

# NATIONAL FEATURES OF THE NITRATE DIRECTIVE IMPLEMENTATION IN AGRICULTURAL PRACTICE

M.M. Miroshnychenko<sup>1,2</sup>, A.V. Revtie-Uvarova<sup>1</sup>,  
Ye.Yu. Hladkikh<sup>1</sup>, T.V. Shevchenko<sup>2</sup>

<sup>1</sup>The National Scientific Center “O. N. Sokolovsky Institute  
for Soil Science and Agrochemistry Research”,  
4, Mykhail Semenko Str., Kharkiv, 61024, Ukraine

<sup>2</sup>The National Academy of Agrarian Sciences of Ukraine,  
9, Mykhailo Omelianovych-Pavlenko Str., Kyiv, 01010, Ukraine

E-mail: [ecosoil@meta.ua](mailto:ecosoil@meta.ua), [alina\\_rev@meta.ua](mailto:alina_rev@meta.ua), [ye.hladkikh@ukr.net](mailto:ye.hladkikh@ukr.net), [nova\\_naan@ukr.net](mailto:nova_naan@ukr.net)

ORCID: <https://orcid.org/0000-0003-2830-5933>,

<https://orcid.org/0000-0002-6838-5440>,

<https://orcid.org/0000-0002-4852-0502>,

<https://orcid.org/0000-0001-9488-0325>

Received November, 15, 2025; revised March, 16, 2026; accepted April, 22, 2026

**Aim.** To substantiate the approach towards the identification of zones, vulnerable to nitrate accumulation, based on the data of mineral nitrogen content in soil according to the requirements of the Nitrate Directive. **Methods.** The study was conducted on arable soils of humus-accumulative genesis on six land plots in the Forest-Steppe of Ukraine with the rate of applying nitrogen-containing fertilizers from 0 to 170 kg/ha. The content of mineral nitrogen ( $N_{\min}$ ), nitrates and productive moisture reserves was determined layer-wise down to the depth of 120 cm, in dynamics during the vegetative periods of 2021, 2024, and 2025. Crops: grain corn, winter wheat, spring barley, oil flax. **Results.** A considerable variability in the content of  $N_{\min}$  and nitrates proper was determined in soil depending on terms, ways, and norms of applying nitrogen-containing fertilizers. The maximal concentrations were observed in the arable soil layer immediately after the application of nitrogen fertilizers, but these parameters gradually decreased with time and depth. In June–July, the highest accumulation of nitrates in deep soil layers was noted when, at the norm of the application of fertilizers of over  $N_{100}$ , the content of nitric nitrogen at the depth from 80 to 120 cm was from 15.6 to 35.8 mg/kg. The accumulation of nitrates in deep layers of soil decreases in the course of the vegetation period, and at the time of harvesting, the content of nitric nitrogen at the depth of 80–120 cm did not exceed 10 mg/kg in a year with normal moisturization conditions and 4 mg/kg in a dry year. At the norm of applying fertilizers up to 100 kg/ha, the accumulation of  $N_{\min}$  and nitrates in deep soil layers is minimal. **Conclusions.** The use of  $N_{\min}$  as an indicator corresponds to the requirements of the Nitrate Directive regarding the identification of zones, vulnerable to the accumulation of nitrates. It is reasonable to take measurements after harvesting the crops. The application of nitrogen-containing fertilizers for the crops of rotations on arable soils of the humus-accumulative genesis in the plains of Ukraine with non-flushing or periodically flushing type of the water regime at the norm, not exceeding 100 kg/ha, does not pose any threat of leaching mineral nitrogen and its nitrate forms from soil and further pollution of the underground waters.

**Keywords:** nitrates, mineral nitrogen, migration, temporal dynamics, chornozem.

**DOI:** <https://doi.org/10.15407/agrisp13.01.003>

## INTRODUCTION

The introduction of the EU Nitrate Directive is one of the urgent tasks for the European integration of the Ukrainian agrarian sector which requires executive

decisions at the level of specific land tenures, aimed at sustainable nitrogen management in agroecosystems (San Martin, 2020; Romero et al., 2024; Xu et al., 2025). The complexity of the solution for this issue

is conditioned by the different impact of nitrogen in the agroecosystems: on the one hand, it has an exclusive role in nurturing plants and ensuring higher yields (Sandhu et al., 2021), and on the other — non-productive losses of this element may cause a cascade of negative changes in the environment (Galloway et al., 2013). The degree of the manifestation of positive or negative effect characterizes nitrogen management as somewhat “unpredictable”, since it depends on a number of soil, geomorphological, and weather-climatic specificities of the territory as well as organizational and industrial conditions (Galloway et al., 2013; Kant et al., 2011).

According to the data of the International Fertilizer Association (IFA), starting with 1980s and until nowadays, there has been a considerable imbalance in NPK in the composition of fertilizers in favor of nitrogen, which takes 58% from the total global consumption (which is 115 million of metric tons, N) (Fertilizer Consumption — Historical Trends by Country or Region, 2023). Ukraine has even greater imbalance — nitrogen takes about 70%, and the ratio of N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O in the structure of the applied fertilizers changed from 1:0.71:0.66 in 1990 to 1:0.22:0.20 in 2023 (Agriculture, forestry and fisheries of Ukraine. Application of mineral and organic fertilizers, pesticides (1990–2023)). Excessive domination of nitrogen in the fertilization systems may lead to its increased losses beyond the limits of the soil profile (Li et al., 2019). To prevent negative consequences of the excessive or inappropriate application of nitrogen-containing fertilizers, in 1991, the Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources (hereinafter — the Nitrate Directive) was adopted (Council Directive 91/676/EEC of 12 December 1991). The total algorithm of implementing the Nitrate Directive into the national legislation envisages obligatory monitoring of the quality of waters to determine the degree of pollution with nitrogen or potential risk of such pollution. The criteria of pollution identification are the excessive concentration of nitrates in water of over 50 mg/l (or 11.3 mg N/cdm) and the availability of features of the eutrophication process in water bodies. Critically relevant is objective determination of territories with nitrogen losses and their identification as zones, vulnerable to nitrate accumulation (Council Directive 91/676/EEC of 12 December 1991; Report from the commission to the council and the European parlia-

ment..., 2021). If the territory is declared to be such a zone, codes of proper agricultural practice are developed for it and programs/plans of actions, obligatory for implementation, are introduced. To estimate the efficiency of the implemented measures, every four years, the member states report to the European Commission about the results of the monitoring, the evaluation of the impact of the Action plan on the quality of water and agricultural practice, review of the zones and Action plans, and the estimation of further tendencies (Council Directive 91/676/EEC of 12 December 1991).

In Ukraine, the process of implementing the Nitrate Directive takes place gradually, with the involvement of specialists from different areas to form interdisciplinary working groups. In 2021, the national legislation was introduced the Methodology for determining zones vulnerable to the accumulation of nitrates (Methodology for determining zones vulnerable to (accumulation of) nitrates..., 2021) and the Rules for ensuring soil fertility and the use of certain agrochemicals (Rules for ensuring soil fertility and the use of certain agrochemicals..., 2021) (the analogue of the code of proper agricultural practice). At the same time, public discussion of these documents revealed the concern of domestic agroproducers regarding excessive limitations on the introduction of fertilizers. A key question is the identification of territories on which the requirements of the Nitrate Directive are to be imposed, taking into consideration the diversity of soil and climatic conditions of Ukraine, local specificities of geomorphology and hydrology, the technologies of cultivating crops, etc. The objective consideration of this issue requires obtaining and summarizing numerous data about the migration of nitric nitrogen under various natural and economic conditions. This article systematizes the results of experimental research of the authors, obtained in the course of five recent years in permanent and temporary field experiments and industrial conditions.

**The aim of the study** — scientific substantiation of the differentiated approach towards the identification of territories as zones vulnerable to the accumulation of nitrates for the implementation of the requirements of the Nitrate Directive.

## MATERIALS AND METHODS

The investigation of the risks of nitrogen losses from arable soils was conducted in 2021 (locations 1–4) and 2024–2025 (locations 5–6). The change of

the places to conduct the studies was conditioned by the beginning of the full-scale aggression of the Russian Federation; however, it allowed for covering a larger geographic area of observations.

*Location 1:* A permanent field experiment “Agroecological monitoring” in the territory of the SE “Experimental Farm Hrakivske” of the NRC “ISSAR named after O. N. Sokolovsky” (Doslidne village, Chuhuiv district, Kharkiv region, geographical coordinates — 49.726528° N, 36.923328° E), the total area of 7.0 ha (two fields of 3.5 ha), where the grain-hoed crop rotation was implemented. The experiment territory covers an even drainage-free plot within a flat terrace of the Siverskyi Donets river, where the depth of the location of underground waters is over 10 m. The soil is typical chernozem on loess-like clay, in terms of the granulometric composition it is heavy loamy, and contains 46.7% particles under 0.01 mm.

The system of mineral fertilization in this experiment included the following variants:

- cultivation of winter wheat (Bogdana variety):
  - control — no fertilizers;
  - $N_{75}P_{55}K_{45}$  —  $N_{45}$  prior to pre-sowing soil treatment +  $N_{30}$  for fertilization;
  - $N_{150}P_{110}K_{90}$  —  $N_{90}$  prior to pre-sowing soil treatment +  $N_{60}$  for fertilization;
- cultivation of grain corn (Adevei hybrid):
  - control — no fertilizers;
  - $N_{90}P_{60}K_{45}$  — prior to spring tilling;
  - $N_{180}P_{120}K_{90}$  — prior to spring tilling.

Soil samples were taken every 20 cm at the depth of 100 cm under winter wheat on April 28, under corn — on June 14. The applied mineral fertilizers — ammophos (10:46), ammonia nitrate (34.5%), urea (46%), potassium chloride (60%).

*Location 2:* The industrial corn field of ALLC “Druzhba-Nova” in Romny district of the Sumy region (geographical coordinates — 50.897185° N, 33.510034° E), with the area of 142 ha, where the grain-hoed crop rotation was implemented. The territory of the field is a flat terrain with the height above the sea of 160 m, where the depth of the location of underground waters is over 5 m. The soil is meadow-chernozem on loess-like clay, in terms of the granulometric composition it is heavy loamy and

contains 52.8% particles under 0.01 mm. The norm of applying  $N_{134}$ : pre-sowing application of  $N_{18.9}$  (granulated ammonium sulfate) and  $N_{70.4}$  (UAN-32) + fertilization with  $N_{44.8}$  (UAN-28).

*Location 3:* The industrial corn field of ALLC “Druzhba-Nova” in Nizhyn district of the Chernihiv region (geographical coordinates — 51.122321° N, 31.996897° E), with the area of 310 ha, where the grain-hoed crop rotation was implemented. The territory of the field is a flat terrain with the height above the sea of 130 m, where the depth of the location of underground waters is over 10 m. The soil is dark grey podzolic on loess-like clay, in terms of the granulometric composition it is light loamy and contains 21.5% particles under 0.01 mm. The norm of applying  $N_{119}$ : pre-sowing application of  $N_{18.9}$  (granulated ammonium sulfate) and  $N_{60.8}$  (UAN-32) + fertilization with  $N_{39.2}$  (UAN-32).

*Location 4:* Scientific experimental field ALLC “Druzhba-Nova” (Varva district of the Chernihiv region, geographical coordinates — 50.437705° N, 32.684625° E), with the total area of 444 ha. The territory of the experimental field is a flat terrain with a low slope and the height above the sea of 170 m, where the depth of the location of underground waters is over 10 m. The soil is typical chernozem on loess-like clay, in terms of the granulometric composition it is light loamy and contains 28.3% particles under 0.01 mm. The cultivated crop is grain corn.

The norms of applying nitrogen-containing fertilizers:

- $N_{16}$  (in the composition of liquid complex fertilizers);
- $N_{100}$  (including  $N_{21}S_{24}$  in the composition of 100 kg/ha ammonium sulfate)
- $N_{120}$  (including  $N_{21}S_{24}$  in the composition of 100 kg/ha ammonium sulfate)
- $N_{140}$  (including  $N_{21}S_{24}$  in the composition of 100 kg/ha ammonium sulfate)
- $N_{155}$  (including  $N_{21}S_{24}$  in the composition of 100 kg/ha ammonium sulfate)
- $N_{170}$  (including  $N_{21}S_{24}$  in the composition of 100 kg/ha ammonium sulfate).

In locations 2–4, the soil samples were taken every 20 cm from the depth of 0–120 cm with the interval of 20–30 days.

*Location 5:* A short-term field experiment in the territory of the SE “Experimental Farm Hrakivske”

of the NRC “ISSAR named after O. N. Sokolovsky” (Kharkiv district of the Kharkiv region, geographical coordinates — 49°58'7.75"N; 36°1'27.61"E) with the total area of 4.2 ha and the grain-hoed crop rotation (crop rotation: winter wheat, sunflower, grain corn, soy (in 2025, oil flax was grown instead of soy), buckwheat). The experimental territory covers the flattened undulating dividing surface, adjusted to the flat loess terrain with poor drainage. Soil waters lie deeper than 8–10 m, the soil water regime is of periodically flushing type. The experimental soil is podzolic chernozem on loess-like clay, in terms of the granulometric composition it is heavy loamy and contains 51.1% particles under 0.01 mm. In 2024, grain corn was cultivated, in 2025 — oil flax, for which four levels of nitrogen fertilization ( $N_0$ ,  $N_{60}$ ,  $N_{100}$  and  $N_{120}$  kg/ha) were applied with stable doses of phosphorus and potassium (60 kg/ha each) during the pre-sowing tilling.

**Location 6:** A short-term field experiment in the territory of the “O.V. Panasenko” farm (Valky district of the Kharkiv region, geographical coordinates — 49°51'13.34"N; 35°37'33.19"E) with the total area of 170 ha and the grain-hoed crop rotation (crop rotation: winter wheat, grain corn, soy, barley, sunflower). The experiment covers flattened undulating territory within flat interfluvial terrace with poor drainage, where the depth of underground waters exceeds 6–8 m, the soil water regime is of periodically flushing

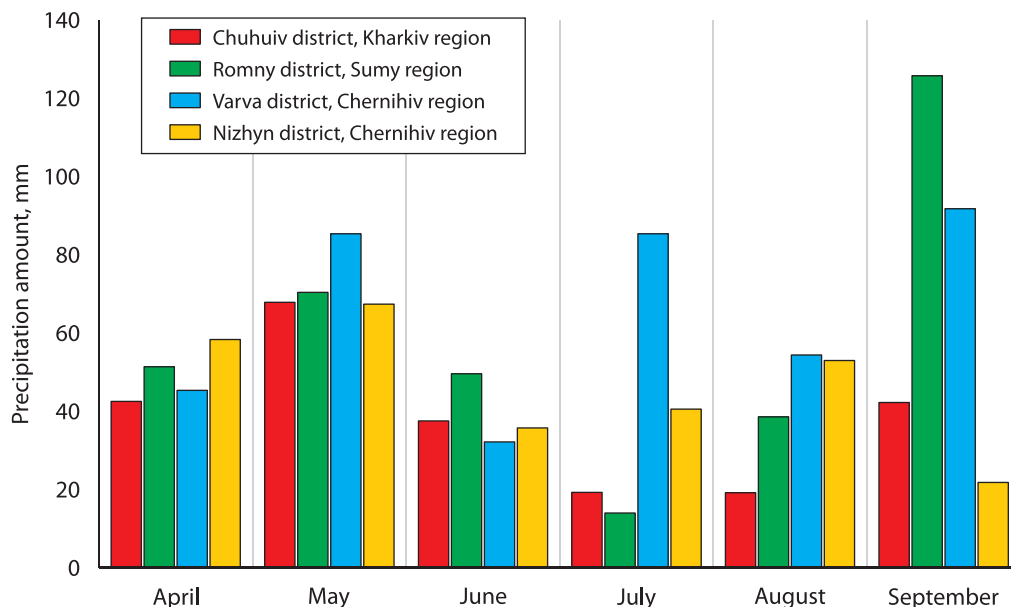
type. The experimental soil is podzolic chernozem on loess-like clay, in terms of the granulometric composition it is medium loamy and contains 38.0% particles under 0.01 mm. In 2024, barley was grown, during the pre-sowing tilling, three levels of nitrogen fertilization were applied ( $N_0$ ,  $N_{60}$ , and  $N_{120}$  kg/ha).

In locations 5–6, the soil samples were taken down to the depth of 100 cm every 20 cm in four periods (May, June, July, early September) in 2024 and in three periods (early June and July, late July) in 2025.

**Hydrothermal conditions.** The climate in the territory of conducting the studies, which belongs to the Left-Bank Forest-Steppe of Ukraine, is moderately continental, where the precipitation amount decreases and the temperature increases from the northern West to the southern East.

The distribution of the precipitation amount in April–September of the study period in locations 1–4 is presented in **Fig. 1**. In 2021, higher air temperature was registered in the territory of Location 1, amounting to 17.8°C on average in April–September, while in locations 2–4, it fluctuated within 16.2–16.9°C.

The hydrothermal conditions of the study year conditioned the corresponding dynamics of the productive moisture reserves (PMR) in soil. Satisfactory PMR were registered in April–June in location 1 both in the 0–20 cm soil layer and in the 0–100 cm



**Fig. 1.** The precipitation amount in April–September in the territory of conducting the study

soil layer under winter wheat, amounting to 26.0–33.6 mm and 111.1–145.6 mm, respectively. Starting with July, the PMR decreased considerably to the unsatisfactory level and their practical absence. In locations 2–4, the highest PMR in the 0–20 cm layer were observed in late May in location 2 after the application of N<sub>134</sub> (satisfactory level), whereas

in other locations, the levels were unsatisfactory and amounted to less than 20 mm (**Table 1**). A similar tendency was notable for the one-meter-deep soil layer. There were practically no PMR from July till September or they were very scarce.

The hydrothermal conditions during the vegetation periods in 2024–2025 were very different (**Table 2**).

**Table 1.** The productive moisture reserves in soil, locations 2–4

Date of soil sampling	Soil layer, cm	Productive moisture reserves, mm						
		Location 2	Location 3	Location 4				
		N <sub>134</sub>	N <sub>119</sub>	N <sub>16</sub>	N <sub>100</sub>	N <sub>140</sub>	N <sub>155</sub>	N <sub>170</sub>
25.05 locations 2 and 3; 27.05 location 4;	0–20	27.1	9.2	8.4	9.2	9.5	13.5	9.7
	20–40	22.7	3.5	10.4	10.2	10.3	14.0	13.3
	40–60	26.0	5.5	8.3	10.7	8.8	15.8	10.5
	60–80	20.5	5.7	6.5	9.4	6.9	17.3	9.0
	80–100	19.4	4.8	3.7	8.6	3.6	9.1	8.0
	0–100	115.7	28.7	37.3	48.1	39.1	69.6	50.4
17.06 locations 2 and 3; 22.06 location 4	0–20	16.3	0.4	9.7	11.7	15.6	11.7	8.4
	20–40	16.7	1.5	13.9	11.7	12.1	10.3	8.6
	40–60	19.6	2.6	18.0	14.7	13.2	12.1	7.9
	60–80	16.9	4.1	9.6	11.4	12.1	10.0	9.3
	80–100	16.2	4.3	12.5	11.9	12.8	12.1	10.0
	0–100	85.6	13.1	63.1	61.3	65.8	56.2	44.2
08.07 locations 2 and 3; 14.07 location 4	0–100	26.8	1.1	0.0	0.0	0.0	0.0	0.7
29.07 locations 2 and 3; 27.07 location 4	0–100	1.6	0.0	0.0	0.0	0.0	0.0	0.0
08.09 locations 2 and 3; 06.09 location 4	0–100	13.4	21.3	0.0	0.0	0.0	0.0	0.0

**Table 2.** Weather and climate conditions in the study years in locations 5–6

Months	Average air temperature, °C			Optimal precipitation amount, mm		
	2024	2025	Average perennial	2024	2025	Average perennial
March	4.3	5.3	–1.9	18.6	34.3	44
April	14.5	9.5	7.1	15.6	14.5	44
May	15.4	14	15.2	21.6	79.5	54
June	21.2	18.1	18.4	58.5	47.5	74
July	24.1	22.5	21.2	4.6	96.7	71
August	21.2	18.3	19.8	13.2	61.4	57
March–August	17.0	14.6	13.5	132.1	333.9	382.0

In the abnormally dry 2024, the air temperature exceeded the average perennial data 1.3 times, and the total precipitation amount was 65% lower than the norm. In 2025, the precipitation amount either somewhat exceeded or was at the level of perennial data (except for April) practically each month, and the temperature indices almost did not differ from the average perennial values.

In 2024, in the experimental plots of locations 5–6, the abnormally low amount of precipitation conditioned the formation of very poor PMR, especially in July–September, when the residues of productive moisture were present only in deep soil layers

(**Table 3**). In 2025, a considerably higher precipitation amount promoted the accumulation of PMR in soil with relatively even distribution along the profile without any considerable differentiation between upper and lower investigated layers. The lowest moisture provision was registered in early July, and in other periods, the PMR fluctuated within 11.4–54.9 mm in the one-meter-deep layer.

**Methods of analytical studies.** The content of nitric nitrogen was determined in soil samples photometrically using phenoldisulfonic acid, that of ammonium nitrogen — photometrically using Nessler's reagent (DSTU 4729:2007, 2008). Field soil humidity

**Table 3.** The productive moisture reserves in soil, locations 5–6

Date of soil sampling	Soil layer, cm	The productive moisture reserves, mm													
		Location 5				Location 6			Date of soil sampling	Location 5					
		N <sub>0</sub>	N <sub>60</sub>	N <sub>100</sub>	N <sub>120</sub>	N <sub>0</sub>	N <sub>60</sub>	N <sub>120</sub>		N <sub>0</sub>	N <sub>60</sub>	N <sub>100</sub>	N <sub>120</sub>		
2024						2025									
29.05	0–20	6.7	9.3	17.0	6.3	2.6	0.0	0.0							
	20–40	15.7	15.5	17.5	20.8	0.0	3.6	0.0							
	40–60	15.5	16.9	20.0	17.9	2.8	8.7	4.6							
	60–80	21.5	21.8	21.5	20.8	13.6	16.5	13.9							
	80–100	22.1	23.8	21.0	21.7	21.3	24.8	23.3							
	0–100	81.6	87.2	97.0	87.5	40.2	53.6	41.8							
26.06	0–20	5.4	8.5	8.7	9.6	0.0	0.0	0.0	10.06	0.0	0.0	0.0	0.0		
	20–40	6.4	7.5	10.3	7.5	0.0	0.2	0.0		10.4	9.4	4.1	9.4		
	40–60	9.9	14.1	12.0	11.4	0.0	2.5	0.0		19.0	18.2	18.6	14.8		
	60–80	11.2	17.6	13.3	13.9	0.7	4.1	6.1		17.5	13.3	18.3	18.2		
	80–100	11.2	18.2	16.0	19.5	2.5	4.4	4.3		5.7	12.8	1.6	12.5		
	0–100	44.1	65.9	60.3	61.9	3.2	11.2	10.4		52.6	53.7	42.5	54.9		
31.07	0–20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	09.07	0.1	0.0	0.0	0.0		
	20–40	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.6	0.4	0.8	0.5		
	40–60	7.0	0.0	0.0	0.0	0.0	0.0	0.0		0.8	1.3	0.8	0.7		
	60–80	2.2	4.7	3.3	1.4	0.0	1.6	1.9		2.2	2.9	2.6	3.0		
	80–100	0.2	7.0	3.7	0.3	1.1	1.8	6.7		3.7	4.3	2.0	3.8		
	0–100	9.5	11.8	7.0	1.7	1.1	3.4	8.6		7.4	8.9	6.2	8.0		
11.09	0–20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.07	0.5	0.5	0.6	1.0		
	20–40	0.0	0.0	0.0	0.0	0.0	0.0	0.0		1.7	1.7	1.8	1.5		
	40–60	0.0	0.0	0.0	0.0	0.0	0.0	0.9		2.0	3.3	0.9	4.1		
	60–80	0.0	4.7	0.0	1.4	0.5	2.1	1.9		5.9	4.8	3.8	5.5		
	80–100	0.0	7.0	0.0	1.2	3.8	1.9	6.7		6.0	6.4	4.3	5.7		
	0–100	0.0	11.8	0.0	2.6	4.3	4.0	9.6		16.1	16.7	11.4	17.7		

was controlled by gravimetric method (DSTU ISO 11465:2001, 2002). The productive moisture reserves were calculated by the formula:

$$W_{\text{prod.}} = (W_{\text{field}} - W_{\text{wither.}}) \times d \times h / 10,$$

where  $W_{\text{prod.}}$  — productive moisture reserves, mm;  $W_{\text{field}}$  — field humidity of soil, %;  $W_{\text{wither.}}$  — humidity of stable withering of plants, %;  $d$  — density of soil layer, g/cc;  $h$  — soil layer, cm; 10 — conversion coefficient into mm.

The study results were processed and summarized using Statistica 10 and Microsoft Excel.

### RESULTS

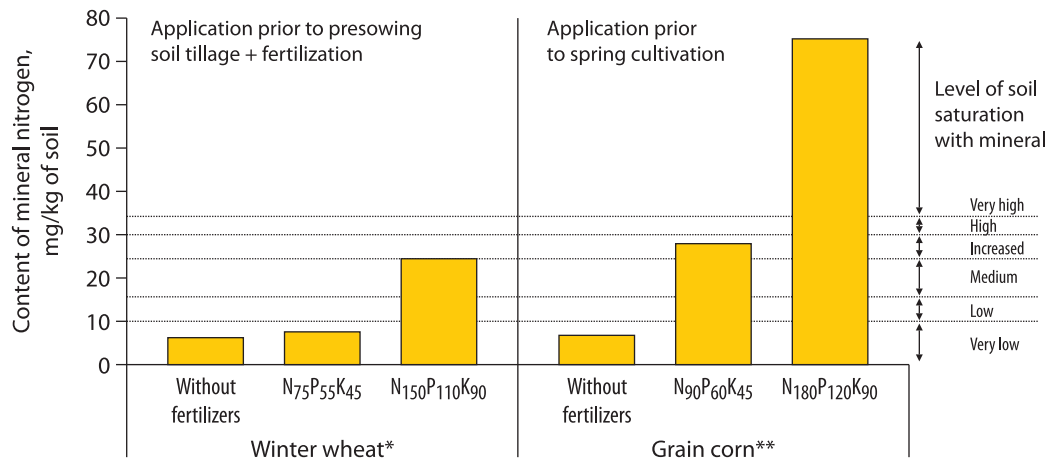
The migration of nitrates in soil (their movement deeper along the soil profile) was investigated using the data of the actual content of mineral nitrogen ( $N_{\text{min}}$ ), defined as the sum of its nitrate and ammonium forms, and nitrogen of the nitrate form proper ( $N\text{-NO}_3$ ) (Revte-Uvarova et al., 2020).

**Table 4** summarizes the data of observations in industrial conditions during the vegetation of corn in locations 2, 3, and 4. In all these locations, the parameters of  $N_{\text{min}}$  content in soil directly depended on the norm of applying nitrogen-containing fertilizers, and the highest values were registered in the 0–20 cm layer. In particular, on typical chernozem of location 4, when corn is fertilized with  $N_{100}\text{-}N_{170}$ , the content of  $N_{\text{min}}$  is very high (over 54.3 mg/kg of soil), whereas in case of applying  $N_{16}$  it corresponds to the average provision level. Split application of  $N_{134}$  into several portions in location 2 and that of  $N_{119}$  in location 3 not only created a high level

of  $N_{\text{min}}$  content, but also ensured the prolongation of this state during the active vegetation of corn.

The results of the studies also demonstrate a considerable dynamic nature of  $N_{\text{min}}$  in soil and its dependence on the terms, ways, and norms of applying nitrogen-containing fertilizers. For instance, in the arable layer of typical chernozem in location 1, in case of applying  $N_{45}P_{55}K_{45}$  prior to the pre-sowing soil tilling and  $N_{30}$  to fertilize winter wheat, the content of  $N_{\text{min}}$  in the third decade of April was very low, whereas the twofold increase in the nitrogen norm ensured the increase in  $N_{\text{min}}$  to a higher level. In case of applying the complete mineral fertilizer  $N_{90}P_{60}K_{45}$  prior to the spring cultivation of corn in the second decade of June, the content of  $N_{\text{min}}$  was 27.9 mg/kg (an increased level), and in case of applying  $N_{180}P_{120}K_{90}$  — 75.3 mg/kg of soil (very high level) (**Fig. 2**).

A general tendency is the maximal increase in  $N_{\text{min}}$  content in the arable soil layer after the application of nitrogen-containing fertilizers and its gradual decrease with depth and with the longer time period after their application. Noteworthy is the fact that the nitrate form prevailed in the structure of mineral nitrogen in all the study locations. In particular, in location 1, in the third decade of April, the highest content of nitrate nitrogen under winter wheat was observed in the 0–20 cm soil layer which was decreasing with depth 1.6–2.2 times (**Fig. 3A**). In two months after the application of  $N_{90}$  and  $N_{180}$  under corn prior to spring tilling, the nitrates were also concentrated in the arable layer. At the same time,



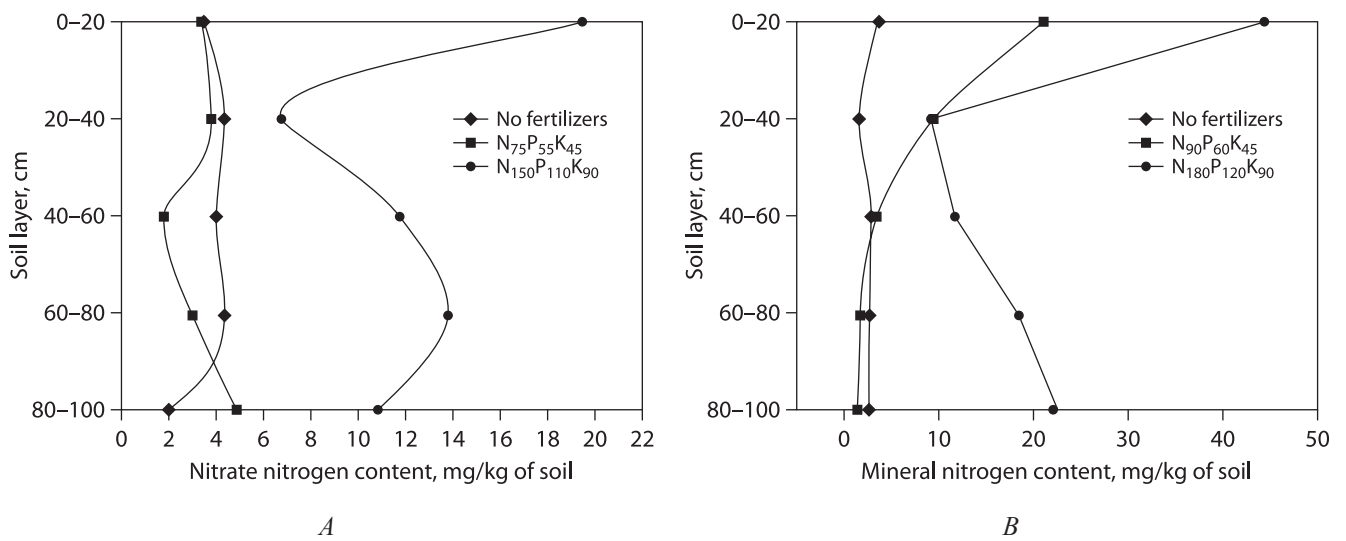
**Fig. 2.** The content of mineral nitrogen in the 0–20 cm layer of typical chernozem under different fertilization of winter wheat and corn, location 1

Notes: \* — determined in the third decade of April; \*\* — determined in the second decade of June.

**Table 4.** The dynamics of the mineral nitrogen content in soil depending on the norms of applying nitrogen-containing fertilizers under grain corn in locations 2–4

Date of soil sampling	Soil layer, cm	Mineral nitrogen content, mg/kg soil						
		Location 2	Location 3	Location 4				
		N <sub>134</sub>	N <sub>119</sub>	N <sub>16</sub>	N <sub>100</sub>	N <sub>140</sub>	N <sub>155</sub>	N <sub>170</sub>
25 May — Locations 2 and 3; 27 May — Location 4	0–20	▲ 155,0	▲ 60,0	▲ 18,7	▲ 71,2	▲ 64,7	▲ 54,3	▲ 72,5
	20–40	■ 72,2	▼ 28,0	▲ 18,0	▼ 26,6	▼ 25,4	▼ 20,1	▼ 31,2
	40–60	▼ 32,7	▼ 22,2	▲ 14,7	▼ 11,7	▼ 15,8	▼ 11,9	▼ 16,8
	60–80	▼ 24,0	▼ 21,3	■ 13,6	▼ 10,6	▼ 17,5	▼ 13,1	▼ 17,7
	80–100	▼ 34,6	▼ 23,0	■ 13,8	▼ 11,2	▼ 27,9	▼ 10,7	▼ 23,5
	100–120	▼ 35,6	▼ 22,8	▲ 18,1	▼ 13,7	▼ 30,6	▼ 9,9	▼ 24,7
17 June — Locations 2 and 3; 22 June — Location 4	0–20	▲ 50,1	▲ 59,8	▲ 18,5	▲ 49,0	▲ 55,9	▲ 48,0	▲ 52,5
	20–40	▲ 47,3	▼ 25,3	▲ 14,0	▼ 19,3	▼ 20,2	■ 22,3	▼ 19,6
	40–60	■ 37,1	▼ 24,9	■ 11,9	▼ 8,0	▼ 11,9	▼ 10,9	▼ 11,1
	60–80	▼ 21,1	▼ 16,8	■ 11,5	▼ 7,7	▼ 11,3	▼ 12,1	▼ 13,1
	80–100	▼ 23,8	▼ 19,2	■ 12,7	▼ 8,1	▼ 11,3	▼ 9,3	▼ 14,3
	100–120	■ 31,5	▼ 20,4	■ 13,4	▼ 8,2	▼ 19,2	▼ 19,2	▼ 16,8
08 July — Locations 2 and 3; 14 July — Location 4	0–20	▲ 47,0	▲ 66,3	■ 11,9	▲ 34,3	▲ 41,0	▲ 30,2	▲ 21,8
	20–40	▼ 16,3	■ 45,6	▼ 6,6	▼ 11,6	▼ 10,4	▼ 10,5	▼ 9,4
	40–60	▼ 12,4	▼ 32,2	▼ 4,7	▼ 5,5	▼ 5,3	▼ 4,9	▼ 5,3
	60–80	▼ 13,7	▼ 27,2	▼ 6,7	▼ 5,5	▼ 6,6	▼ 5,8	▼ 6,7
	80–100	▼ 23,1	▼ 28,8	▼ 7,9	▼ 6,0	▼ 8,7	▼ 10,5	▼ 9,3
	100–120	▲ 38,5	▼ 26,1	▼ 8,1	▼ 6,2	▼ 12,4	▼ 10,4	▼ 10,8
29 July — Locations 2 and 3; 27 July — Location 4	0–20	▲ 61,7	▲ 64,9	■ 9,9	▲ 14,1	Н.д.	▲ 11,0	▲ 12,8
	20–40	▼ 27,6	▼ 20,6	▼ 5,7	▼ 6,1	Н.д.	▼ 6,5	■ 6,7
	40–60	▼ 17,7	▼ 12,8	▼ 4,6	▼ 4,3	Н.д.	■ 8,2	▼ 3,4
	60–80	▼ 15,0	▼ 9,1	▼ 7,5	■ 7,8	Н.д.	▼ 5,4	▼ 5,2
	80–100	▼ 11,3	▼ 10,5	▼ 6,7	▲ 11,1	Н.д.	▼ 5,2	▼ 5,9
	100–120	▼ 13,4	▼ 14,5	▼ 7,5	▲ 11,1	Н.д.	▼ 5,5	■ 6,5
08 September — Locations 2 and 3; 06 September — Location 4	0–20	▲ 23,9	▲ 68,9	■ 11,6	▲ 22,1	Н.д.	▲ 23,9	▲ 13,3
	20–40	▲ 23,3	■ 44,2	■ 9,1	▼ 10,2	Н.д.	▼ 10,1	■ 10,0
	40–60	▼ 11,1	▼ 15,0	▼ 4,1	▼ 4,8	Н.д.	▼ 7,2	▼ 5,9
	60–80	▼ 11,2	▼ 12,5	▼ 6,8	▼ 7,9	Н.д.	▼ 8,4	▼ 7,3
	80–100	▼ 11,4	▼ 12,7	▼ 6,1	▼ 7,4	Н.д.	▼ 11,8	▼ 7,1
	100–120	▼ 14,7	▼ 18,0	▼ 6,9	▼ 7,4	Н.д.	▼ 10,6	▼ 8,2

Note. ▲ — high values; ■ — average values; ▼ — low mineral nitrogen content in successive soil layers down to a depth of 120 cm at each soil sampling period.

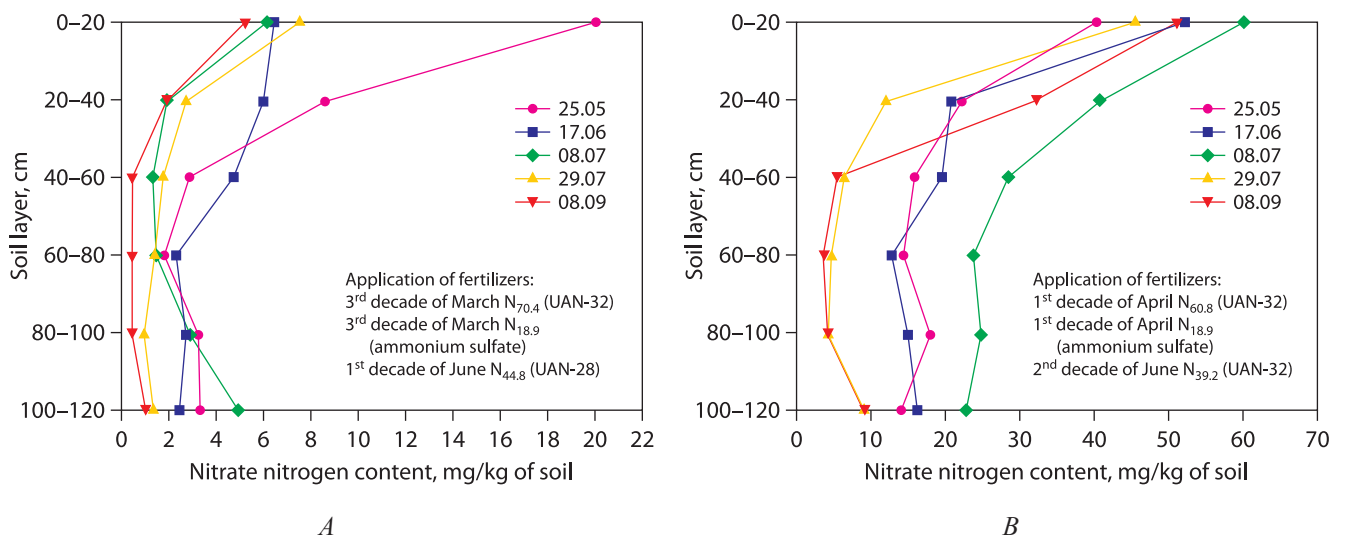


**Fig. 3.** The distribution of nitrate forms of nitrogen in soil in case of applying the complete mineral fertilization in location 1: *A* — under winter wheat; *B* — under corn

under both crops, the accumulation of nitrates in the subarable soil layers down to the depth of 100 cm was found to be much higher in case of a double norm of fertilizers than in case of a single norm. It should be noted that the average monthly precipitation amount at the time of sampling soil was 32% lower than the perennial indices.

In case of a split application of  $N_{134}$  in location 2 and  $N_{119}$  in location 3 in the industrial fields of corn, the highest content of nitrates was also registered in the 0–20 cm soil layer (**Fig. 4**). The fluctuations of

the absolute values of the content of nitrates in this layer may be related to the nitrification course of ammonium nitrogen of mineral fertilizers and, possibly, ammonium nitrogen of the mineralized organic matter in soil (“extra”-nitrogen) (Nosko, 2013). A general regularity in the transition of nitrate nitrogen in the 0–120 cm soil layer is its gradual decrease with the depth. For instance, in case of applying  $N_{134}$ , its content at the depth of 100–120 cm is 5.9 lower than that in the arable layer at the start of vegetation, and 1.2–5.6 times lower — in other periods. The diffe-



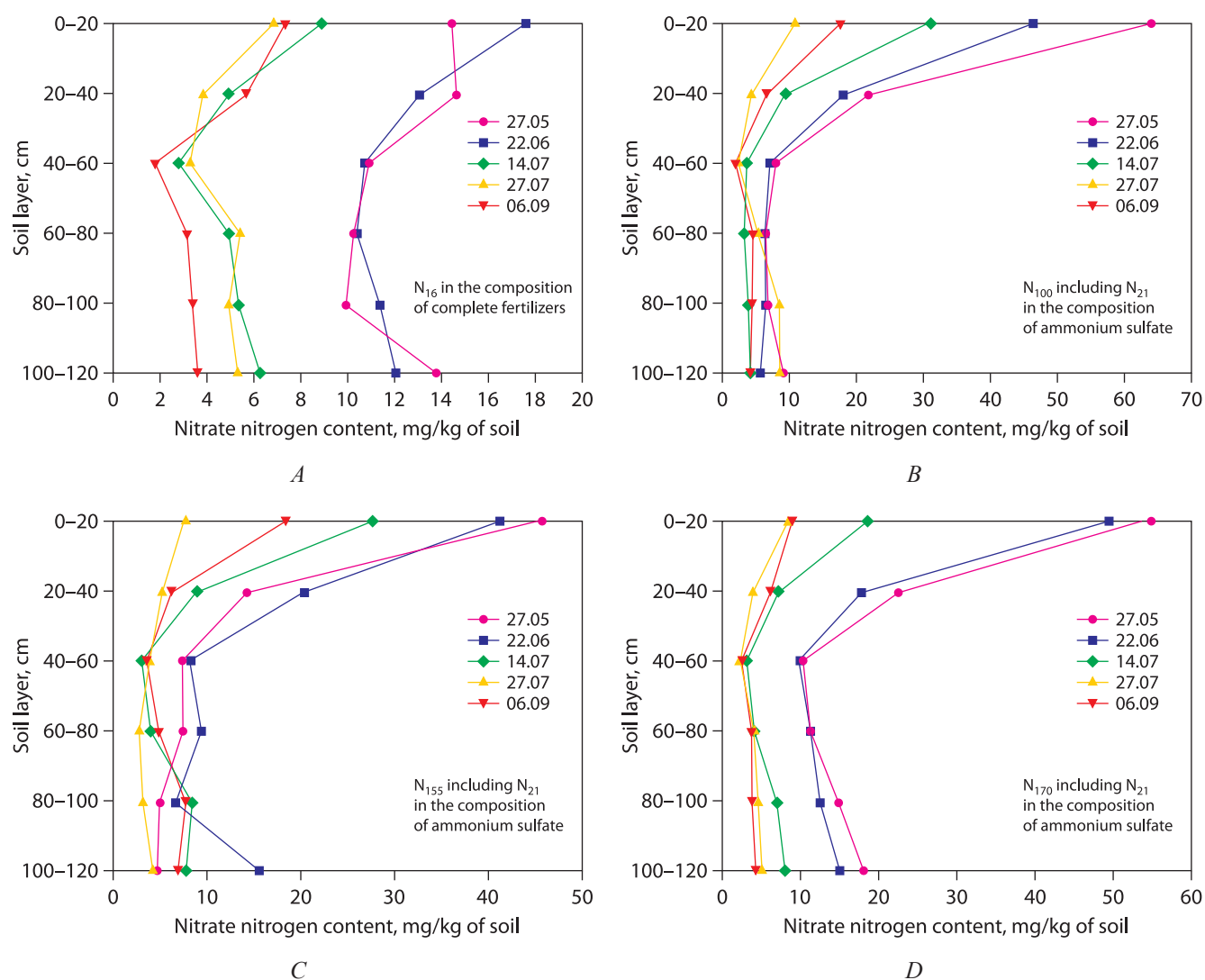
**Fig. 4.** The distribution of nitrate forms of nitrogen in soil in case of the split application of  $N_{134}$  and  $N_{119}$  in location 2: *A* — location 2 (application of  $N_{134}$  in meadow-chernozem soils); *B* — location 3 (application of  $N_{119}$  in dark-grey podzolic soils)

rence between the content of nitrates at the depth of 100–120 cm from the first to the last determination is 3.3-fold: there is a decrease from 24.6 mg/kg of soil to 7.5 mg/kg of soil. In case of applying  $N_{119}$ , the content of nitrate nitrogen decreases at the depth of 100–120 cm as compared to the arable layer, depending on the period of determination. The content of nitric nitrogen in the 100–120 cm soil layer decreased from 14.1 mg/kg of soil to 9.0 mg/kg of soil from the first to the last determination.

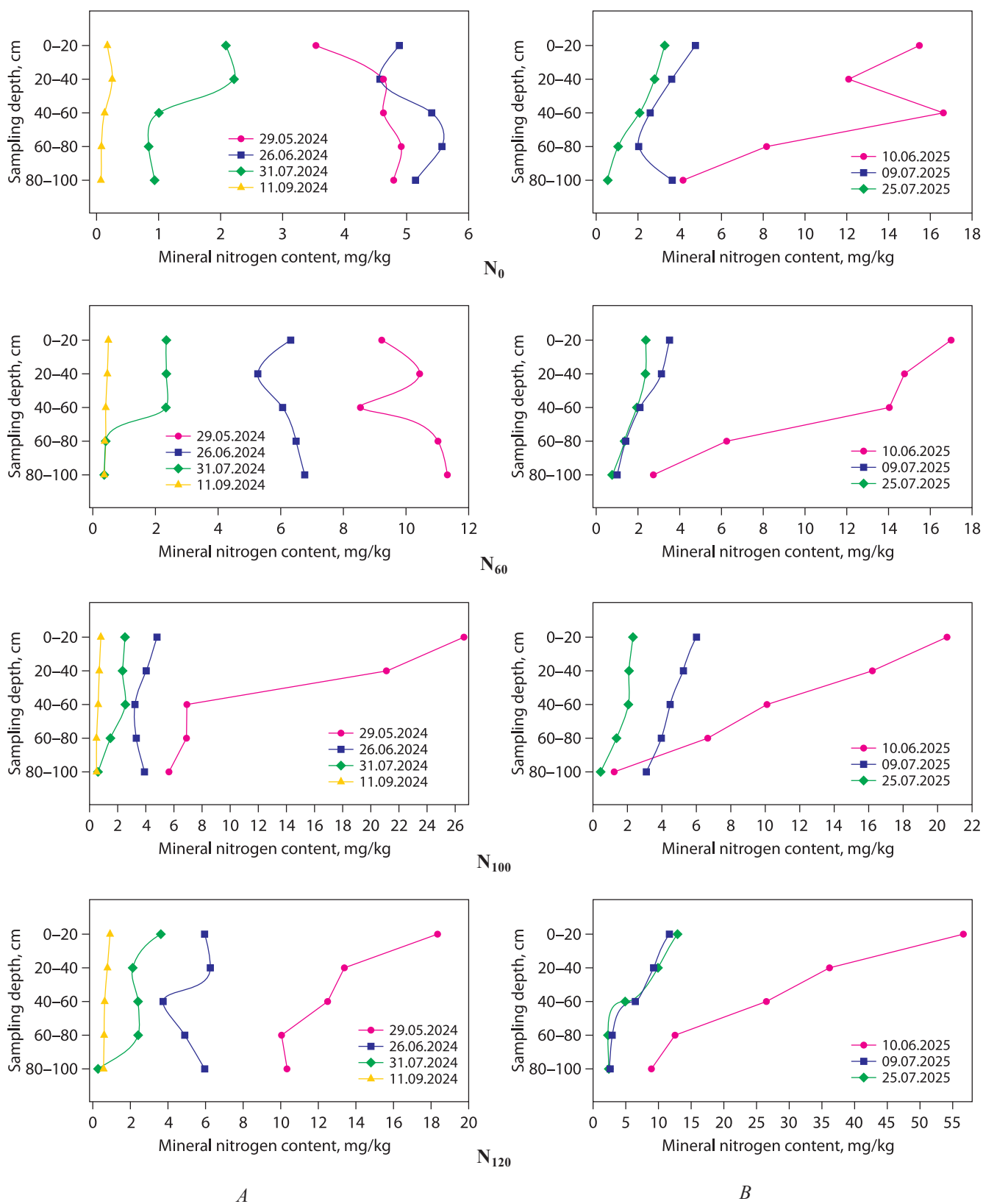
Similar regularities in the accumulation and migration of nitric nitrogen in the 0–120 cm soil layer were also found in location 4 in case of the application of different norms of nitrogen-containing fertilizers under corn (Fig. 5). The maximal content of nitric

nitrogen was noted in the 0–20 cm soil layer with the decrease with depth and time. In case of applying the maximal norm of  $N_{170}$ , the 0–20 cm layer contained 53.7 mg/kg of nitric nitrogen, whereas in the 100–120 cm layer it was three times lower, and in the last period of observations, these parameters decreased to 8.9 mg/kg and 4.3 mg/kg, respectively. In general, at the end of the corn vegetation period, the content of nitric nitrogen in the 0–20 cm layer fluctuated within the interval from 7.4 to 18.2 mg/kg, and at the depth of 100–120 cm from 3.6 to 6.9 mg/kg of soil.

In podzolic chernozem of locations 5 and 6, during abnormal drought of 2024, in June, the content of  $N_{min}$  fluctuated for all the levels of applying mineral



**Fig. 5.** The distribution of nitric nitrogen in soil in case of applying different norms of nitrogen-containing fertilizers in location 4: *A* — application of  $N_{16}$ ; *B* — application of  $N_{100}$ ; *C* — application of  $N_{155}$ ; *D* — application of  $N_{170}$



**Fig. 6.** The distribution of mineral nitrogen in soil in case of applying different doses of nitrogen-containing fertilizers in locations 5 and 6: *A* — during the vegetation period of barley and corn in 2024; *B* — during the vegetation period of oil flax in 2025

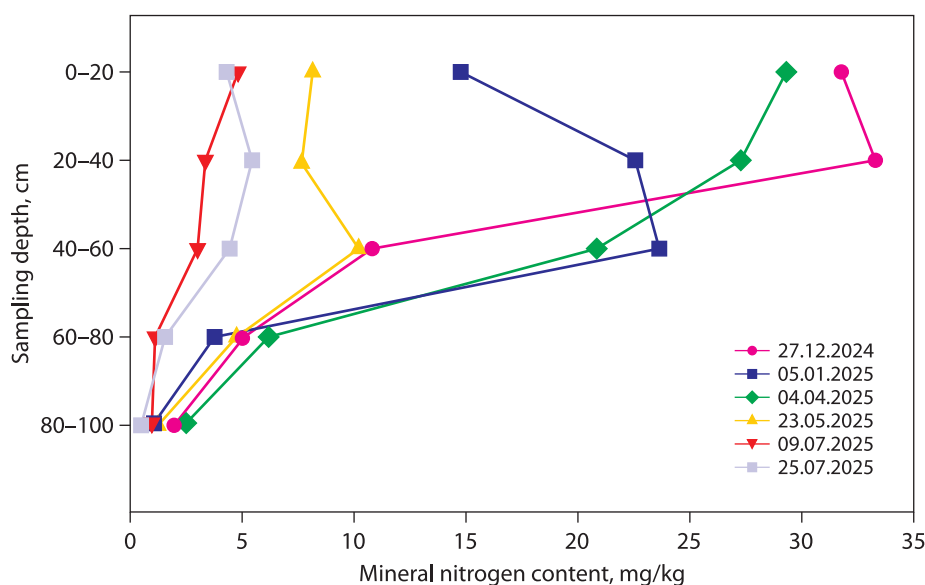
## DISCUSSION

fertilizers ( $N_{60}$ ,  $N_{100}$  and  $N_{120}$ ) from 2.1–2.4 mg/kg in the 0–60 cm layer to 0.40–0.95 mg/kg in the 80–100 cm layer, and in September, it was 0.42–0.82 mg/kg of soil without considerable differentiation among soil layers (**Fig. 6A**). In 2025, due to a considerably higher precipitation amount during the vegetation period and relatively higher soil humidity and more favorable conditions for the course of microbiological processes, the  $N_{\min}$  content was higher than in 2024, namely: in control — 4.2–2.6 times,  $N_{60-100}$  — 2.3–2.1 times,  $N_{120}$  — 3.0–2.1 times (**Fig. 6B**). At the same time, in 2025, for levels of applying mineral fertilizers ( $N_{60}$ ,  $N_{100}$ ,  $N_{120}$ ) the  $N_{\min}$  content at the depth of 80–100 cm did not exceed the value of the control variant  $N_0$ . In case of applying  $N_{120}$ , the  $N_{\min}$  content at the depth of 80–100 cm was 2.0–3.5 times higher as compared to  $N_{60-100}$ , but it did not exceed the value for 15 mg/kg of soil which corresponds to a low rate of saturating the soil with mineral nitrogen.

The observations in locations 5 and 6 registered the highest concentrations of nitric nitrogen in case of applying  $N_{120}$  in winter and spring months in the 0–60 cm soil layer, whereas at the depth of 80–100 cm, the amount of  $N-NO_3$  decreased 2.5–6.0 times and did not exceed 6 mg/kg of soil (**Fig. 7**). It demonstrates the possibility of increasing the content of nitric nitrogen in deeper soil layers in case of higher precipitation amount during the vegetation period, but only in case of applying nitrogen-containing fertilizers in the dose above 100 kg/ha.

Two approaches to identification of zones, vulnerable to the accumulation of nitrates, are used in the EU (Report from the commission to the council and the European parliament..., 2021). The general territorial approach envisages expanding the requirements of the Nitrate Directive to the area of the entire territory of the country, which is implemented in Austria, Denmark, Finland, Germany, Ireland, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Romania, Slovenia, and Belgium (except for Flanders). Bulgaria, Spain, Hungary, Italy, Slovakia, Cyprus, Estonia, Latvia, and Portugal single out only the territories in which nitrate losses penetrate water bodies, and in some countries they define additional local zones (“hot spots” or “red zones”) with a higher pollution level or proximity to points of abstracting drinking water (Report from the commission to the council and the European parliament..., 2021).

According to the estimate of Osadcha et al. (2020), vulnerable zones are limited territories of the river basin (parts of drainage territories), from which nitric nitrogen is flushed to the massives of surface and underground waters (Osadcha et al., 2020). However, considering the biogeochemical instability of nitrogen compounds, the status of a vulnerable zone may change with time. It should be noted that this publication is dedicated to flushing nitrogen compounds (their movement deeper along the profile), whereas their flushing with the superficial drainage has other specificities and is more notable for territo-



**Fig. 7.** The distribution of nitric nitrogen in soil in case of applying  $N_{120}$  in location 5

ries, vulnerable to erosion, i.e. territories, which, due to their natural features (complex landscape: slopes of different steepness, divided forms) are inclined to intense development of erosion processes, in this case, this is water erosion of soils. As for the territory of conducting the study, these are water-dividing plots or flattened interfluvial terrains.

Mineral nitrogen, presented by ammonium and nitrate forms, is the most common quantitative indicator in Ukraine, which allows estimating the amounts of nitrate migration in the soil depth. A nitrate form is not constrained by the absorbing complex in soil and migrates in it freely, and ammonium ions transform into nitrates in the nitrification process. To determine the suitability of mineral nitrogen indicator in soil for identification of zones, vulnerable to the accumulation of nitrates, it is necessary to confirm two provisions, envisaged in the Nitrate Directive. Firstly, is the content of mineral nitrogen sufficient for the current understanding of the behavior of nitrogen compounds in the environment (water and soil)? Secondly, is the content of mineral nitrogen sufficient for the current understanding of the impact of the measures taken to minimize the input of nitrogen compounds into water bodies?

Our studies demonstrate that after the application of nitrogen-containing fertilizers, there is a considerable increase in mineral nitrogen in the 0–40 cm soil layer (**Table 3**, **Fig. 2** and **6**), increasing with larger doses of nitrogen application. This tendency has a direct impact on the vertical migration of nitric nitrogen in the 0–120 cm soil layer: the increase in upper layers with a gradual decrease in its content along the soil profile and in time (**Fig. 3–5**, **7**). In addition, the nitric nitrogen in the lower soil layers is a potential source of fertilization of plants with nitrogen which is brought to upper layers with the ascending stream of moisture. The studies demonstrate (Feng et al., 2019) that the penetration of the roots to the depth of 40 and more cm promotes the increase in nitrogen absorption and lower flushing of nitric nitrogen. Sebilo et al. (2013) used labelled (stable) isotopes of nitrogen ( $^{15}\text{N}$ ) in the composition of nitrogen fertilizers to determine that 61–65% of  $^{15}\text{N}$  applied fertilizers are absorbed by plants mostly during the first years of application, 12–15% of  $^{15}\text{N}$  is accumulated in the composition of the organic matter of soil, and 8–12% of  $^{15}\text{N}$  is removed to the hydrosphere during a 30-year-long period of observations.

According to our results, the content of mineral nitrogen in soil decreases considerably by the end of the crop vegetation. In early September, the content of nitric nitrogen under corn in the arable 0–20 cm layer fluctuated from 7.4 to 18.2 mg/kg of soil, whereas the difference between the minimal and maximal norms was  $N_{154}$ . At the depth of 100–120 cm, the content of  $\text{N-NO}_3$  fluctuated from 3.6 to 6.9 mg/kg of soil, and its average content in the 0–120 cm soil layer did not exceed 7.8 mg/kg of soil (**Fig. 5**).

The presented specificities of the re-distribution of mineral nitrogen in soil give grounds to recommendations on conducting soil sampling to determine the risk of flushing nitrates in autumn, after crop harvesting. There is a similar practice in Flanders, where the content of mineral nitrogen is regularly determined in the 0–90 cm soil layer within the period from October 1 and November 15, which is the main leaching period (D’Haene et al. 2014). It also allows avoiding non-objective limitations on the use of mineral nitrogen fertilizers, especially in the territories with deep underground waters and minimal manifestation of erosion processes.

The behavior of nitrogen compounds in soil is closely related to the life activity of soil microorganisms which are very sensitive to weather and climate fluctuations, and their activity directly depends on humidity (Schimel, 2018). Similar to most European countries, in Ukraine a decrease in the total precipitation amount is forecast which is caused by their considerable reduction in summer, and a thinner snow cover which, in its turn, changes the terms and volumes of drainage (Kundel et al., 2021; Wilson et al., 2021). At present, the situation with moisture provision for soils deteriorated sharply, especially in the southern and eastern regions of Ukraine. According to the experts, due to the limited precipitation amount in spring and summer, the one-meter-deep soil layer accumulates from 10 to 80 mm of productive moisture (Soil moisture reserves are decreasing in Ukraine — corn and sunflower harvests are at risk, 2025). This is confirmed by the results of our studies, in which the fluctuations in PMR in the one-meter-deep soil layer in locations 2, 5, 6 in spring were 80–115 mm, and in July–August, they decreased to 8–13 mm, and in locations 3–4, the moisture, available for plants, was not registered at all in late summer. Drought conditions inhibit the course of ammonification and nitrification processes as well as the consumption of nitrogen by plants (Lori et al., 2020), instead the

increase in soil humidity increases the content of mineral nitrogen in soil considerably (Lu et al., 2025). A similar regularity is notable for chernozem soils of our objects of study, where in locations 5–6, we observed a close positive correlation between the precipitation amount, moisture provision and mineral nitrogen content in soil.

Therefore, in drought years, there is lower leaching of nitrates due to a smaller amount of filtration water (Rupp et al., 2021), and the excess of nitrogen in fertilizers is accumulated in the pool of organic nitrogen of the soil (Engels et al., 1993; Werisch et al., 2021). The obtained data also demonstrate the decrease in the descending movement of mineral nitrogen to deep soil layers in drought years (**Fig. 3-7**). In addition, the flushing type of the water regime is registered ever more seldom, and in terms of the moisturization regime (the course in time) in the zonal soils of the Forest-Steppe zone, there is a stable tendency to the manifestation of the features of the non-flushing type of the water regime (Demydenko et al., 2025), which is notable for the Steppe zone of Ukraine and immediate chernozem soils even in case of optimal moisture provision (at the level of average perennial amount of precipitation). Enhanced evaporation of soil moisture leads to a reduction in the descending movement of water and promotes drawing of mineral nitrogen from deeper layers of soil to the layer with roots (Rupp et al., 2021). Thus, current climate changes and deep location of underground waters make the penetration of nitrogen fertilizers into water bodies via flushing less probable. For instance, location 1 is an even drainage-free territory within a flat terrace with poor drainage of the Siverskyi Donets river, where the depth of the underground waters is over 10 m.

From the standpoint of current understanding of the impact of the measures taken regarding the minimization of the input of nitrogen compounds to water bodies, the indicator of the content of mineral nitrogen and its structure allows for objective determination of the efficiency of the measures, envisaged by the best practices and action plans. It was determined in the conditions of locations 2 and 3 that split application of nitrogen fertilizers ensures the formation of enhanced, high or very high level of providing the soil with mineral nitrogen during the entire active vegetation of corn. The maximal increase in the mineral nitrogen content was registered in the arable 0–20 cm soil layer which was gradually decreasing

with depth and longer time periods after the application. It should also be noted that pre-sowing application of UAN-32 and granulated ammonium sulfate ensured prolonged action via the course of processes of microbiological transformation of amide nitrogen into ammonium nitrogen, and ammonium nitrogen into nitric nitrogen.

## CONCLUSIONS

The content of mineral nitrogen in soil is a convenient indicator to ensure a differentiated approach to identification of zones, vulnerable to the accumulation of nitrates. It is recommended to determine the content of mineral nitrogen in the arable soils, which are potentially vulnerable, after harvesting the crops.

After the application of fertilizers, the maximal content of mineral nitrogen in soil is registered in the 0–20 cm soil layer and decreases with depth and time. The observations on soils of six locations of upland soils in the years with dry and normal moisturization conditions did not reveal considerable volumes of flushing mineral nitrogen and nitrates directly into lower soil layers in spring and summer.

The application of nitrogen fertilizers under crop rotations on the arable soils of humus-accumulative genesis in the plain territories of Ukraine with non-flushing or periodically flushing type of water regime at the norm, which does not exceed 100 kg/ha, does not pose any threat of mineral nitrogen leaching, including its nitrate forms, and pollution of underground waters. In case of split application, it is possible to increase the norm of nitrogen fertilizers which ensures their prolonged effect.

The sources of financing: the publication contains the results of the studies, conducted in 2021 pursuant to task 01.03.03P “Improvement of normative and methodological foundation for ecological norm setting for the application of mineral fertilizers in agriculture in the context of the European integration of Ukraine” (No. 0121U100739), PNR NAAS 01 “Soil resources of Ukraine”, in 2024–2025 — within the implementation of the grant “Future Agricultural Resource Management and Water Innovations for a Sustainable Europe (FARMWISE)”, project number 101135533 of the “Horizon Europe” program and implementation of the agreement with the Ministry of Science and Education of Ukraine “Complex scientific study of innovational solutions for soil restoration and prevention of their degradation with the purpose

of improving the ecological state of the regions of Ukraine” (agreement number 0125U003696).

The authors declare the absence of any conflicts of interests in conducting this work.

The authors express their deep gratitude to the agrochemical service of the Kernel company for their assistance in conducting field studies and to the engineering personnel of the NRC “ISSAR named after O. N. Sokolovsky” for high quality chemical and analytic work.

## REFERENCES

- Agriculture, forestry and fisheries of Ukraine. Application of mineral and organic fertilizers, pesticides (1990–2023). State Statistics Service of Ukraine. (In Ukrainian). Retrieved from [https://www.ukrstat.gov.ua/operativ/menu/menu\\_u/cg.htm](https://www.ukrstat.gov.ua/operativ/menu/menu_u/cg.htm)
- Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources: Council of the European Union. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A31991L0676>
- D’Haene K, Salomez J, De Neve S, De Waele J, Hofman G (2014) Environmental performance of the nitrogenfertiliser limits imposed by the EU Nitrates Directive. *Agric. Ecosyst. Environ.*, 192:67–79. <https://doi.org/10.1016/j.agee.2014.03.049>
- Demydenko OV, Velychko VA (2025) Moisturization regime and implementation of chornozem agropotential under climate changes in the central Forest-Steppe. *Agricultural Science and Practice*, 12(2):66–97. <https://doi.org/10.15407/agrisp12.02.066>
- DSTU 4729:2007 Soil quality. Determination of nitrate and ammonium nitrogen in the modification of the National Scientific Center “Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky”. Effective from 01.01.2008. Official edition. Kyiv: Derzhspozhyvstandart of Ukraine, 2008. 10 p. (in Ukrainian)
- DSTU ISO 11465:2001 (ISO 11465:1993, IDT) Soil quality. Determination of dry matter and moisture content by mass. Gravimetric method. Effective from 01.01.2003. Official edition. Kyiv: Derzhspozhyvstandart of Ukraine, 2002. 5 p. (in Ukrainian)
- Engels T, Kuhlmann H (1993) Effect of the rate of N fertilizer on apparent net mineralization of N during and after cultivation of cereal and sugar beet crops. *Z. Pflanz. Bodenkd.*, 156:149–154. <https://doi.org/10.1002/jpln.19931560209>
- Feng GZ, He XL, Coulter JA, Chen YL, Gao Q, Mi GH (2019) Effect of limiting vertical root growth on maize yield and nitrate migration in clay and sandy soils in Northeast China. *Soil and Tillage Research*, 195:104407. <https://doi.org/10.1016/j.still.2019.104407>
- Fertilizer Consumption — Historical Trends by Country or Region (Fertilizer consumption for N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O by country or region). IFASTAT Consumption Database. Retrieved from [https://www.ifastat.org/databases/graph/1\\_1](https://www.ifastat.org/databases/graph/1_1)
- Galloway JN, Leach AM, Bleeker A, Erisman JW (2013) A chronology of human understanding of the nitrogen cycle. *Philosophical Transactions of the Royal Society B*, 368: 20130120. <https://doi.org/10.1098/rstb.2013.0120>
- Kant S, Bi YM, Rothstein SJ (2011) Understanding plant response to nitrogen limitation for the improvement of crop nitrogen use efficiency. *J Exp Bot.*, 62(4):1499–509. <https://doi.org/10.1093/jxb/erq297>
- Kundel D, Lori M, Fliessbach A, van Kleunen M, Meyer S, Mäder P (2021) Drought Effects on Nitrogen Provisioning in Different Agricultural Systems: Insights Gained and Lessons Learned from a Field Experiment. *Nitrogen*, 2:1–17. <https://doi.org/10.3390/nitrogen2010001>
- Li Z, Zhang R, Xia S, Wang L, Liu C, Zhang R, Fan Z, Chen F, Liu Y (2019) Interactions between N, P and K fertilizers affect the environment and the yield and quality of satsumas. *Global Ecology and Conservation*, 19:e00663. <https://doi.org/10.1016/j.gecco.2019.e00663>
- Lori M, Piton G, Symanczik S, Legay N, Brussaard L, Jaenicke S, Nascimento E, Reis F, Sousa JP, Mäder P (2020) Compared to conventional, ecological intensive management promotes beneficial proteolytic soil microbial communities for agro-ecosystem functioning under climate change-induced rain regimes. *Sci. Rep.*, 10: 1–15. <https://doi.org/10.1038/s41598-020-64279-8>
- Lu T, Wang J, Zhu H, Zhong Z, Wang X, Jia X, Shao M, Wei X (2025) Soil moisture determines effects of climates and soil properties on nitrogen cycling: Examination of arid and humid soils. *Journal of Environmental Management*, 73:123831. <https://doi.org/10.1016/j.jenvman.2024.123831>
- Methodology for determining zones vulnerable to (accumulation of) nitrates : Order of the Ministry of Environmental Protection and Natural Resources of Ukraine of April 15, 2021 No. 244. (In Ukrainian) Retrieved from <https://ips.ligazakon.net/document/RE36398?an=24>
- Nosko BS (2013) Nitrogen regime of soils and its transformation in agroecosystems. Kharkiv. 130 p. (In Ukrainian)
- Osadcha NM, Osadchyi VI, Osypov VV, Biletska SV, Kovalchuk LA, Artemenko VA (2020) Methodology for the nitrate vulnerable zones designation in surface and ground water. *Ukr. geogr.zh.*, 4(112):38–48. (In Ukrainian) <https://doi.org/10.15407/ugz2020.04.038>
- Report from the commission to the council and the Eu-

- ropean parliament on the implementation of Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources based on Member State reports for the period 2016–2019. European Commission. Brussels, 11.10.2021 Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2021%3A1000%3AFIN>
- Romero E, Beusen AHW, Bouwman AF, Einarsson R, Garnier J (2024) Nitrogen in agri-food systems and the environment: Next steps to a sustainable future. *Science of The Total Environment*, 947:174555. <https://doi.org/10.1016/j.scitotenv.2024.174555>
- Rules for ensuring soil fertility and the use of certain agrochemicals: Order of the Ministry of Agrarian Policy and Food of Ukraine of November 24, 2021 No. 382. (In Ukrainian) Retrieved from <https://zakon.rada.gov.ua/laws/show/z0034-22#Text>
- Rupp H, Tauchnitz N, Meissner R (2021) The Effects of Soil Drying Out and Rewetting on Nitrogen and Carbon Leaching — Results of a Long-Term Lysimeter Experiment. *Water*, 13(18):2601. <https://doi.org/10.3390/w13182601>
- San Martin W (2020) Global Nitrogen in Sustainable Development: Four Challenges at the Interface of Science and Policy. In: Leal Filho W, Azul A, Brandli L, Lange Salvia A, Wall T (eds) Life on Land. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham 1–16. [https://doi.org/10.1007/978-3-319-71065-5\\_114-1](https://doi.org/10.1007/978-3-319-71065-5_114-1)
- Sandhu N, Sethi M, Kumar A, Dang D, Singh J, Chhuneja P (2021) Biochemical and genetic approaches improving nitrogen use efficiency in cereal crops: a review. *Front. Plant Sci*, 12:657629. <https://doi.org/10.3389/fpls.2021.657629>
- Schimel J (2018) Life in Dry Soils: Effects of Drought on Soil Microbial Communities and Processes. *Annu. Rev. Ecol. Evol. Syst.*, 49:409–432. <https://doi.org/10.1146/annurev-ecolsys-110617-062614>
- Sebilo M, Mayer B, Nicolardot B, Pinay G, Mariotti A (2013) Long-term fate of nitrate fertilizer in agricultural soils. *The Proceedings of the National Academy of Sciences*, 110(45):18185–18189. 05372110 <https://doi.org/10.1073/pnas.13>
- Soil moisture reserves are decreasing in Ukraine — corn and sunflower harvests are at risk. *J. Agronom*, 2025. (in Ukrainian) <https://www.agronom.com.ua/v-ukrayinistrimko-zmenshuyutsya-zapasy-vology-v-grunti-pidzagrozoyu-vrozhaj-kukurudzy-j-sonyashnyku/>
- The improved diagnostics of the level of nitrogen provision in soil using the methods of field and laboratory testing: Scientific and methodological recommendations / A. V. Revtie-Uvarova, O. V. Karatsiuba, V. M. Nikonenko, O. I. Slidenko. Kharkiv: PE Brovyn O. v., 2020. 94 p. ISBN 978-617-7912-82-7 (in Ukrainian)
- Werisch S, Burghardt D (2021) Identification of mechanisms controlling nitrogen export from agricultural lysimeters. In *Proceedings of the 19<sup>th</sup> Gumpensteiner Lysimetertagung*, Raumber-Gumpenstein, Raumberg, Austria, 13–14 April. Pp. 71–78. ISBN: 978-3-902849-83-0
- Wilson L, New S, Daron J, Golding N (2021) Climate Change Impacts for Ukraine. Met Office. 34 p. [https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/services/government/met-office-climate-change-impacts-for-ukraine\\_report\\_08dec2021\\_english.pdf](https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/services/government/met-office-climate-change-impacts-for-ukraine_report_08dec2021_english.pdf)
- Xu J, Ren C, Zhang X, Wang C, Wang S, Ma B, He Y, Hu L, Liu X, Zhang F, Lu L, Li S, Zhang J, Zhu Y-G, Vitousek P, Gu B (2025) Soil health contributes to variations in crop production and nitrogen use efficiency. *Nat Food*, 6:597–609. <https://doi.org/10.1038/s43016-025-01155-6>

UDC 631.84:631.95:502.55

### НАЦІОНАЛЬНІ ОСОБЛИВОСТІ ВПРОВАДЖЕННЯ НІТРАТНОЇ ДИРЕКТИВИ В СІЛЬСЬКОГОСПОДАРСЬКУ ПРАКТИКУ

Мірошниченко М.М.<sup>1,2</sup>, Ревтьє-Уварова А.В.<sup>1</sup>,  
Гладкіх Є.Ю.<sup>1</sup>, Шевченко Т.В.<sup>2</sup>

<sup>1</sup> Національний науковий центр  
“Інститут ґрунтознавства та агрохімії  
імені О. Н. Соколовського”

Україна, 61024, Харків, Михайля Семенка, 4

<sup>2</sup> Національна академія аграрних наук України  
Україна, 01010, Київ,  
вул. Михайла Омеляновича-Павленка, 9

E-mail: [ecosoil@meta.ua](mailto:ecosoil@meta.ua), [alina\\_rev@meta.ua](mailto:alina_rev@meta.ua),  
[ye.hladkikh@ukr.net](mailto:ye.hladkikh@ukr.net), [nova\\_naan@ukr.net](mailto:nova_naan@ukr.net)

ORCID 0000-0003-2830-5933,  
0000-0002-6838-5440,  
0000-0002-4852-0502,  
0000-0001-9488-0325

**Мета.** Обґрунтування підходу до виокремлення зон, уразливих до накопичення нітратів, на основі даних вмісту мінерального азоту в ґрунті згідно вимог Нітратної Директиви. **Методи.** Дослідження проводилися на орних ґрунтах гумусово-акумулятивної генези 6 земельних ділянок у межах ґрунтово-кліматичної зони Лісостепу України із рівнем застосування азотовмісних добрив від 0 до 170 кг/га. Визначення вмісту мінерального азоту ( $N_{\min}$ ), нітратів та запасів продуктивної вологи проводилися пошарово до глибини 120 см, у динаміці впродовж вегетаційного періоду 2021, 2024 і 2025 рр. Культури: кукурудза на зерно, пшениця озима, ячмінь ярий, льон олійний. **Результати.** Встановле-

но значну варіабельність вмісту  $N_{\min}$  та безпосередньо нітратів в ґрунті залежно від строків, способів і норм внесення азотовмісних добрив. Максимальні концентрації спостерігаються у орному шарі ґрунту одразу після внесення азотних добрив, і ці параметри поступово зменшуються у часі та з глибиною. У червні–липні відмічене найбільше накопичення нітратів у глибоких шарах ґрунту, коли за норми внесення добрив понад  $N_{100}$  вміст нітратного азоту на глибинах від 80 до 120 см становив від 15,6 до 35,8 мг/кг. Накопичення нітратів у глибоких шарах ґрунту зменшується впродовж вегетаційного періоду, і на час збирання врожаю вміст нітратного азоту на глибинах від 80 до 120 см не перевищував 10 мг/кг ґрунту у рік з нормальними умовами зволоження та 4 мг/кг ґрунту у посушливий рік. За норми внесення добрив до 100 кг/га накопичення

$N_{\min}$  та нітратів у глибоких шарах ґрунту мінімальне. **Висновки.** Використання  $N_{\min}$  у якості індикатора відповідає вимогам Нітратної Директиви для виявлення зон, уразливих до накопичення нітратів. Вимірювання доцільно проводити після збирання врожаю сільськогосподарських культур. Внесення азотних добрив під культури польової сівозміни на орних ґрунтах гумусово-аккумулятивної генези рівнинних територій України з непромивним або періодично промивним типом водного режиму у нормі, яка не перевищує 100 кг/га, не несе загрози вилугування мінерального азоту та його нітратних форм з ґрунту та подальшого забруднення підґрунтових вод.

**Ключові слова:** нітрати, мінеральний азот, міграція, часова динаміка, чорноземи.