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The problem of nitrogen in modern agriculture

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Abstract. Optimal nitrogen supply to plants, in conditions of sufficient moisture, allows for high crop productivity with high-quality indicators. The aim of this article was to summarize and analyze statistical data on the dynamics of nitrogen input and expenditure from arable land worldwide and in Ukraine, as well as provide practical recommendations for addressing the nitrogen issue in modern agriculture. The research utilized theoretical generalization, comparative analysis, graphical, abstract-logical methods and statistical data from FAOSTAT for the period of 2000-2020. The research results have shown that nitrogen input from mineral fertilizers has been constantly increasing both globally and in Ukraine. In contrast to global indicators, there has been a significant reduction in nitrogen input from manure in Ukraine, as well as a decrease in nitrogen input from atmospheric precipitation and through biological fixation by leguminous crops. The components of nitrogen balance, such as leaching, evaporation, and denitrification, play a significant role in nitrogen expenditure. These expenditure components tend to increase both globally and in Ukraine. The largest share in the expenditure component of all countries worldwide, including Ukraine, is occupied by nitrogen removal by cultivated crops. Calculations showed that the nitrogen balance on arable land, both globally and in most countries across different continents for the researched period, was positive. However, in Ukraine, it was negative for 18 out of 21 years. To solve this problem, practical recommendations are proposed using the best practices and developments of economically developed countries worldwide

Keywords: mineral fertilizers; organic fertilizers; biological fixation; nitrogen removal; leaching; evaporation; nitrogen balance

INTRODUCTION

Of all the elements of nutrition that are known to modern science, one of the most important is nitrogen. It, together with other nutrients, provides the highest yield gains on most types of soils known in world agriculture (Bavar *et al.*, 2016; Pandit *et al.*, 2022). In addition, it is a component of atmospheric air, which contains about 78% nitrogen.

The nitrogen cycle is the most complex, since this element of nutrition is quite mobile, it has the property of moving from one form to another, migrating and

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redistributing along the soil profile, being lost in the process of denitrification, binding to atmospheric nitrogen by legumes by symbiotic fixation, etc. (Moreau *et al.*, 2019; Wang *et al.*, 2021; Stepanov *et al.*, 2021).

In general, the development of agriculture and obtaining appropriate crop yield levels are determined precisely by the amount of nitrogen available to plants in the soil. In the Southern steppe of Ukraine, the first place in the formation of plant productivity among the totality of all factors is occupied by their moisture supply, and the second pone is the content of available (mobile) forms of nitrogen (Vozhegova *et al.*, 2021; Zayets *et al.*, 2022).

This element of nutrition prolongs the duration of vegetation, increases the accumulation of more aboveground biomass of plants, increases their habit and, accordingly, the area of the assimilation surface, and therefore contributes to the strengthening of photosynthetic activity, intensive formation of dry matter and yield growth in general (Andrews *et al.*, 2019; Wang *et al.*, 2020). In addition, the formation of an optimal amount of aboveground biomass obscures the field surface well and prevents excessive and unproductive evaporation of moisture (Naorem *et al.*, 2023).

The aim of this article was to summarize statistical data, review literature sources, conduct analytical research on the dynamics of nitrogen input and expenditure on arable land worldwide and in Ukraine, and formulate and justify practical recommendations for achieving a positive nitrogen balance in the modern conditions of the agricultural sector using the advanced experience of economically developed countries worldwide.

MATERIALS AND METHODS

In the process of scientific research to achieve this goal, the following general scientific methods were used: methods of theoretical generalization (abstraction and formalization), method of comparative analysis, graphical and abstract-logical methods. The method of theoretical generalization (abstraction and formalization) was used to formulate an approach to understanding the essence of the nitrogen problem in modern agriculture, taking into account its dynamics over a 20-year period in the regions of the world and Ukraine. The method of comparative analysis was used to compare factual data on the dynamics of nitrogen in the agricultural sector of the world, world regions, and Ukraine for individual years and overall, for a 20-year period. The results of the research were visually represented in the form of diagrams using the graphical method. The abstract-logical method was used in the process of forming theoretical generalizations and formulating conclusions.

The information base of the study was statistical data from FAOSTAT (2022). Time coverage is from 1961 to the most recent data available (2020). Monographic, periodic and reference publications, results of author's research and calculations also compose and supple the information base of the study. According to the formulated goal, the stages of the study were as follows: study of the theoretical foundations of the problem of nitrogen, analysis of statistical data, justification of practical recommendations.

At the first stage, the theoretical foundations of the nitrogen problem in modern agriculture were investigated, and its dynamics in terms of major income and expenditure items were determined. The theoretical foundations of the research reveal the importance of the problem and allow other researchers to understand it; provide tools for critical analysis and help the researcher distinguish what is relevant and what is not.

Subsequently, an analysis of statistical data on the dynamics of nitrogen in the modern conditions of the agricultural sector of the world regions and Ukraine was conducted. Analysis is a method of cognition that allows dividing research objects into component parts. Direct or empirical analysis was used (to identify characteristics and properties from global indicators, separate regional indicators for Ukraine); reverse or elementary-theoretical analysis (theoretical reasoning regarding the cause-effect relationship of the studied phenomena, identification of their regularities); structural-genetic analysis (identification of individual elements that had a decisive impact on the studied indicators).

In the final stage, the ways to create a positive nitrogen balance in the current conditions of economic activity were substantiated. The methodology used contributed to solving the problem and substantiating practical recommendations for solving the problem of nitrogen as the main element of nutrition for plants, using the best practices of leading countries of the world.

RESULTS AND DISCUSSION

It is known that the balance of any element of nutrition and its losses or growth under a particular crop or over a certain period is determined by the difference between its entry into the soil and costs (Ullah *et al.*, 2019; Putra *et al.*, 2020). The results of the conducted research demonstrate the state of the nitrogen balance in the world and in Ukraine.

According to FAOSTAT (2022), 107.4 million tons of nitrogen were added worldwide in 2020 year. Of the total amount, 59.9% of the total global application was applied in Asia, 4.1% was applied in Africa, 13.8% was applied in Europe and 1.2% was applied in Oceania. It should be noted that since 2000, when the use of nitrogen in the world amounted up to 76.9 million tons, the application of nitrogen fertilizers in the subsequent period was constantly increased, which can be clearly traced according to Table 1 data.

Nitrogen fertilizer applications in Ukraine also grew with a similar dependence: from 0.350 million tons in 2000 year up to 1.689 million tons in 2020 year (Fig. 1).

Table 1. *Dynamics of nitrogen applied mineral fertilizers on arable land*

Year	Regions of the world										World deposit of nitrogen, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from the world deposit	mln tons	% from the world deposit	mln tons	% from the world deposit	mln tons	% from the world deposit	mln tons	% from the world deposit	
2000	46.802	60.9	14.935	19.4	2.384	3.1	11.855	15.4	0.887	1.2	76.863
2001	46.970	60.5	15.063	19.4	2.482	3.2	12.128	15.6	0.968	1.2	77.611
2002	49.915	62.2	15.125	18.9	2.609	3.3	11.658	14.5	0.924	1.2	80.231
2003	50.365	61.4	16.420	20.0	2.527	3.1	11.851	14.4	0.885	1.1	82.049
2004	53.122	62.6	16.117	19.0	2.868	3.4	11.804	13.9	1.010	1.2	84.923
2005	54.621	63.9	15.627	18.3	2.744	3.2	11.558	13.5	0.912	1.1	85.462
2006	57.386	64.3	16.620	18.6	2.828	3.2	11.586	13.0	0.819	0.9	89.240
2007	58.168	63.6	17.415	19.0	2.632	2.9	12.494	13.7	0.813	0.9	91.521
2008	57.853	64.9	15.828	17,8	2.796	3.1	11.829	13.3	0.804	0.9	89.109
2009	62.042	66.3	16.258	17.4	2.843	3.0	11.657	12.5	0.818	0.9	93.619
2010	61.342	64.2	17.659	18.5	3.253	3.4	12.291	12.9	0.939	1.0	95.484
2011	63.623	63.8	19.358	19.4	3.101	3.1	12.545	12.6	1.042	1.0	99.670
2012	63.737	63.7	19.362	19.3	3.046	3.0	12.928	12.9	1.058	1.1	100.132
2013	64.934	63,4	19.756	19.3	3.366	3.3	13.133	12.8	1.202	1.2	102.390
2014	63.439	62.5	20.030	19.7	3.454	3.4	13.269	13.1	1.328	1.3	101.519
2015	64.162	63.3	18.976	18.7	3.395	3.3	13.551	13.4	1.263	1.2	101.346
2016	63.018	61.7	19.823	19.4	3.782	3.7	14.139	13.8	1.414	1.4	102.176
2017	61.609	60.3	20.441	20.0	4.358	4.3	14.391	14.1	1.440	1.4	102.239
2018	61.627	60.7	20.436	20.1	4.183	4.1	13.989	13.8	1.275	1.3	101.509
2019	62.808	60.7	20.904	20.2	4.106	4.0	14.356	13.9	1.278	1.2	103.452
2020	64.342	59.9	22.489	20.9	4.412	4.1	14.816	13.8	1.314	1.2	107.373

Source: *compiled by authors based on the data from FAOSTAT (2022)*

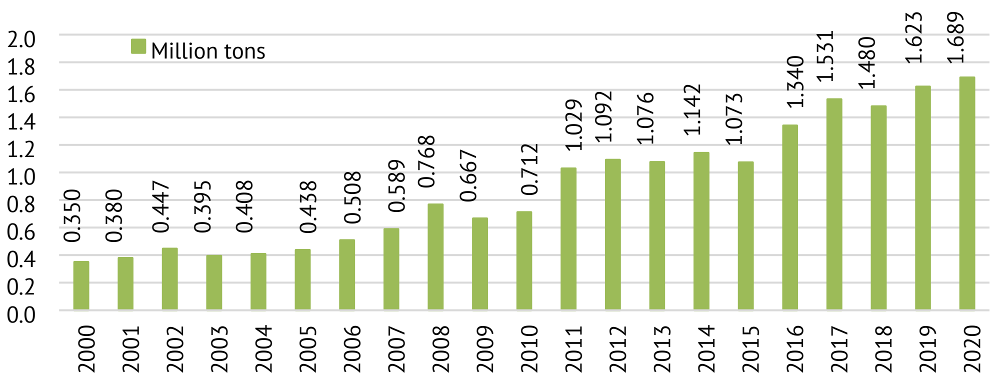

Figure 1. *Dynamics of nitrogen applied mineral fertilizers in Ukraine, million tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

At the same time, it should be noted that the share of nitrogen introduced with mineral fertilizers in Ukraine to the total volume of nitrogen in the world in 2020 was 1.6%, and in European countries it was 11.4%. And a significant share of nitrogen introduced on arable land in the world was satisfied by embedding manure in the soil. According to FAOSTAT (2022), from 2000 year to 2020 year, the amount of nitrogen used with manure increased from 22.85 up to 26.20 million tons. The increase was due to Asian countries (from 9.66 to 12.54 million tons). In Europe, the volume of nitrogen application due to manure over a 20-year period, on the contrary, decreased from 7.19 down to 6.26 million tons, in Oceania they practically did not change (0.162 and 0.156 million tons, respectively, in 2000 year and 2020 year).

In Ukraine, the amount of nitrogen introduced with manure on arable land almost halved over the same 20-year period. So, if in 2000 its volumes were 520.9, then in 2020 year they were 264.9 thousand tons (Fig. 2). This negative state of manure use in Ukraine is explained by a significant decrease in the number of animals in the public sector. It should be noted that the application of manure to the fields served not only as a source of soil enrichment with nitrogen, but also with phosphorus, potassium, trace elements, and most importantly – enriched the soil with organic matter, and later (after its mineralization) with humus, improved the structure, water permeability, microbiological state, etc. Organic-fertilized soil preserves the main components of fertility elements, retains moisture well, it ensures optimal development of the root system of plants, its respiration, and so on. The maximum yield levels of all agricultural crops with high quality indicators are formed precisely by the organo-mineral fertilizer system in crop rotation. The effectiveness of manure application was monitored for several consecutive years (Action and aftereffect) until its final decomposition in the soil. Thus, the introduction of manure provided a fairly significant contribution to the overall nitrogen balance.

Atmospheric precipitation also accounts for a significant share in ensuring the nitrogen balance, that is, a certain amount of nitrogen gets to the fields with rain. Changes in this nitrogen supply to the soil over the past 20 years in the world are shown in Table 2.

***Figure 2.** Dynamics of nitrogen introduced with manure on arable land in Ukraine, thousand tons*
***Source:** compiled by authors based on the data from FAOSTAT (2022)*

***Table 2.** Dynamics of nitrogen entering the soil with precipitation*

Year	Regions of the world										Global nitrogen supply, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	
2000	7.581	55.5	2.594	19.0	1.214	8.9	2.212	16.2	0.048	0.4	13.649
2001	7.563	55.7	2.525	18.6	1.250	9.2	2.191	16.1	0.048	0.4	13.577
2002	7.911	56.9	2.549	18.3	1.264	9.1	2.138	15.4	0.044	0.3	13.906
2003	8.002	57.5	2.487	17.9	1.348	9.7	2.039	14.6	0.052	0.4	13.928
2004	8.194	57.8	2.489	17.5	1.366	9.6	2.087	14.7	0.049	0.3	14.184
2005	8.481	57.9	2.534	17.3	1.475	10.1	2.101	14.4	0.049	0.3	14.640
2006	8.764	59.1	2.470	16.7	1.412	9.5	2.123	14.3	0.052	0.4	14.820

Table 2, Continued

Year	Regions of the world										Global nitrogen supply, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	mln tons	% from the world supply	
2007	8.788	59.2	2.517	17.0	1.470	9.9	2.024	13.6	0.046	0.3	14.845
2008	8.845	59.8	2.389	16.1	1.459	9.9	2.059	13.9	0.045	0.3	14.797
2009	9.235	61.2	2.338	15.5	1.474	9.8	1.988	13.2	0.055	0.4	15.090
2010	9.204	60.6	2.436	16.0	1.521	10.0	1.985	13.1	0.051	0.3	15.197
2011	9.287	61.2	2.378	15.7	1.539	10.1	1.900	12.5	0.066	0.4	15.169
2012	9.526	61.6	2.365	15.3	1.580	10.2	1.923	12.4	0.060	0.4	15.455
2013	9.544	61.7	2.338	15.1	1.595	10.3	1.919	12.4	0.061	0.4	15.456
2014	9.386	60.9	2.375	15.4	1.616	10.5	1.980	12.8	0.063	0.4	15.421
2015	9.414	60.9	2.370	15.3	1.626	10.5	1.981	12.8	0.061	0.4	15.452
2016	9.386	60.9	2.356	15.3	1.646	10.7	1.973	12.8	0.059	0.4	15.419
2017	9.401	60.7	2.383	15.4	1.663	10.7	1.983	12.8	0.061	0.4	15.491
2018	9.477	60.9	2.378	15.3	1.677	10.8	1.975	12.7	0.060	0.4	15.566
2019	9.475	60.9	2.375	15.3	1.677	10.8	1.979	12.7	0.060	0.4	15.566
2020	9.484	60.9	2.369	15.2	1.686	10.8	1.970	12.7	0.060	0.4	15.569

Source: *compiled by authors based on the data from FAOSTAT (2022)*

According to Table 2, the supply of nitrogen with precipitation in the world in 2000 was 13.65, and by 2020 it increased up to 15.57 million tons. Some growth in this nitrogen supply was mainly due to countries in Asia and Africa. In the countries of America and Europe, nitrogen intake with precipitation, on the contrary, slightly decreased during this period. As for Ukraine, the supply of nitrogen to the soil with snow or rain for the period from 2000 year to 2020 year practically did not change, although in dry years nitrogen was received somewhat less (Fig. 3). At the same time, the share of Ukraine in the total volume of nitrogen entering the soil with precipitation in 2020 year, according to FAOSTAT (2022) data, in Europe was 12.4%, and in the world volume, it was 1.6%.

In the positive part of the nitrogen balance, the main place belongs to the arrival of this element of nutrition due to biological fixation by legumes. Over a 20-year period, the amount of nitrogen entering the soil due to symbiotic fixation of air nitrogen by plant nodule bacteria increased significantly. So, if the global fixation of biological nitrogen in 2000 was 23.36 million tons, then in 2020 this figure increased up to 39.2 million tons (Table 3).

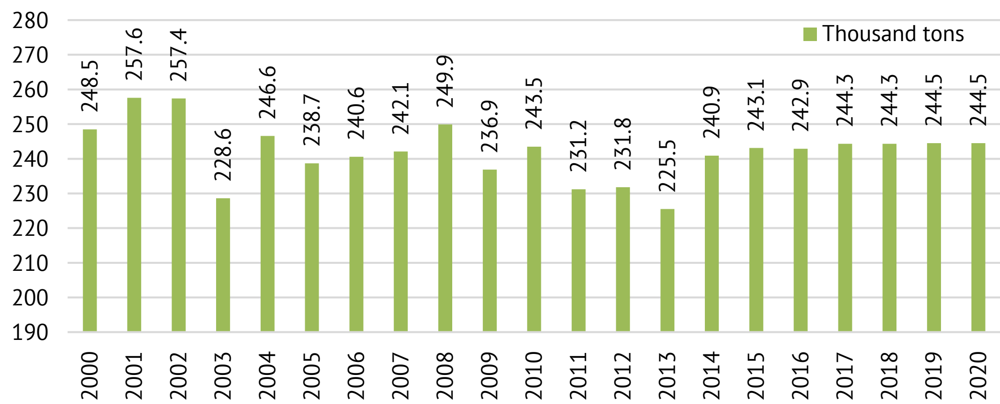

Figure 3. *Dynamics of nitrogen entering the soil with precipitation on arable land of Ukraine, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

Table 3. *Dynamics of biological nitrogen fixation on arable land*

Year	Regions of the world										World biological nitrogen fixation, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from world nitrogen fixation	mln tons	% from world nitrogen fixation	mln tons	% from world nitrogen fixation	mln tons	% from world nitrogen fixation	mln tons	% from world nitrogen fixation	
2000	9.673	41.4	11.364	48.6	1.531	6.6	0.567	2.4	0.225	1.0	23.359
2001	9.602	39.7	12.122	50.1	1.607	6.6	0.617	2.6	0.247	1.0	24.195
2002	9.439	38.5	12.596	51.4	1.690	6.9	0.621	2.5	0.159	0.6	24.505
2003	9.768	38.2	13.320	52.1	1.663	6.5	0.619	2.4	0.209	0.8	25.580
2004	9.960	36.9	14.458	53.6	1.688	6.3	0.692	2.6	0.175	0.6	26.973
2005	10.165	36.7	14.871	53.7	1.778	6.4	0.659	2.4	0.231	0.8	27.704
2006	9.946	35.8	15.215	54.8	1.825	6.6	0.667	2.4	0.131	0.5	27.784
2007	10.265	37.1	14.884	53.8	1.829	6.6	0.513	1.9	0.158	0.6	27.649
2008	10.439	36.1	15.831	54.8	1.939	6.7	0.529	1.8	0.158	0.5	28.896
2009	10.243	35.7	15.660	54.5	2.034	7.1	0.595	2.1	0.194	0.7	28.727
2010	10.759	34.1	17.552	55.6	2.282	7.2	0.732	2.3	0.228	0.7	31.554
2011	10.828	34.3	17.403	55.2	2.295	7.3	0.791	2.5	0.225	0.7	31.543
2012	10.630	34.3	16.881	54.5	2.511	8.1	0.769	2.5	0.199	0.6	30.990
2013	10.938	32.6	18.996	56.7	2.635	7.9	0.760	2.3	0.196	0.6	33.524
2014	10.698	30.4	20.596	58.5	2.729	7.8	0.962	2.7	0.196	0.6	35.181
2015	10.278	28.7	21.512	60.0	2.744	7.7	1.122	3.1	0.184	0.5	35.839
2016	10.709	28.9	21.953	59.3	2.856	7.7	1.213	3.3	0.266	0.7	36.997
2017	11.545	29.4	22.940	58.3	3.050	7.8	1.411	3.6	0.379	1.0	39.326
2018	11.514	29.9	22.262	57.7	3.173	8.2	1.327	3.4	0.276	0.7	38.552
2019	11.358	30.3	21.553	57.5	3.116	8.3	1.266	3.4	0.179	0.5	37.472
2020	11.875	30.3	22.743	58.0	3.161	8.1	1.244	3.2	0.172	0.4	39.196

Source: *compiled by authors based on the data from FAOSTAT (2022)*

The largest share of nitrogen arrivals in the total world balance in the increase in this item was provided by the countries of America, Europe and Africa. To a lesser extent, this occurred in Asian countries, where, as a percentage of the global nitrogen fixation rate, this balance sheet item even decreased from 41.4% in 2000 down to 30.3% in 2020. Although in fact the increase in nitrogen was in Oceania countries, the dynamics of biological nitrogen fixation by legumes tended to decrease in both actual and percentage terms.

In Ukraine, since 2000, there was an increase in the amount of biologically fixed nitrogen by legumes (Fig. 4). Due to this, the nitrogen balance was met from 47.1 thousand tons in 2000 year and reached a maximum in 2017 year, when this figure in the state was 293.8 thousand tons. In subsequent years, the supply of nitrogen due to its biological fixation by legumes began to decrease and in 2020 amounted down to 191.6 thousand tons or compared to 2017 it decreased by 34.8%. The share of Ukraine in the total volume of fixed nitrogen in Europe in 2020 was 15.4%, and in the world, it was 0.49%. During 2012-2018 years, it was significantly larger and ranged from 20.8-24.8% relative to Europe and 0.68-0.75% of the world (FAOSTAT, 2022). This negative situation was again associated with a significant reduction in the number of animals in the public sector and a reduction in the area under perennial legumes, which were used to produce high-quality feed with a high protein content (hay, haylage, green mass, pellets, etc.). The trend of reducing the area under perennial grasses would continue in the coming years.

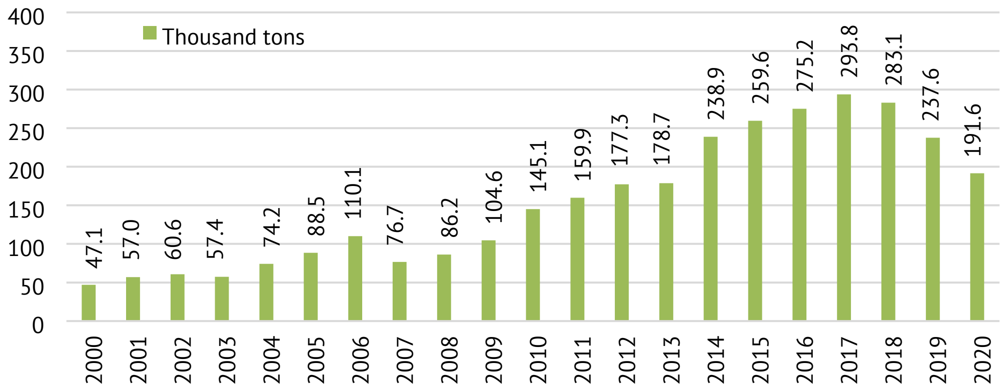

Figure 4. *Dynamics of biological nitrogen fixation on arable land in Ukraine, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

So, the main indicators regarding the ways of nitrogen supply to the soil with various most important sources are given. Now it was necessary to indicate which were the components of losses of that extremely important element of nutrition that was known and widespread in nature. First of all, this was due to the process of leaching nitrogen from cultivated land. This was the process of washing nitrate nitrogen (NO_3) on irrigated, waterlogged soils or as a result of heavy rains, when the nitrogen of mineral fertilizers introduced into the upper layers of the soil was redistributed to much deeper horizons or to ground water, it became inaccessible to plants. At the same time, soil residues that were well enriched with organic matter and they had a high-water absorption capacity, on the contrary, they could contain significantly more water along with dissolved nitrate compounds. Nitrogen losses due to leaching over the analyzed 20-year period in the world as a whole were increasing. So, if this item of expenditure in 2000 accounted for 12.204, then in 2020 it was 16.038 million tons from the total area of arable land. In Asia, this figure increased from 53.9% up to 56.5%, in America it was from 20.3% up to 21.1%, in Africa it was from 3.4% up to 4.7%, in Oceania it did not change (1.0%), and in Europe, the number of actual leaching losses also remained virtually unchanged: 2.606 and 2.664 million tons, and as a percentage of total leaching in the world it decreased from 21.4% in 2000 down to 16.6% in the United States. 2020, respectively (FAOSTAT, 2022).

In Ukraine, this component of the balance sheet continued to grow (Fig. 5). Since 2000, in which leaching losses amounted to 139.2, by 2020 they increased up to 261.3 thousand tons, or almost doubled. At the same time, it should be noted that the area of large-scale irrigation of land during this period significantly decreased. Ukraine's share of total nitrogen losses from arable land in Europe due to leaching in 2020 was 9.8%, and world land it was 1.63% (FAOSTAT, 2022).

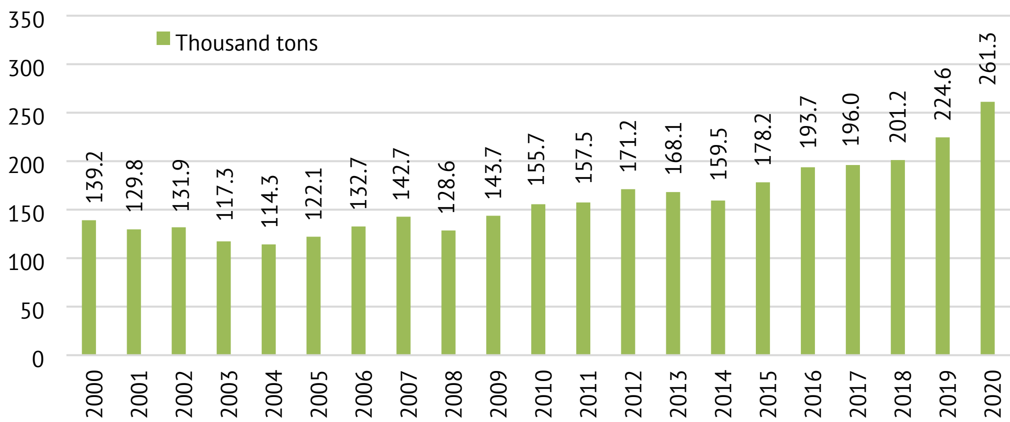

Figure 5. *Dynamics of nitrogen losses of arable land in Ukraine due to leaching, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

Even greater were the nitrogen losses that occur during evaporation and denitrification of NO_3^-. This occurred during the conversion of nitrates by soil bacteria into gaseous oxides and molecular nitrogen. Nitrogen fertilizers were well soluble in water, their compounds were quite mobile, quickly redistribute along the soil profile in the presence of moisture and together with it evaporate from the field surface. Changes in nitrogen losses from arable land over a 20-year period were shown in Table 4. Its data show that during this period, nitrogen losses due to evaporation from arable land in the world increased significantly – from 29.758 in 2000 up to 40.253 million tons in 2020. The largest increase in this component of the nitrogen balance was typical for Asian and African countries. Much slower over the years, the rate of nitrogen loss to evaporation occurred in the countries of Oceania, Europe and America. In Ukraine, during the specified period of observations, nitrogen losses from arable land due to evaporation more than doubled (Fig. 6). It should be noted that in the total volume of nitrogen losses from arable land in Europe and the world due to evaporation in 2020, the share of Ukraine was 9.7 and 1.48%, respectively (FAOSTAT, 2022).

Table 4. *Dynamics of nitrogen losses of arable land due to evaporation*

Year	Regions of the world										World evaporation of arable land nitrogen, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from world evaporation	mln tons	% from world evaporation	mln tons	% from world evaporation	mln tons	% from world evaporation	mln tons	% from world evaporation	
2000	16.851	56.6	5.947	20.0	0.985	3.3	5.661	19.0	0.315	1.1	29.758
2001	16.940	56.5	6.027	20.1	0.997	3.3	5.677	18.9	0.340	1.1	29.981
2002	17.761	57.5	6.093	19.7	1.084	3.5	5.598	18.1	0.325	1.1	30.862
2003	18.109	57.3	6.462	20.4	1.063	3.4	5.658	17.9	0.314	1.0	31.605
2004	18.854	58.2	6.406	19.8	1.186	3.7	5.575	17.2	0.352	1.1	32.372
2005	19.410	59.4	6.326	19.4	1.162	3.6	5.434	16.6	0.323	1.0	32.655
2006	20.088	59.8	6.555	19.5	1.203	3.6	5.443	16.2	0.297	0.9	33.586
2007	20.527	59.3	6.941	20.0	1.142	3.3	5.730	16.5	0.295	0.9	34.635
2008	20.815	60.6	6.516	19.0	1.180	3.4	5.556	16.2	0.291	0.8	34.358
2009	21.792	61.9	6.522	18.5	1.207	3.4	5.362	15.2	0.295	0.8	35.179
2010	22.112	60.8	7.049	19.4	1.332	3.7	5.559	15.3	0.329	0.9	36.382
2011	22.429	60.0	7.678	20.5	1.305	3.5	5.592	15.0	0.363	1.0	37.366
2012	22.484	60.1	7.628	20.4	1.318	3.5	5.634	15.0	0.372	1.0	37.437
2013	22.715	59.8	7.696	20.3	1.380	3.6	5.763	15.2	0.399	1.1	37.954
2014	22.866	59.7	7.787	20.3	1.418	3.7	5.788	15.1	0.449	1.2	38.308
2015	22.928	60.3	7.362	19.4	1.436	3.8	5.864	15.4	0.422	1.1	38.012
2016	22.918	59.6	7.534	19.6	1.560	4.1	5.954	15.5	0.466	1.2	38.431
2017	23.056	58.9	7.798	19.9	1.744	4.5	6.089	15.5	0.475	1.2	39.162
2018	22.828	58.9	7.882	20.3	1.696	4.4	5.926	15.3	0.455	1.2	38.787
2019	22.665	58.5	7.953	20.5	1.716	4.4	5.982	15.4	0.434	1.1	38.750
2020	23.447	58.2	8.480	21.1	1.781	4.4	6.113	15.2	0.432	1.1	40.253

Source: *compiled by authors based on the data from FAOSTAT (2022)*

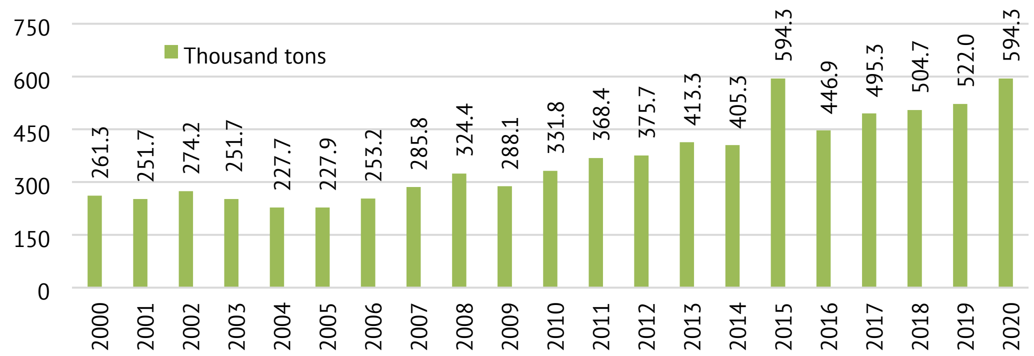

Figure 6. *Dynamics of nitrogen losses from arable land in Ukraine due to evaporation, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

Most of all nitrogen from the soil and fertilizers was spent by agricultural crops on crop formation. The higher was the yield, the greater the amount of nitrogen removed. During the period from 2000 to 2020 years, nitrogen removal in all countries of the world increased: during the specified period, it increased from 64,433 up to 103,336 million tons (Table 5).

Table 5. *Dynamics of nitrogen removed from the soil by cultivated crops*

Year	Regions of the world										World nitrogen removal, mln tons
	Asia		America		Africa		Europe		Oceania		
	mln tons	% from world re-moval	mln tons	% from world re-moval	mln tons	% from world re-moval	mln tons	% from world re-moval	mln tons	% from world re-moval	
2000	28.811	44.0	21.615	33.0	4.126	6.3	9.650	14.7	1.232	1.9	65.433
2001	29.170	43.3	22.268	33.0	4.385	6.5	10.411	15.4	1.199	1.8	67.432
2002	29.133	43.3	21.834	32.5	4.479	6.7	10.573	15.7	1.234	1.8	67.253
2003	29.888	43.6	23.910	34.9	4.785	7.0	9.150	13.4	0.802	1.2	68.535
2004	30.994	41.8	25.630	34.5	4.896	6.6	11.375	15.3	1.301	1.8	74.195
2005	31.880	42.7	25.837	34.6	5.116	6.8	10.630	14.2	1.224	1.6	74.688
2006	32.835	43.4	25.885	34.2	5.360	7.1	10.254	13.6	1.265	1.7	75.599
2007	34.439	44.3	27.561	35.4	5.113	6.6	9.935	12.8	0.777	1.0	77.826
2008	34.931	42.4	28.918	35.1	5.424	6.6	12.257	14.9	0.929	1.1	82.460
2009	34.917	42.9	28.073	34.5	5.527	6.8	11.661	14.3	1.147	1.4	81.325
2010	36.173	43.0	30.541	36.3	5.859	7.0	10.398	12.4	1.151	1.4	84.122
2011	38.227	43.5	30.575	34.8	5.885	6.7	11.847	13.5	1.341	1.5	87.875
2012	38.742	44.8	29.390	33.9	6.217	7.2	10.750	12.4	1.471	1.7	86.569
2013	39.452	42.5	33.342	35.9	6.430	6.9	12.220	13.2	1.316	1.4	92.760
2014	39.426	41.3	34.836	36.5	6.637	6.9	13.295	13.9	1.364	1.4	95.559
2015	39.435	40.9	36.027	37.4	6.659	6.9	12.969	13.5	1.280	1.3	96.371
2016	40.013	40.5	37.503	38.0	6.682	6.8	13.221	13.4	1.271	1.3	98.690
2017	41.170	40.2	38.415	37.5	7.146	7.0	13.863	13.5	1.727	1.7	102.321
2018	41.702	41.3	37.315	37.0	7.417	7.4	13.096	13.0	1.330	1.3	100.861
2019	42.595	41.7	37.083	36.3	7.382	7.2	13.943	13.7	1.106	1.1	102.109
2020	43.099	41.7	38.428	37.2	7.467	7.2	13.373	12.9	0.970	0.9	103.336

Source: *compiled by authors based on the data from FAOSTAT (2022)*

Nitrogen removal with the crop of agricultural plants in Ukraine changed with an even greater trend (Fig. 7). So, if 657.6 thousand tons of nitrogen were used in 2000, then in 2019 they were 2044.9 thousand tons, or three times more. It should be noted that in 2019 year, this indicator was an item of negative balance-reached its maximum. Already in the next 2020 year, less nitrogen with the harvest was taken out as 1752.1 thousand tons. This had an exceptionally close relationship with the availability of years of growing crops with precipitation during the growing season, namely: the more favorable the year for climatic indicators, the higher the yield was formed, and therefore more plants used nitrogen for its formation. Such peaks and, conversely, insignificant nitrogen removals from the fields of Ukraine were clearly illustrated by Figure 7. In particular, 2000, 2003, 2007, 2010 and 2012 years were characterized by low harvest levels. The lower productivity of agricultural crops was formed in 2020 year, compared to 2019 yr. Thus, the share of Ukraine in the total volume of nitrogen removed from the soil to European countries in 2019 was 14.7%, and in 2020 it was 13.1%, and in the world volume it was 2.0 and 1.7%, respectively.

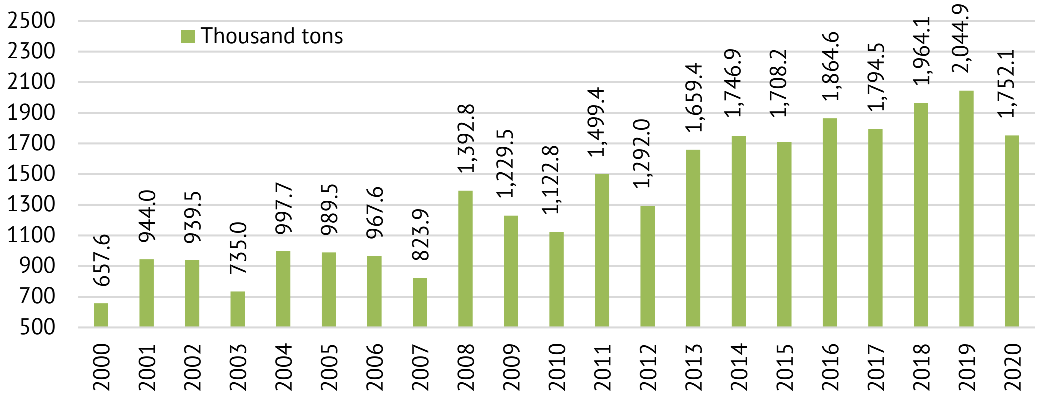

Figure 7. *Dynamics of nitrogen removed from the soil by cultivated crops in Ukraine, thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

Based on the difference in incoming and outgoing parts relative to nitrogen, the overall balance of this battery was determined. Calculations showed that the nitrogen balance on arable land both in the world and in most countries of different continents for the period from 2000 to 2020 years was positive, which indicated that more nitrogen entered the soil compared to its total costs of plants for crop formation and other sources of costs (Table 6). The negative nitrogen balance for almost the entire period of definitions was only in Oceania (except for 2003, 2007 and 2020 years), whose share in the world balance was quite insignificant.

Table 6. *Nitrogen balance of arable land in the world by region (ratio of income and expenditure items), mln tons*

Year	World balance	Regions of the world				
		Asia	America	Africa	Europe	Oceania
2000	29.322	21.475	3.780	0.501	3.911	-0.346
2001	28.469	21.096	3.932	0.450	3.231	-0.240
2002	31.018	23.338	4.905	0.493	2.672	-0.391
2003	31.666	23.043	4.300	0.216	4.035	0.072
2004	29.639	24.289	3.553	0.355	1.830	-0.389
2005	30.703	24.878	3.510	0.268	2.365	-0.317
2006	32.834	26.045	4.491	0.069	2.735	-0.506
2007	31.583	25.065	2.843	0.316	3.357	0.001
2008	26.398	24.334	1.385	0.257	0.583	-0.161
2009	31.268	27.651	2.433	0.317	1.189	-0.323
2010	31.851	25.808	2.731	0.562	2.979	-0.229
2011	30.816	25.677	3.402	0.466	1.613	-0.341

Table 6, Continued

Year	World balance	Regions of the world				
		Asia	America	Africa	Europe	Oceania
2012	32.432	25.407	4.136	0.367	3.017	-0.496
2013	30.399	25.934	2.550	0.547	1.602	-0.235
2014	28.019	23.912	2.893	0.525	0.910	-0.221
2015	28.320	24.362	2.057	0.484	1.604	-0.188
2016	27.654	23.293	1.638	0.842	1.892	-0.012
2017	25.839	21.753	1.948	0.945	1.526	-0.333
2018	26.539	21.711	2.288	0.738	1.977	-0.175
2019	26.022	21.842	2.205	0.676	1.320	-0.020
2020	28.710	22.629	2.927	0.873	2.140	0.141

Source: *compiled by authors based on the data from FAOSTAT (2022)*

In Ukraine, during the analyzed period, out of the total number of years, only in extremely unfavorable precipitation in 2000, 2003 and 2007 years, the nitrogen balance was positive, and in 18 years out of 21 it was negative (Fig. 8). Moreover, significantly higher nitrogen consumption relative to its entry into the soil provided negative balance indicators in the most favorable years of crop cultivation for moisture, which was clearly illustrated by Figure 8.

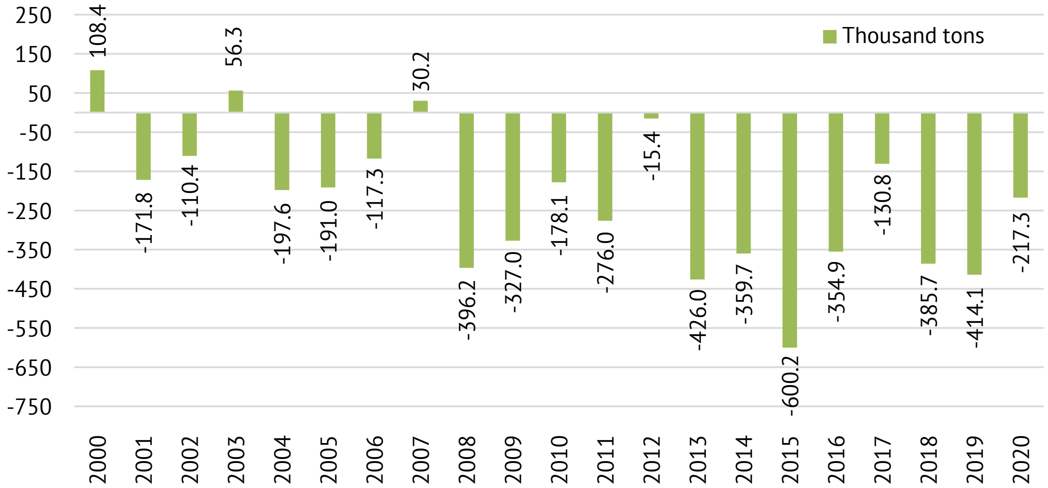

Figure 8. *Nitrogen balance of arable land in Ukraine (ratio of items of income and costs), thousand tons*
Source: *compiled by authors based on the data from FAOSTAT (2022)*

The most significant shortage of nitrogen nutrition on the cultivated soils of Ukraine was manifested in 2015 year and it amounted to 600.2 thousand tons. Such the lack of nitrogen in the soil caused by the already known, above-mentioned factors such as: a decrease in the volume of application of traditional organic fertilizer-semi-rotted manure, a violation of the reasonable alternation of crops in crop rotations, including excessive growth of areas under sunflower, which dried the soil and carried out a significant amount of nutrients, including nitrogen. At the same time, starting from the 90s of the 20th centuries, perennial grasses grown significantly less than necessary, which during three years of use were able to leave an average of 200 kg/ha or more of biologically fixed nitrogen after formation development, which was not washed out or lost from the soil and was free of charge. In many farms, even annual legumes or grass mixtures with them were not sown practically, which also provided replenishment of the soil with valuable crop-root residues and nitrogen (Gamajunova *et al.*, 2021). If this was not done, the soil would continue to lose the main signs of fertility, because for the formation of the crop, plants would use nutrients directly from humus and thus they impoverished and depleted the soil.

Previously, in Ukraine (1987-1990 years), about 150 kg of mineral fertilizers were applied for each hectare of arable area (in the amount of NRK), and on irrigated land – 325 kg/ha. In the composition of mineral fertilizers, the proportion of nitrogen fertilizers was significantly higher, which most increased the yield and affected its quality.

The same trend remains in the future. According to Pro-Consulting, in the structure of fertilizer use in agricultural enterprises of Ukraine, 68% of the total amount accounted for nitrogen. The share of potash was 3.7%, phosphorous one was 0.3%, and the complex one was 28%. The total amount of fertilizer application in 2018 it decreased from 4.4 to 2.3 million tons, but the share of nitrogen increased to 65% (Gamayunova *et al.*, 2020).

According to FAO, the actual level of mineral fertilizers applied in countries around the world varies significantly. Most of them were used in the Netherlands as 258 kg/ha, in Great Britain as 247, in Israel as 240, in Germany as 202 kg/ha. Slightly fewer mineral fertilizers are applied in Belarus as 194, in Poland as 176, in France as 169, in the Czech Republic as 157, in the USA as 137 kg/ha of active substance (Prokhopchuk, 2018).

The amount of nitrogen entered the soil with mineral fertilizers in the countries of the world for the years 2000-2020 was shown in Table 7. At the same time, it was quite positive that since 2000, when only 10.45 kg of nitrogen was applied to the cultivated hectare of soil in Ukraine, which was significantly less compared to the volume of application in the world, by 2020 this figure increased almost fivefold and it amounted to 50.02 kg/ha.

Table 7. *Dynamics of nitrogen entering the soil with mineral fertilizers, kg/ha of arable land*

Year	Regions of the world					World supply	Ukraine
	Asia	America	Africa	Europe	Oceania		
2000	83.30	40.35	10.37	39.02	33.19	51.50	10.45
2001	83.25	40.56	10.82	40.39	35.22	51.99	11.36
2002	88.34	40.94	11.23	39.13	35.56	53.82	13.35
2003	88.68	44.38	10.54	40.08	34.79	54.74	11.83
2004	93.00	43.52	11.92	40.03	36.14	56.43	12.21
2005	95.58	42.14	11.20	39.31	31.84	56.59	13.15
2006	100.44	44.81	11.46	39.64	30.99	59.19	15.25
2007	101.50	46.96	10.52	42.99	31.96	60.61	17.67
2008	101.11	43.01	11.03	40.60	30.41	58.96	23.01
2009	107.87	44.46	11.18	40.05	27.64	61.76	20.00
2010	106.53	48.07	12.53	42.38	33.40	62.78	21.34
2011	110.14	52.77	11.74	43.31	30.48	65.04	30.81
2012	110.01	52.80	11.23	44.54	31.00	64.95	32.69
2013	111.73	53.72	12.28	45.34	35.54	66.21	31.95
2014	108.97	54.56	12.57	45.83	38.43	65.58	33.94
2015	109.73	51.68	12.32	46.87	37.65	65.38	31.87
2016	107.15	54.20	13.60	48.99	43.42	65.79	39.79
2017	104.33	55.26	15.56	49.84	43.36	65.44	45.48
2018	104.27	55.42	14.91	48.53	38.09	64.98	43.84
2019	106.38	56.80	14.65	49.69	38.59	66.29	48.05
2020	108.82	61.24	15.66	51.44	39.61	68.76	50.02

Source: *compiled by authors based on the data from FAOSTAT (2022)*

If there is a lack of nitrogen for plant nutrition, in addition to a shortage of crops, the grown products would be formed with a low protein content. This is especially true for grain crops, as it is nitrogen which provides an increase in valuable protein fractions in grain (Hawkesford & Griffiths, 2019; Guerrini *et al.*, 2020). For this reason, at the beginning of the earing phase, foliar top dressing of winter cereals with urea is carried out at the rate of N_{30}. This measure makes it possible to increase the grain content to 6% gluten and, accordingly, to 2% or more protein in the optimal state of plants (Sydiakina & Gamayunova, 2020). In addition, such top dressing is combined with simultaneous protection of grain crops from the bug of the harmful turtle, which also provides an increase in the protein content in the grain (Tomchuk, 2020).

At the same time, high nitrogen rates lead to a decrease in the fat content in oilseeds due to the formation of greater protein content (Sydiakina & Pavlenko, 2021). The use of high standards of mineral nitrogen for vegetable crops can lead to a significant increase in nitrates in fruits. This occurs most intensively when the ratio of nitrogen with phosphorus and potassium is unbalanced and there is a lack of trace elements (Padilla *et al.*, 2020; Tei *et al.*, 2020).

Many researchers determined that the yield levels of agricultural crops and the quality of grown products was formed optimal with the combined application of organic and mineral fertilizers. In this case, even increased rates of nitrogen fertilizers will not negatively affect the main indicators of crop quality, as a certain part of nitrogen is partially fixed by soil microorganisms that decompose fresh organic matter. The nitrogen used by them will be fixed by the microbiota for a certain period of time and it will not be able to be "harmful". On the contrary, it acquires the properties of biological nitrogen: it is not lost from the soil and becomes available to plants after the death and decomposition of microorganisms (Lopusniak, 2011; Kerru *et al.*, 2020). This is an important sign of the activity of microorganisms in ensuring a favorable nitrogen regime of the soil and the full use of its compounds by plants without loss.

In modern agriculture, with a significant reduction in the volume of manure use, post-harvest and root residues are used as organic fertilizers after harvesting agricultural crops. To accelerate their decomposition, small rates of nitrogen fertilizers and stubble biodestructors, which include microorganisms, are used simultaneously with their sealing. It also has a positive effect on some increase in the content of nitrogen and other nutrients in the soil. In addition, most importantly, the soil is enriched with organic matter, its structure, water absorption capacity, etc. improves (Kovalenko, 2022; Panfilova & Byelov, 2022; Sydiakina, 2021). In soils with a sufficient content of organic matter, the introduced mineral nitrogen will be converted much faster from one form to another, unproductive losses of this element will significantly decrease due to temporary fixation by microorganisms (Yu *et al.*, 2020; Voltr *et al.*, 2021).

A significantly larger proportion of nitrogen in the nitrogen balance earlier, due to the conduct of scientifically based crop rotations (8-10-saw crops with alfalfa selection), is provided by systematic application of semi-rotted manure under row crops in the recommended standards, as well as by growing perennial grasses (D'Amours *et al.*, 2021; Oruj *et al.*, 2021). Now, due to the violation of the alternation of agricultural crops, the introduction of short-rotation crop rotations, insufficient saturation of their legumes, a significant reduction in the use of manure due to a reduction in the number of animals, the application of organic fertilizers is stopped practically. During this period, the saturation of soils with organic substances occurs only due to the embedding in the soil of post-harvest-root residues of cultivated crops, as well as straw of grain spikelet crops (Assefa & Tadesse, 2019; Kavun & Loboda, 2020; Gamajunova *et al.*, 2021).

So, it is necessary to incorporate all residues after crop harvesting into the soil with simultaneous addition of mineral nitrogen and stover biodegraders. Crop rotation should always include legume components, regardless of the number of fields. Nitrogen fertilizers should be applied in recommended norms for the zone, taking into account the predecessor and nitrogen content in the specific field's soil. This will ensure consistent yields with high quality indicators and maintain the nitrogen balance of soils in an optimal state.

CONCLUSIONS

The nitrogen balance in the soils of most countries of the world for the period from 2000 up to 2020 years is positive, that is, more of this element of nutrition enters the cultivated soils than it is lost and taken out by plants for crop formation. In Ukraine the nitrogen balance in soils is negative. This condition is explained by a number of reasons, which are as follows:

- non-compliance with scientifically based crop alternation in crop rotations;
- significant reduction of the area under perennial grasses and annual legumes;
- reducing the use of manure and mineral fertilizers per hectare of cultivated soil;
- limited use of the organo-mineral fertilizer system for cultivated crops in production conditions, despite the fact that many studies prove that the main indicators of soil fertility are preserved with the combined use of organo-mineral fertilizers in the recommended standards and with scientifically based alternation of agricultural crops in crop rotation.

The agricultural sector in Ukraine should be based on the use of scientifically based selection of agricultural crops in crop rotations (including legumes). This is the simplest and cheapest measure that allows you to maintain (even improve) soil fertility, enrich it with the optimal number of organic substances and free biological nitrogen. Due to crop rotation, the cost of growing crops is reduced by 15-20% (for fertilizers, plant protection products against weeds, pests and diseases). In addition to enriching the soil with nitrogen, legumes contribute to the dissolution of fixed phosphates in the soil, which also plays an important role in the nutrition system of agricultural plants.

Nitrogen nutrition plays an extremely important role in crop yield and quality formation, which requires maintaining its positive balance. To achieve this, it is necessary to systematically monitor the presence of this nutrient in the soil and follow recommendations for maintaining its positive balance, avoiding significant losses.

ACKNOWLEDGMENTS

None.

CONFLICT OF INTEREST

None.

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Проблема азоту в сучасному сільському господарстві

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Анотація. Оптимальне азотне живлення рослин в умовах достатнього зволоження дозволяє отримати високу продуктивність сільськогосподарських культур з якісними показниками. Метою даної статті було узагальнення та аналіз статистичних даних щодо динаміки надходження та витрат азоту з ріллі у світі та в Україні, а також надання практичних рекомендацій щодо вирішення азотного питання в сучасному сільському господарстві. У дослідженні використано методи теоретичного узагальнення, порівняльного аналізу, графічний, абстрактно-логічний методи та статистичні дані FAOSTAT за період 2000-2020 рр. Результати дослідження показали, що надходження азоту з мінеральними добривами постійно зростає як у світі, так і в Україні. На відміну від світових показників, в Україні спостерігається значне скорочення надходження азоту з гноєм, а також зменшення надходження азоту з атмосферними опадами та за рахунок біологічної фіксації бобовими культурами. Такі компоненти азотного балансу як вилуговування, випаровування та денітрифікація, відіграють значну роль у витратах азоту. Ці компоненти витрат мають тенденцію до зростання як у світі, так і в Україні. Найбільшу частку у структурі витрат усіх країн світу, включаючи Україну, займає винос азоту сільськогосподарськими культурами. Розрахунки показали, що баланс азоту на орних землях як у світі, так і в більшості країн на різних континентах за досліджуваний період, складався позитивно. Проте в Україні він був від'ємним упродовж 18 з 21 року. Для вирішення цієї проблеми запропоновано практичні рекомендації з використанням кращих практик і напрацювань економічно розвинених країн світу

Ключові слова: мінеральні добрива; органічні добрива; біологічна фіксація; видалення азоту; вилуговування; випаровування; баланс азоту