SOIL SCIENCE ANNUAL
2022, 73(1), 146855

https://doi.org/10.37501/soilsa/146855

Changes in the agrochemical indices of Luvic Greyzemic Phaeozems under the impact of west Ukraine climate aridization

Volodymyr Polovyy[1], Petro Hnativ[2], Józef Chojnicki[3*], Natalia Lahush[2], Viktor Ivaniuk[2], Mariya Avhustynovych[4], Oksana Haskevych[2], Liudmyla Lukashchuk[1], Mykola Lukyanik[1]

[1]Institute of Agriculture of Western Polissia of NAAS, 5 Rivne Street, Shubkiv, Rivne district, Rivne region, 35325, Ukraine, ORCID iD: https:// orcid.org/0000-0002-3133-9803 (V. Polovyy), https://orcid.org/0000-0003-0416-4654 (L. Lukashchuk), https://orcid.org/0000-0002-5657-1262 (M.Lukyanik)

[2]Lviv National Agrarian University, 1 Vladimir the Great Str., Dubliany, Zhovkva District, 80381 Lviv region, Ukraine, ORCID iD https://orcid.org/0000-0003-2519-3235 (P. Hnativ), https://orcid.org/0000-0002-1467-5805 (N. Lahush), https://orcid.org/0000-0002-6885-9212 (V. Ivaniuk), orcid.org/0000-0002-4354-3860 (Oksana Haskevych)

[3]Warsaw University of Life Sciences – SGGW, Department of Soil Science, Nowoursynowska 159 Str., 02-776 Warszawa, Poland (Józef Chojnicki)

[4] Lutsk National Technical University, Ministry of Education and Science of Ukraine, street Lvivska, 75, Lutsk city, 43018 Volyn region, Ukraine, ORCID iD: https orcid.org/0000-0001-7301-7581 (Mariya Avhustynovych)

* prof. dr hab. J. Chojnicki, jozef_chojnicki@sggw.edu.pl, ORCID iD: https://orcid.org/0000-0001-7719-4331

Received: 2021-07-21
Accepted: 2022-02-22
Published online: 2022-02-22
Associated editor: B. Rutkowska

Key words:

Climate
Nitrogen
Phosphorus
Potassium
Fertilizers
Cereals

Abstract

Modern agriculture has not been so strongly affected by the climate change we are seeing today. There are no systematic studies and predictions regarding the response of soils to rising air temperatures and changes in the water supply of landscape ecosystems. Ultimately, it is unknown how climate fluctuations affect the balance of nutrients and humus in soil depending on the crops grown. There is not enough scientific data to indicate that warming or aridization affect the efficiency of plant fertilizers. Our aim is to find out how changes in the climate of the Western Ukrainian mesoclimate interacts with the trends in soil processes and crop yields in the Northwestern Forest-Steppe. We analysed the weather data from 1945–2018 provided by the Rivne State Weather Station (Ukraine) and the crop yields of the Main Directorate of Statistics of Ukraine in Rivne region. Field studies were conducted in the conditions of the Northwestern Forest-Steppe of Ukraine during 1960–2018 at the stationary field experiments of the Luvic Greyzemic Phaeozems (WRB. 2015) of the Institute of Agriculture of the Western Polissia of NAAS (Ukraine). Laboratory analyses were performed using standard techniques. Observations of climatic processes have allowed us to offer polynomial models that confirm, with high degree of certainty, the steady trend of regional climate change towards warming in the Northwestern Forest Steppe of Ukraine (an average annual temperature R^2 = 0.76; the sum of T >5°C R^2 = 0.91 and the sum T >10°C R^2 = 0.90. Rainfall has declined sharply in the last five years, significantly limiting soil moisture resources. There was a steady tendency towards aridization of the agrolandscape mezoclimate. We cannot say that climate warming has had a significant impact on increasing the nutrient content of soils to contribute to a significant increase in crop yields in the absence of field fertilization. However, crop production of Rivne region (Ukraine), N, P and K application rates have increased periodically over the whole observed period of 1960–2001. There has been a steady upward trend in fertilizer application rates since 2000 and agricultural harvests have been steadily growing together with the warming of the climate zone of the Northwestern Forest Steppe of Ukraine in this period.

1. Introduction

The features of Earth's rapidly changing views on climate change have been analysed in articles (Hnativ, 2016; Polovyy et al., 2021). Climate change is the least studied cause of the dynamics and evolution of the basic component of agroecosystems – the soil, and the prospects for development of the agro-industrial complex (Olesen et al., 2011; White et al., 2011; Shi et al., 2012; Climate…, 2020). It is unknown how changes in soil fertility of agricultural regions of Ukraine will affect processes in the economy and development of society as a whole (Hnativ, 2016; Hnativ and Snintynskyy, 2017). Generally, scientists have recognized (Jouzel et al., 1999) and reflected on numerous graphical models (Fig. 1) that show there have been three distinct cycles of Earth's temperature over the last 250,000 years alone.

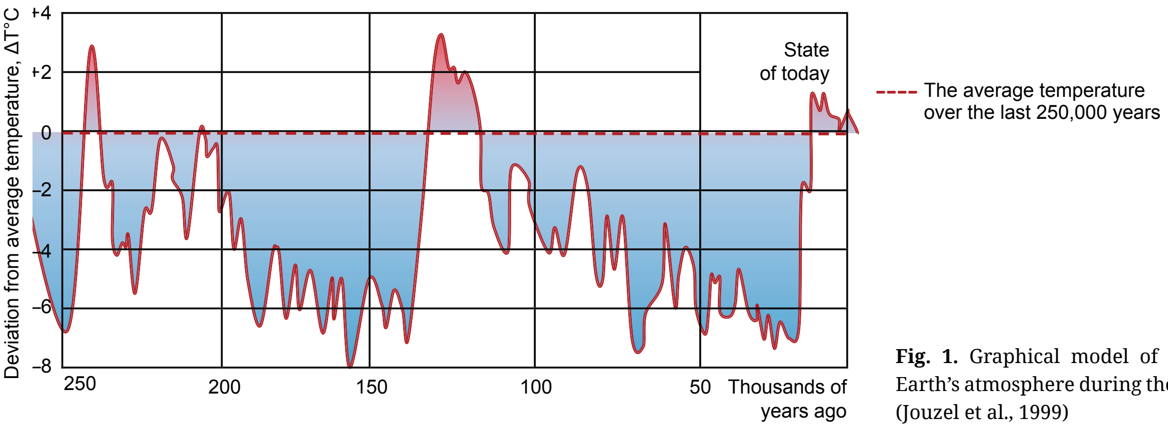


Fig. 1. Graphical model of the temperature of the Earth's atmosphere during the last 400 thousand years (Jouzel et al., 1999)

We have already described a more rapid rise in the temperature of the surface atmosphere in Holocene (Hnativ, 2016) than we observed at the beginning of the 21st century. However, today's industrialized high-efficiency agriculture has never experienced such intense climate change impacts (Harrison et al., 2016; Stevanović et al., 2016; Holman et al., 2017; Blanco et al., 2017). There are neither systematic studies nor reliable predictions regarding the response of soils to surface air temperature rise (Blanco et al., 2017) and change in the hydrological regime of landscape ecosystems (Brouder and Volenec, 2008; Elliott, 2013). Meteofactors directly affect biotic processes in ecosystems, causing the correction of agrochemical processes, which changes the pace of the small biogeochemical cycle. Ultimately, it is unknown how climate fluctuations affect the soil nutrient and humus balance depending on crops grown and their productivity.

It has been investigated that soil formation is directly influenced by overall temperatures and the precipitation to evaporation ratio (Karmakar et al., 2016; Pareek, 2017). Climate warming adds more energy to the decomposition of the soil's soil matrix, increasing the proportion of weathering resistant chemical compounds. This results in loss of fertility and greater dependence on fertilizers for crop yields. By increasing soil warming, the absorption functions of plant roots are activated. Warming can lead to an acceleration of mineralization of nitrogen organic compounds, leading to an increase in the pool of its readily available forms (Pendall et al., 2004; TidĺKera et al., 2016) and to the release of nitrogen into the atmosphere (Bai et al., 2013). As the temperature increases, the colloidal properties and reaction of the soil change, which also affects its nutritional regime. Finally, warming of the soil causes more carbon dioxide emissions and may increase mycorrhizal biomass. As plants' demand for nitrogen (TidĺKera et al., 2016) and phosphorus (MacDonald et al., 2011) will increase simultaneously with increasing carbon assimilation rates, they will transport more photo-assimilates into the root zone and mycorrhizal fungi than needed to meet this increased nutrient requirement.

Scientists report that climate change has significantly affected crop yields in Europe (Moore and Lobell, 2015; Iizumi et al., 2017). In particular, significant change in the yield of corn, oats, and wheat were identified (Elsgaard et al., 2012), cereals production in Norway was evaluated (Korsaeth et al., 2012), and potato yield increases in Scotland since 1960 (Gregory and Marshall, 2012). Scientists argue that climate fluctuations have significant impact not only on growth and development of garden crops (Avolio et al., 2012) but also on invasive pests and pathogens (Caffarra et al., 2012). In Ukraine (Osadchyj and Babichenko, 2012; Boychenko et al., 2016; Tarariko et al., 2016), the agriculture is considered to be the sector most dependent on climatic conditions. To ensure sustainable development of agro-production, a systematic study of the features and trends of change in all components of agro-climatic resources is required (Veremeienko et al., 2016; Polovyy et al., 2021).

The aim of this research was to study the relationship between changes in the climate with the trends in soil processes and crop yields in the Northwestern Forest Steppe of Western Ukraine.

2. Materials and methods

We use paleoclimatology techniques to reconstruct climate change in verbal and graphic models (Jouzel et al., 1999; Schönwiese, 2008; Braconnot et al., 2012; Rapp, 2019). We collected weather data from 1945–2018 from the Rivne State Weather Station (Ukraine).

Calculations of temperatures active for most local field crops (act >5°C) and effective for most local field crops (eff >10°C) were performed according to the formula (Osadchyj and Babichenko, 2012):

$$\Sigma\, t_{act/eff} = (t_m - t_{act/eff}) \cdot n_{act/eff}$$

where: $\Sigma\, t_{act}$ – the sum of active air temperatures for the period with a temperature >5°C, °C;
tm – the average temperature for the period with active temperature >5°C, °C;
t_{act} – 5°C, °C;
n_{act} – the number of days in the period with a temperature >5°C;

where: $\Sigma\, t_{eff}$ – the sum of effective air temperatures for the period with a temperature >10°C, °C;
tm is the average temperature for the period with an effective temperature >10°C, °C;
t_{eff} – >10°C, °C;
n_{eff} – the number of days in a period with a temperature >10°C.

Data on the structure of sown areas and crop yields were selected from the Main Department of Statistics of Ukraine in Rivne region (www.rv.ukrstat.gov.ua).

Field studies were conducted in the conditions of the Northwestern Forest-Steppe of Ukraine (Fig. 2) during 1960–2018 in the stationary field experiments of the Institute of Agriculture of the Western Polissia of the NAAS (Ukraine). The research was conducted on ten field crop rotation (1 field–red clover; 2, 5 and 8 fields – winter wheat; 3 field – sugar beets; 4 field – peas; 6 field – corn for grain; 7 field – potatoes; 9 field – corn for silage; 10 field – spring barley) between 1960–2001. Short crop rotations of six and four crops did not include maize for grain and silage and peas and were practiced from 1985 to 2018.

Mineral fertilizers were applied in the rotation system in the form of ammonia nitrate, potassium chloride and ammophos. Phosphorus-potassium was applied during the principal soil treatment and nitrogenous fertilizers during the pre-cropping treatment. The experiment was conducted on the Luvic Greyzemic Phaeozems (WRB, 2015) with 3.08% of the humus content and 99 mg·kg^{-1} of nitrogen, which was easily hydrolyzed (by Cornfield) and 105 and 71 mg·kg^{-1} of available phosphorus and potassium (by Kirsanov) respectively. The physical, physicochemical properties and texture of these soils is presented in Tables 1 and 2. Laboratory analyses were performed using standard techniques (State Standard..., 2005 and 2015; Klute, 1987).

Fig. 2. The Northwestern Polissya and Northwestern Forest-Steppe of Ukraine and localization of Meteorological Station in Rivne (geographic coordinates: latitude – 48°14'50" N; longitude – 31°45'15" E; height above sea level – 151 m) (https://www.britannica.com/place/Ukraine)

Table 1
Physical and physicochemical properties of Greyic Luvic Phaeozems (1961)

Horizon	Depth cm	Physical properties			Physicochemical properties				
		Particle density	Bulk density	Total porosity %	Humus* %	pH_{KCl}	H^+	TEB	BS %
		g·cm^{-3}					cmol·kg^{-1}		
Ah	0–35	2.64	1.52	42.4	3.08	5.42	2.75	8.71	76.0
Bwth	36–70	2.68	1.42	47.0	1.22	5.54	1.25	10.89	89.7
Bwt	71–130	2.67	1.41	47.2	0.83	5.73	0.68	9.70	93.5
BwCk	131–150	2.73	1.53	44.0	0.48	6.94	0.11	–	–
Ck	>150	–	–	–	–	7.01	–	–	–

* Humus, H^+ – hydrolytic acidity, TEB – total exchangeable base, BS – degree of base saturation

Table 2
Texture of Greyic Luvic Phaeozems (1961)

Horizon	Depth cm	Hygroscopic moisture %	Size of soil particles in mm, quantities in %						Total of particles <0,01 mm %
			Sand		loam			clay	
			1.0–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	<0.001	
Ah	0–35	1.4	1	4	64	9	8	14	31
Bwth	36–70	2.3	2	3	64	10	7	14	31
Bwt	71–130	2.6	1	3	61	7	9	19	35
BwCk	131–150	3.0	1	3	57	4	5	30	39
Ck	>150	1.7	1	3	54	8	7	27	42

Statistical analysis was performed using third degree polynomial regression and COY analysis – Combined-Over-Years (Talbot, 2000).

3. Results and discussion

As previously reported (Polovyi et al., 2021), the Northwestern Forest-Steppe of Ukraine is one of the regions with the most active increase in heat supply. The increase in the average annual air temperature in 2018 reached +1.8°C with the climatic norm for this region +7°C. The increase in the average annual temperature was due to warming in the summer months although the winter was also slightly warmer. We have described the long-term dynamics of the average surface atmosphere monthly temperature Y_t with a third-degree polynomial model: $Y_t = -0.0006x^3 + 0.0287x^2 - 0.2089x + 7.2753$ as a curve which approximates the actual (*x*) course of indicators with high confidence ($R^2 = 0.76$). The calculated dynamics of the effective temperature ($Y_{t>5}$ and $_{t>10}$) of sums >5 and >10°C indicates their steady growth from 1961 to 2018. This is most clearly reflected in the polynomial models of the dependence $Y_{t>5}$ and $_{t>10}$ on the actual indicators (*x*) of the third degree: $Y_5 = -28{,}194x^3 + 297{,}92x^2 - 795{,}17x + 2358$ and $Y_{10} = -23{,}972x^3 + 255{,}83^2 - 691{,}34x + 1375$. The coefficients of approximation to the actual dynamics are respectively $R^2 = 0.91$ and $R^2 = 0.90$. The relative growth of sums >5 and >10°C was respectively 31% and 52%. this sum of effective temperatures >10°C was typical for the Southern (warm) Podillya (Vinnytsia region, Ukraine) before local climate warming. This area extends south to 200–250 km or 4 degrees north latitude.

There is a clear (Polovyy et al., 2021) falling trend in the amount of precipitation during 1945–2018. The amount of precipitation decreased by 29% in 2013–2018 compared to the norm of 569 mm per year. However, the statistical total annual rainfall during the growing season cannot be a self-sufficient criteria for assessing the actual moisture supply for crops during their growth and development (Klute, 1987). To assess the impact of climate change on soil moisture reserves, we compared their dynamics for winter wheat over two different periods: 1986 to 1990 and 2014 to 2018 (Polovyy et al., 2021). In general, processes caused by climate warming and reduced rainfall have significantly cut the supply of moisture for plants in the area of the Northwestern Forest-Steppe of Ukraine. It was stated that with practically the same amount of rainfall, the reserves of productive moisture for winter wheat were two times smaller in the soil layer of 0–100 cm in June-July 2013–2018 than in 1985–1990. Productive moisture is the part of the soil moisture, which is greater than wilting point moisture content, is retained in the soil and is fully available to cultivated plants. This data indicates a gradual aridization of the landscape. As a result from June there is a rapid decline in soil moisture that only begins to be restored in the second half of autumn.

Once we have objectively assessed the changes in hydrothermal resources in the zone of the Northwestern Forest-Steppe of Ukraine, we can proceed to the analysis of soil processes and the impact of their dynamics on crops. The Institute of Agriculture of the Western Polissia of the National Academy of Sciences of Ukraine conducted studies of the effects of fertilizers of different ten-crop rotations on crop yields, product quality and fertility of Luvic Greyzemic Phaeozems (WRB, 2015) for 40 years (1960 to 2001) (Polovyy, 2007). The average humus content in the Ah horizon (0–35 cm) was 3.08% in 1960. If taken as 100% in the control variant (Fig. 3), after 40 years without fertilization this horizon contained 15% (2.62%) less and for optimal fertilization of crops (on average 1 ha of the crop rotation area N72P64K65 +10 t·ha 1) 6% (2.9%) less humus respectively. The soil of the field without fertilizer lost 21 mg·kg^{-1} of easily hydrolyzed nitrogen (by Cornfield) compared to the crop rotation over the four rotation. Unfertilized soil for 40 years lost only 3.5 mg·kg^{-1} of available phosphorus (by Kirsanov – State Standard, 2005), while the introduction of P_{64} + 10 t·ha^{-1} manure together with nitrogen and potassium fertilizers led to an increase from 46.6 to 92.4 mg·kg^{-1}. Four rotations of 10-field crop rotation have caused a significant reduction in available potassium reserves (by Kirsanov – State Standard, 2005).

Removal potassium with yields for 40 years without fertilization resulted in the reduction of its available content in the humus horizon from 77.2 mg·kg^{-1} to 53.1 mg · kg^{-1} of the soil. Application of an average of 1 hectare of crop rotation area K_{65} + 10 t·ha^{-1} with nitrogen and phosphorus fertilizers did not offset the balance and only slightly reduced available potassium resource depletion.

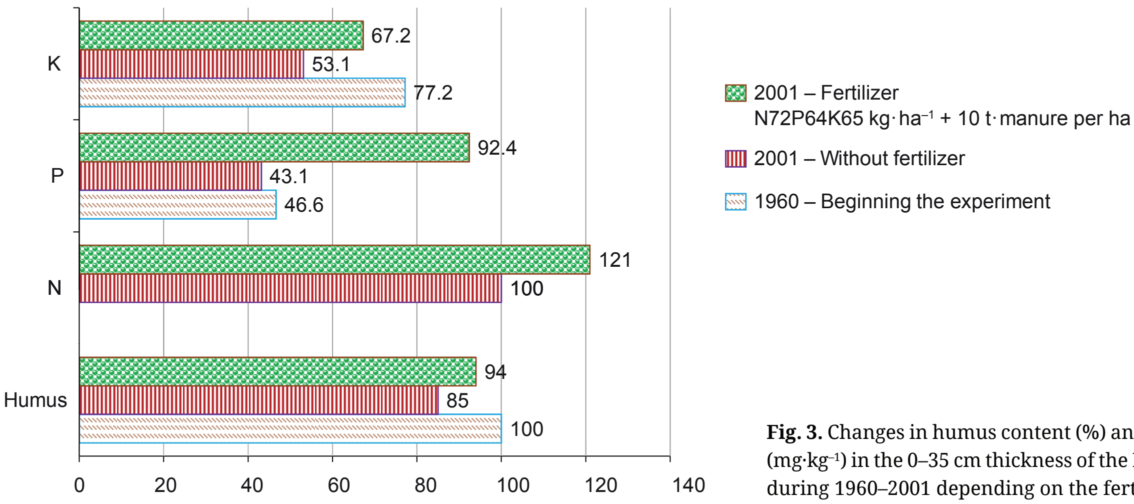


Fig. 3. Changes in humus content (%) and available N, P, and K forms (mg·kg^{-1}) in the 0–35 cm thickness of the Luvic Greyzemic Phaeozems during 1960–2001 depending on the fertilizer (Polovyy, 2007)

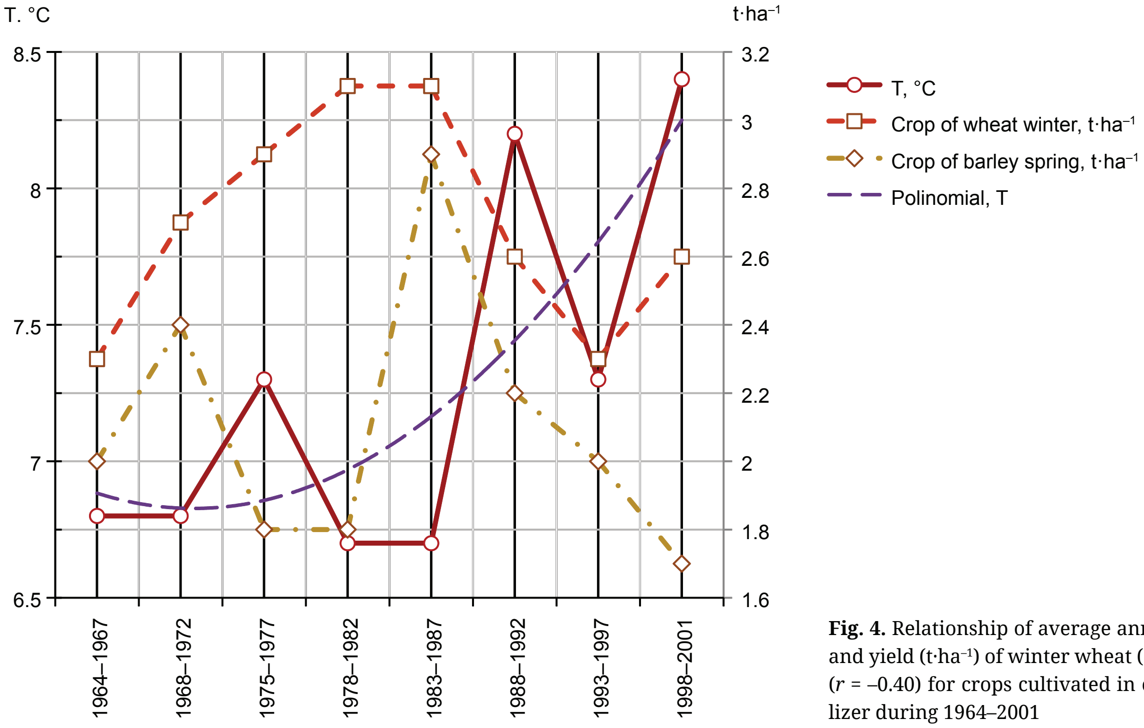


Fig. 4. Relationship of average annual air temperature (T, °C) and yield (t·ha^{-1}) of winter wheat (r = –0.32) and spring barley (r = –0.40) for crops cultivated in crop rotation without fertilizer during 1964–2001

The yield dynamics of winter wheat and spring barley in a crop rotation without fertilizer in the years 1964–2001 was analysed in order to correlate it with the dynamics of climate change (Fig. 4).

The correlation coefficients of medium closeness are r = – 0.32 and r = – 0.40 respectively. The average annual temperature trend line shows a 2.25°C increase in the zone of the Northwestern Forest Steppe of Ukraine in the time period 1964–2001.

For rotated crop cultivation without fertilizer, the increase of the average annual rainfall and yields of winter wheat and spring barley have a weak and medium negative relationship respectively. The correlation coefficients are r = –0.26 and r = –0.62. Note that warming closely correlated positively with the increase in the supply of moisture (r = 0.55) in the analysed region in this period. Therefore detected climate changes did not have a significant impact on soil in the Northwestern Forest Steppe of Ukraine during 1964–2001. These have not influenced chemical, biochemical and microbiological processes so much that they can contribute to a significantly better supply of nitrogen, phosphorus and potassium, and maintain yield growth without fertilizing winter wheat and spring barley. These and other field crops used both the natural nutrient resources of the Luvic Greyzemic Phaeozems and its climate-activated reserves, but reduced their available forms to the levels indicated in Fig. 2 in the version without fertilizer for a total of 40 years. The rapid decline in grain yields began in the second half of the experiment, which lasted for 40 years.

It is important, in our opinion, to summarize the experience of practical application of fertilizers in crop production under the dynamic changes in the climatic conditions of the Northwestern Forest Steppe of Ukraine. Agrochemical indicators of the available phosphorus and potassium (according to Kirsanov – State Standard, 2005) in the soils were obtained from the reports of regional branches of the State Soil Guard (Dolzhenchuk and Krupko, 2015) and the introduction of nitrogen, phosphorus and potassium (State production..., 2019). The graphical model (Fig. 5) reflects the steady increase in available phosphorus and potassium content in arable soils by the average in the Northwestern Forest-Steppe of Ukraine from 1966 to 1995.

The cessation of fertilizer application to the fields due to the stagnation of the agricultural sector from 1990 caused a rapid loss of soils of nutrients up to 1996–2000, which led to a decrease in their number below the level of 1986–1990. In Fig. 5 we see that the stocks of available forms of phosphorus and potassium grew similar to the warming dynamics of the Northwestern Forest Steppe from 1966–1970, but only as long as the amount of nitrogen, phosphorus and potassium introduced with all types of fertilizers declined rapidly. It should be noted that the fertility resource of Luvic Greyzemic Phaeozems is powerful because, due to the practical cessation of fertilizer use during the crisis of agricultural production, a high level of nutrients was maintained for almost five years. Using our research data (Polovyy et al. 2020), we can compare the dynamics of thermal resources in the Northwestern Forest Steppe of Ukraine between 1963 and 2002 with the content dynamics of the available forms of phosphorus and potassium in arable soils.

Grain yield dynamics in Rivne region over 1966–1990 tended to increase (Crop production..., 2019) until fertilizer rates were reduced during the stagnation of agriculture (Fig. 6).

From 2001, farmers have begun to increase fertilization rates (Fig. 7), especially nitrogen, and crop yields grew from 1.9 to 4.7 t·ha^{-1} in 1996–2018 (Fig. 6).

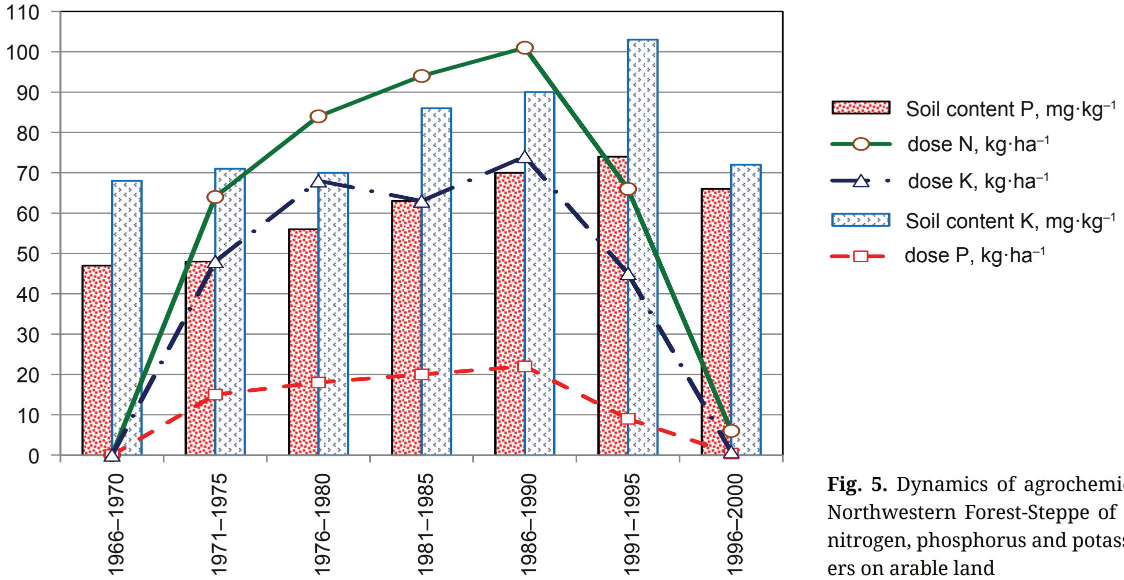


Fig. 5. Dynamics of agrochemical indicators of soils of the Northwestern Forest-Steppe of Ukraine and introduction of nitrogen, phosphorus and potassium with all types of fertilizers on arable land

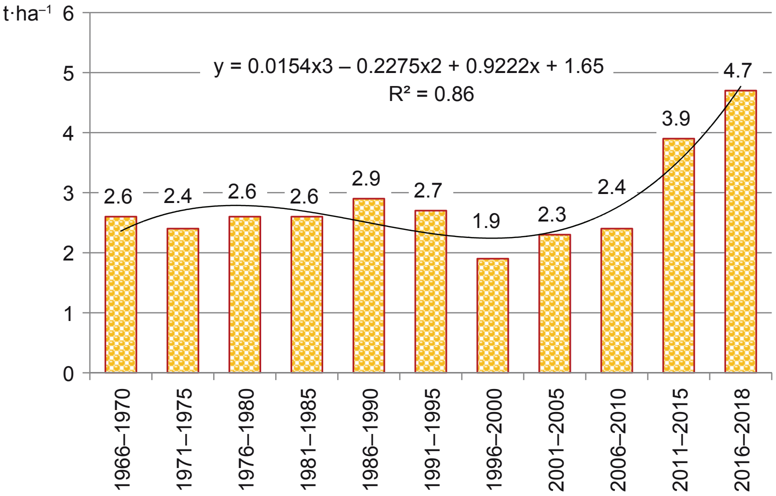


Fig. 6. Average yield of cereal crops in Rivne region (Ukraine) during 1966–2018 (Crop production..., 2019)

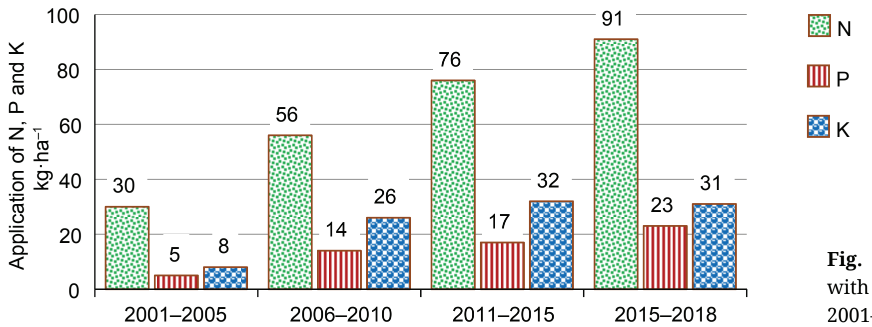
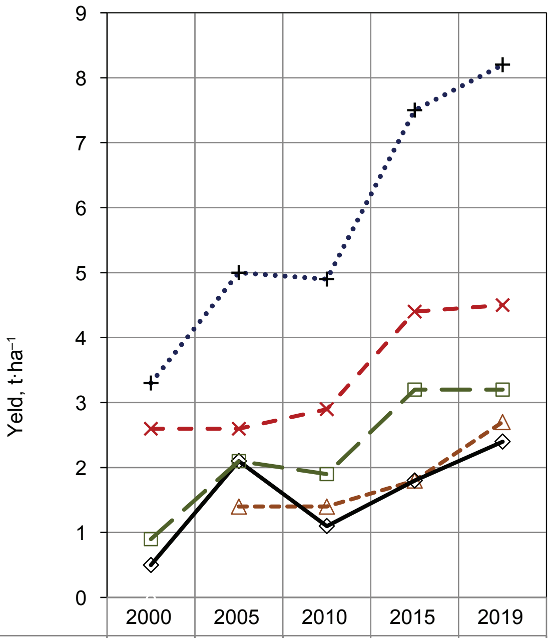


Fig. 7. Application of nitrogen, phosphorus and potassium with mineral fertilizers in Rivne region (Ukraine) during 2001–2018 (Crop production..., 2019)

The rapid increase in the sums of effective temperatures in the area of the Northwestern Forest-Steppe created favourable conditions for the cultivation of thermophilic crops like corn, soybeans, sunflowers and others. The area of their cultivation is growing today. Climate change, coupled with the latest agronomic techniques and breeding offers, ensures the growth of crop production efficiency in Rivne region (Ukraine). Data analysis for 2000–2019 shows a significant increase in the yield of field crops (Fig. 8). During this period, the yield of winter wheat increased from 2.9 to 4.6 t·ha^{-1}, corn to grain – from 4.9 to 8.2 t·ha^{-1}, soybeans – from 1.4 to 2.7 t·ha^{-1}, winter rapeseed – from 2.3 to 3.8 t·ha^{-1}, sunflower – from 1.1 to 2.4 t·ha^{-1}, or 59, 67, 93, 65 and 118% respectively.

Observation of climatic processes confirms the steady trend of regional climate change in the Northwestern Forest-Steppe of Ukraine. Soil warming has improved significantly with increas-



	2000	2005	2010	2015	2019
Maize	3.3	5	4.9	7.5	8.2
Winter wheat	2.6	2.6	2.9	4.4	4.5
Soya	0	1.4	1.4	1.8	2.7
Sunflower	0.5	2.1	1.1	1.8	2.4
Winter rapeseed	0.9	2.1	1.9	3.2	3.2

Fig. 8. Dynamics of yield of basic crops in farms in Rivne region (Ukraine), (Crop production..., 2019)

ing air temperature, but annual rainfall has declined sharply over the past five years, significantly limiting soil moisture. Thus, there was a steady trend towards aridization of the mesoclimate of agricultural landscapes of the Northwestern Forest-Steppe of Ukraine.

4. Conclusion

It was not found that global warming had a significant effect on increasing the nutrient content of the soil, which further contributed to a significant increase in yields due to insufficient fertilization.

From 1960 to 1990, N, P and K application rates only increased in the Rivne region (Ukraine) to 100 kg·ha^{-1} of nitrogen, 22 kg·ha^{-1} of phosphorus and 74 kg·ha^{-1} of potassium. When a steady trend of increasing fertilizer application rates in the Rivne region in combination with the warming of the climatic zone of the Northwestern Forest-Steppe of Ukraine resumed in 2000, the average cereal yield steadily increased from 1.9 to 4.7 t·ha^{-1}. However, over the last decade, we have seen a downward trend in rainfall, which has reduced the effectiveness of fertilizers used for growing crops.

Further long-term studies of the dynamics of agrochemical parameters in natural (virgin) and cultivated soils are needed to determine the direct impact of mesoclimate aridization on soil processes and fertilizer efficiency in the Northwestern Forest-Steppe of Ukraine.

References

Avolio, E., Orlandi, F., Bellecci, C., Fornaciar, M. and Federico, S., 2012. Assessment of the impact of climate change on the olive flowering in Calabria (southern Italy). Theoretical and Applied Climatology 107 (3–4), 531–540. https://doi.org/10.1007/S00704-011-0500-2

Bai, E., Li, S., Xu, W., Li, W., Dai, W. and Jiang, P., 2013. A meta-analysis of experimental warming effects on terrestrial nitrogen pools and dynamics. New Phytologist 199, 441–451. https://doi.org/10.1111/nph.12252

Blanco, M., Ramos, F., Van Doorslaer, B., Martínez, P., Fumagalli, D., Ceglar, A. and Fernández, F.J., 2017. Climate change impacts on EU agriculture: A regionalized perspective taking into account market-driven adjustments. Agricultural Systems 156, 52–66. https://doi.org/10.1016/j.agsy.2017.05.013

Boychenko, S., Voloshchuk, V., Movchan, Y., Serdjuchenko, N., Tkachenko, V., Tyshchenko, O. and Savchenko, S., 2016. Features of climate change on Ukraine: scenarios, consequences for nature and agroecosystems. Proceedings of the National Aviation University 69.4, 96–113. https://doi.org/10.18372/2306-1472.69.11061

Braconnot, P., Harrison, S.P., Kageyama, M., Bartlein, P.J., Masson-Delmotte, V., Abe-Ouchi, A., Otto-Bliesner, B. and Zhao, Y., 2012. Evaluation of climate models using palaeoclimatic data. Nature Climate Change 2, 417–424. doi.org/10.1038/nclimate1456

Brouder S.M. and Volenec J.J., 2008. Impact of climate change on crop nutrient and water use efficiencies. Physiologia Plantarum 133, 705–724. https://doi.org/10.1111/j.1399-3054.2008.01136.x

Caffarra, A., Rinaldi, M., Vittorio, E., Rossi, V. and Pertot, I., 2012. Modelling the impact of climate change on the interaction between grapevine and its pests and pathogens: European grapevine moth and powdery mildew. Agriculture, Ecosystems and Environment 148, 89–101. https://doi.org/10.1016/j. agee.2011.11.017

Climate Change and Land. 2020. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Summary for Policymakers. 2020. Intergovernmental Panel on Climate Change. 36 p. Available at: https://climatechange.insightconferences.com/

Crop production of Ukraine, 2019. Statistical yearbook. 2018. State Statistics Service of Ukraine, 2019. Available at: http://www.ukrstat.gov.ua/druk/publicat/kat_u/2019/zb/04/zb_rosl_2018.pdf

Dolzhenchuk, V.I. and Krupko, G.D., 2015. Monitoring of land degradation and desertification processes in Rivne region. Agro-ecological journal 1, 67–73. Available at: http://irbis-nbuv.gov.ua/cgi-bin/irbis_nbuv/cgiirbis_64.exe?C21COM=2and I21DBN=UJRNand P21DBN=UJRNand IMAGE_FILE_DOWNLOAD=1and Image_file_name=PDF/agrog_2015_1_10.pdf

Elliott, J., 2013. Constraints and potentials of future irrigation water availability on agricultural production under climate change. PNAS first published. December 16, 2013. https://doi.org/10.1073/pnas.1222474110

Elsgaard, L., Børgesen, C.D., Olesen, J.E., Siebert, S., Ewert, F., Peltonen-Sainio, P., Rötter, R.P. and Selvage, A.O., 2012. Shifts in comparative advantages for maize, oat and wheat cropping under climate change in Europe. Food Additives and Contaminants: Part A 29(10), 1514–1526. https://doi.org/10.1080/19440049.2012.700953

Gregory, P.J. and Marshall, B., 2012. Attribution of climate change: A methodology to estimate the potential contribution to increases in potato yield in Scotland since 1960. Global Change Biology 18(4), 1372–1388. https://doi.org/10.1111/j.1365-2486.2011.02601.x

Harrison, M.T., Cullen, B.R. and Rawnsley, R.P., 2016. Modelling the sensitivity of agricultural systems to climate change and extreme climatic events. Agricultural Systems 148, 135–148. https://doi.org/10.1016/j.agsy.2016.07.006

Hnativ, P., 2016. Climate dynamics in the late Holocene and genesis of ecosystems of ukrainian society (from the collapse of the Roman Empire to the formation of Cossack Ukraine). Proceedings of the Scientific Shevchenko Society. Ecological collection 46, 46–69. Available at: http://nbuv.gov.ua/UJRN/pntsh_ek_2016_46_7

Hnativ, P.S. and Snintynskyy, V.V., 2017. Ekosystemy i systemnyy analiz (Book: Ecosystems and System Analysis). Lviv: Kolir PRO. 416 p. (in Ukrainian).

Holman, I.P., Brownb, C., Janesa, V. and Sandarsa, D., 2017. Can we be certain about future land use change in Europe? A multi-scenario, integrated-assessment analysis. Agricultural Systems 151, 126–135. https://doi.org/10.1016/j.agsy.2016.12.001

Iizumi, T., Furuya, J., Shen, Z., Kim, W., Okada, M., Fujimori, S., Hasegawa, T. and Nishimori, M., 2017. Responses of crop yield growth to global temperature and socioeconomic changes. Scientific Reports 7(1), 7800. https://doi.org/10.1038/s41598-017-08214–4

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Jouzel, J., Barkov, N.I., Basile, I., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M. and Lipenkov, V.Y., 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core. Antarctica. Nature 399, 429–436. https://doi.org/10.1038/20859

Karmakar, R., Das, I., Dutta, D. and Rakshit, A., 2016. Potential Effects of Climate Change on Soil Properties: A Review. Science International 4(2), 51–73. https://doi.org/10.17311/sciintl.2016.51.73

Korsaeth, A., Jacobsen, A.Z., Roer, A.G., Henriksen, T.M., Sonesson, U., Bonesmo, H., Skjelvåg, A.O. and Strømman, A.H., 2012. Environmental life cycle assessment of cereal and bread production in Norway. Acta Agriculturae Scandinavica, Section A – Animal Science. 62, 242–253. https://doi.org/10.1080/09064702.2013.783619

MacDonald, G.K., Bennett, E.M., Potter, P.A. and Ramankutty, N., 2011. Agronomic Phosphorus Imbalances Across the World's Croplands. PNAS, February 15, 2011 108(7), 3086–3091. https://doi.org/10.1073/pnas.1010808108

Memorized agroecosystems. Estimation and rational use of agro-resource potential of Ukraine (irrigation and drainage areas). 2017. Edited by: M.I. Romashchenka, Yu. O.Tarariko. K.; Nizhyn: Publisher PP Lysenko M.M. 696 s. (in Ukrainian).

Moore, F.C. and Lobell, D.B., 2015. The fingerprint of climate trends on European crop yields. Proceedings of the National Academy of Sciences of the United States of America 112(9), 2670–2675. https://doi.org/10.1073/pnas.1409606112

Olesen, J.E., Trnkab, M., Kersebaumc, K.C., Skjelvågd, A.O., Seguine, B., Peltonen-Sainiof, P., Rossig, F., Kozyrah, J. and Micalei, F., 2011. Impacts and adaptation of European crop production systems to climate change. European Journal of Agronomy 34(2), 96–112. https://doi.org/10.1016/j.eja.2010.11.003

Osadchyj, V. and Babichenko, V., 2012. Dynamics of adverse meteorological phenomena in Ukraine. Ukrainian Geographical Journal 4: 8–14. Available at: https://ukrgeojournal.org.ua/en/node/345

Pareek, N., 2017. Climate change impact on soils: adaptation and mitigation. MOJ Ecology & Environmental Sciences 2(3), 136–139. https://doi.org/10.15406/mojes.2017.02.00026

Pendal, E., Bridgham, S., Hanson, P.J., Hungate, B., Kicklighter, D.W., Johnson, D.W., Law, B.E., Luo, Y., Patrick, J., Maria, M., Michael, O., Ryan, G. and Wan S., 2004. Below-ground process responses to elevated CO_2 and temperature: a discussion of observations, measurement methods, and models. New Phytologist 162, 311–322. https://doi.org/10.1111/j.1469-8137.2004.01053.x

Polovyy, V., Hnativ, P., Balkovskyy, V., Ivaniuk, V., Lahush, N., Shestak, V., Szulc, W., Rutkowska, B., Lukashchuk, L., Lukyanik, M., Lopotych, N., 2021. The influence of climate changes on crop yields in Western Ukraine. Ukrainian Journal of Ecology 11(1), 384–390. https://doi.org/10.15421/2021_56

Polovyy, V.M., 2007. Optimization of fertilizer systems in modern agriculture: monogr. Rivne: Volyn oberehy, 2007. 320 c. (in Ukrainian).

Rapp, D., 2019. Ice Core Data. In: Ice Ages and Interglacials. Springer. Chapter First Online. https://doi.org/10.1007/978-3-030-10466-5_4

Schönwiese, C.D., 2008. Klimatologie. Ulmer (UTB), 3. Aufl., Stuttgart, 472 s.

Shi, X., Zhang, W., Huang, B. and Yu, D., 2012. Soil Information Acquisition and Monitoring in the Anthropocene of a Changing World. Soil Horizons 3.2, 16–19. doi.org:10.2136/sh12-01-0001.

Klute, A. (Ed.), 1987. Methods of Soil Analysis, Part 1 (Physical and Mineralogical Methods). Agronomy Monograph Nr. 9, Second Edition. Verlag Amer. Soc. Agron. und Soil Sci. Soc. Amer., Madison (Wisconsin), USA, 1188 S. https://doi.org/10.1002/jpln.19871500519

State Standard of Ukraine 4405: 2005. Soil quality. Determination of available phosphorus and potassium compounds by the Kirsanov method in the modification of the NSC IGA.

State Standard of Ukraine 7863: 2015. Soil quality. Determination of light hydrolysis nitrogen by the Cornfield method.

Stevanović, M., Popp, A.A., Lotze-Campen, H., Dietrich, J.Ph., Müller, Ch., Bonsch, M., Schmitz, Ch., Bodirsky, B.L., Humpenöder, F. and Weindl, I., 2016. The impact of high-end climate change on agricultural welfare. Science Advances 2.8, e1501452. https://doi.org/10.1126/sciadv.1501452

Tarariko, Yu.O., Saidak, R.V. and Soroka, Yu.V., 2016. Prospects for the use of the soils of humic zone of Ukraine in climate change. Visnyk ahrarnoi nauky 7, 55–59. (in Ukrainian)

Tabolt, M., 2000. The Combined-Over-Years Distinctness and Uniformity criteria. Technical Working Party on Automation and Computer Programs-UPOV, TWC/18/10, Genewa.

Tidåkera, P., Bergkvist, G., Bolinder, M., Bolinder, M., Eckersten, H., Johnsson, H., Kätterer, T. and Weih, M., 2016. Estimating the environmental footprint of barley with improved nitrogen uptake efficiency – a Swedish scenario study. European Journal of Agronomy 80, 45–54. https://doi.org/10.1016/j.eja.2016.06.013

Veremeienko, S.I., Polovyi, V.M. and Furmanets, O.A., 2016. The evolution of dark gray soils during prolonged agricultural use. Monograph. Rivne, Kamianets-Podilskyi: TOV «Drukarnia «Ruta», 224 s. (in Ukrainian)

White, J.W., Hoogenboomb, G., Kimball, B.A. and Walla, G.W., 2011. Methodologies for simulating impacts of climate change on crop production. Field Crops Research 124.3, 357–368. https://doi.org/10.1016/j.fcr.2011.07.001