–10	98±6	123±7	197±9	-	-	4.9±0.2	3.6±0.2
1990							
0–10	104±6	132±7	138±7	-	-	5.4±0.3	3.1±0.2
2002							
0–20	98±5	66±5	166±8	0.14±0.02	884±24	4.8±0.2	3.7±0.2
20–40	59±4	68±5	142±7	0.10±0.01	806±22	4.8±0.2	3.8±0.2
2003							
0–20	91±5	79±6	200±9	0.15±0.02	940±25	4.7±0.2	3.8±0.2
20–40	60±4	66±5	152±7	0.13±0.02	987±25	4.7±0.2	3.8±0.2
2010							
0–20	88±5	101±6	184±8	0.14±0.02	785±21	4.8±0.2	3.7±0.2
20–40	64±	64±5	165±7	0.12±0.02	801±22	4.6±0.2	3.8±0.2
2014							
0–20	88±5	97±6	192±9	0.15±0.02	823±22	5.4±0.3	3.1±0.2
20–40	65±4	71±5	140±7	0.11±0.01	724±21	4.6±0.2	3.5±0.2
2024							
0–20	92±5	100±7	195±9	0.15±0.02	842±22	5.2±0.3	3.1±0.2
20–40	64±4	73±5	149±7	0.12±0.01	735±21	4.6±0.2	3.4±0.2

Table 5. Content of inorganic elements in the soil under continuous winter rye cultivation (x ±SD)

Inorganic elements	Content, mmol/100 g of soil			
	1969	**1982**	**2014**	**2024**
Li	31.2±2.4	18.2±1.8	14.8±1.6	12.3±1.4
Be	6.1±0.4	3.2±0.3	2.2±0.3	2.1±0.2
Na	185±8	168±7	151±6	139±6
Mg	3 815±34	3 717±32	3 710±32	3 702±32
K	4 997±42	4 869±40	5 195±43	5 190±43
Ca	3 913±35	3 756±32	3 706±32	3 701±32
V	38.7±2.9	40.0±3.0	36.7±2.8	37.1±2.8
Cr	36.5±2.7	36.5±2.7	35.0±2.5	35.0±2.5
Mn	928±17	856±16	833±16	829±15
Fe	17 785±142	18 439±146	17 054±141	17 124±142
Co	9.0±0.8	9.2±0.8	8.7±0.8	8.8±0.8
Ni	11.8±1.0	9.8±0.9	8.4±0.8	8.4±0.8
Cu	20.1±1.9	17.7±1.8	20.2±1.9	19.9±1.9
Zn	55.5±3.6	50.2±3.2	56.2±3.5	56.0±3.5
Ga	38.7±2.9	38.7±2.9	36.2±2.8	36.1±2.8
Rb	44.3±3.2	41.6±3.1	41.3±3.1	41.3±3.1
Sr	32.7±2.7	33.2±2.7	31.1±2.6	31.4±2.6

A gradual reduction in the mobile forms of lithium (Li) and beryllium (Be) suggests their leaching or intensive uptake by plants. The slight fluctuation in copper (Cu) and a modest increase in zinc (Zn) may be due to natural enrichment through weathering or atmospheric deposition. The concentrations of rubidium (Rb), strontium (Sr), and lead (Pb) remained stable, indicating their low mobility in the soil.

In the absence of chemical plant protection, the rye crops were infested with weeds. Over the years, there was a shift in the predominant weed species and the degree of infestation. Among the dominant weeds, chamomile (*Matricaria perforata* Merat.), cornflower (*Centaurea cyanus* L.), and violet (*Viola arvensis* Murr.) were observed, their numbers ranging from 30.0 to 164.3 plants/m². The number of less common weeds ranged from 9.7 to 21.8 plants/m²; these included beaked fumitory (*Fumaria rostellata* Knaf.), Schleicher's fumitory (*Fumaria schleicherii* Soy. Willem), white melandrium (*Melandrium album* Mill. Garke), field spurge (*Spergularia arvensis* L.), hybrid pigweed (*Chenopodium hybridum* L.), curlyhead Sofia (*Descurainia sophii* (L.) Webb ex Prantl), sticky bedstraw (*Galium aparine* L.), common gromwell (*Lithospermum arvesis* L.), forget-me-not (*Myosotis arvesis* (L.)), Lesel's hoary cress (*Sisymbrium Loeselii* L.), hedge bindweed (*Fallopia convolvulus* (L.) Love), common knotgrass (*Polydomum aviculare* L.), dirty pea (*Vicia sordid* Waldstet Kit.), dead-nettle (*Lamium amplexicaule* L.), field bindweed (*Convolvulus arvense* L.), thistle (*Cirsium setosum* (Wild.) Besser), and scentless mayweed (*Tripleurospermum inodorum* (L.) Sch. Bip.).

Several common weeds in the the continuous rye crops have disappeared since the late nineteenth century, such as cockle (*Agrostemana githago* L.) and salgo (*Salgola* L.). Weeds like common vetch (*Vicia cracca* L.), field pennycress (*Thlaspi arvense* L.), cornflower (*Centaurea cyanus* L.), and field violet (*Viola arvensis* Murr.) have diminished but others like small-flowered forget-me-not (*Myositis micrantha* Pall.), field larkspur (*Delphinium consolida* L.), and sticky bedstraw (*Galium aparine* L.) and common ragweed (*Ambrosia artemisiifolia* L.) have increased.

It appears that the weather conditions observed during the years of the study did not have a significant impact on the quantitative composition of pests although, in some years, the economic threshold of pest damage was exceeded by thrips, cereal aphids, and the shield bug (adult stage). In our opinion, the stabilisation of pest populations in continuous rye cultivation was influenced by several factors, including, alongside the spread of pests, the dynamic reproduction of their antagonists.

4. Conclusions

The remarkable aspect of the Poltava eternal rye trial is that harvests are undiminished after 140 years of harvesting, albeit very modest harvests. Understanding this simple system may lay a foundation for understanding more complex systems that can yield greater sustainable harvests.

Over the course of this long-term experiment, significant changes have occurred in the voluntary, segetal vegetation, both in terms of quantity and species composition. Dominant species in the rye crop include field violet (*Viola arvensis* L.), scentless chamomile (*Matricaria perforata* L.), and cornflower (*Centaurea cyanus* L.).

The economic threshold of pest damage by thrips, cereal aphids, and the shield bug (adult stage) varied from year to year but pest populations also appear to be stable.

The average yield of this crop has been 1.19 t/ha, yields fluctuating from1.15-2.38 t/ha depending on the weather, soil preparation, the amount of productive moisture in the seedbed at the time of sowing, weed infestation, pests and diseases. However, we do not discern any obvious effect of climatic warming in recent decades. The periodic replacement of the rye variety with a better genetic potential did not significantly affect the yield.

The black earth appears to be maintaining its topsoil humus content in the range 2.2-2.4% and stable NPK levels without fertilisation.

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