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EFFICIENCY OF WINTER WHEAT FERTILIZATION SYSTEMS IN THE STEPPE ZONE OF SOUTHERN UKRAINE

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ABSTRACT

The results of the fifth and sixth rotations (2007–2020) of a long-term stationary experiment to study the effectiveness of various mineral fertilizer systems for growing winter wheat in the field crop rotation are summarized. The stationary experiment was established in 1971 on the southern low-humus heavy loam chernozem on forests. The natural and climatic zone is the Steppe; the agro-soil province is the dry Black Sea Steppe. Alternation of crops in the field crop rotation: black pair – winter wheat – winter rapeseed – winter wheat – sideral pair – winter wheat – winter wheat. The weighted average indicators of fertilizer efficiency in winter wheat crops were determined: $N_{60}P_{30–60}K_{30–60}$ – yield gave increase of 1,52 t/ha; energy efficiency coefficient was of 3,63; net profit was of 0,98 $/ha; $N_{120}P_{30–60}K_{30–60}$ – yield gave increase of 2,04 t/ha; energy efficiency coefficient was of 2,41; net profit was of 0,79 $/ha; $N_{180}P_{30–60}K_{30–60}$ – yield gave increase of 2,22 t/ha; energy efficiency coefficient was of 2,09; net profit was of 0,69 $/ha. For the zone of the Black Sea Steppe of Ukraine, the parameters of the payback of a unit of the active substance of mineral fertilizers are determined by the increments of the protein content in winter wheat grain, which on average amount to (mg/kg a. s.): 202 NPK kg/ha and the ratio N:P:K = 2,5:1:1 – 10,68, N_{60} – 28,20, N_{120} – 28,20 and N_{180} – 21,48. It is shown that the systematic use of a complete mineral fertilizer with a total rate of 202 NPK kg/ha and a ratio of N:P:K = 2,5:1:1 for black and sideral pairs provides winter wheat grain with a protein content of 14,18%; winter rapeseed – 13,21% and 12,40% – for a stubble precursor. It is noted that at high and very high level of availability of available phosphorus and potassium in the southern chernozem, which was created in a stationary experiment during the years preceding the presented period (37 years), the maximum protein content in wheat grain is noted when N_{180} is applied: for black pairs – 14,84%, for sidereal – 15,25%, for winter rapeseed – 14,38% and for stubble predecessor – 13,86%.

Keywords: winter wheat, mineral fertilizers, precursor, crop rotation, agrotechnical efficiency, economic and energy efficiency, net income.

INTRODUCTION

Ukraine's agriculture accounts for up to 25% of the country's national income and its products account for up to 15% of total exports, with the majority of both production and export accounted for by winter wheat grain.

According to experts, the export potential of Ukraine can be almost doubled by optimizing the growing area and increasing the yield (Fedulova I. V., 2011; Serdyuk T. Yu, 2012). In the last decade, the acreage of wheat in Ukraine stabilized at the level of 6,3–6,8 million ha, of which 52,8% of the total area was sown in the Steppe zone, including in the Odessa region as 17,5% , Mykolaiv region as 12,1% and Kherson region as 13,1% (Agriculture of Ukraine, 2020). A powerful factor in increasing productivity is the application of mineral fertilizers, the norms and ratios of which are established experimentally for the soil and climatic zones of Ukraine (Poperelya F. *et al*., 2008).

Analysis of literature sources, problem statement

In Germany, when systematizing long-term data (1979–2016) of stationary experiment with different doses of nitrogen fertilizers (Heil K. *et al*., 2020), it was shown that different levels of nitrogen fertilizers changed the response of plants to drought: reducing the amount of nitrogen fertilizers by 20–30% reduced the sensitivity to the absence of precipitation. Scientists of Kharkiv National University conducted an analysis of winter wheat yield over a 37-year period (Kobchenko Yu. F. *et al*., 2014), which showed a high degree of correlation ($r = 0.67$ up to 0.85) between the effectiveness of fertilizers, weather conditions and crop productivity.

Thus, the research of scientists showed that the variability of weather and climatic conditions was the cause of significant variability in the yield of grain crops and the payback of fertilizers. In statistical studies to determine the degree of influence of climate factors on the productivity of grain crops, the results of temporary field experiments were mainly used, and large samples were based on official data in general for regions or countries (Melnyk A. V. *et al*., 2013; Foreign economic…, 2021). At the same time, studies based on the results of long-term stationary experiments can be of high theoretical importance for crop production in certain soil and climatic zones and economically strategic, since it would allow predicting the volume of gross grain production.

The purpose and objectives of the study

Fertilizers have the most effective and powerful effect on the quality of wheat (Bakaeva N. P. *et al*., 2007; Hury G. *et al*., 2015). And since grain crops remain the main source of vegetable protein, it is important to establish their payback not only by increasing yield, but also by increasing quality, especially by increasing the content of “raw” protein.

MATERIALS AND METHODS

To determine the effectiveness of fertilizers in winter wheat crops in the weather conditions of the Black Sea Steppe, it was systematized the data of the field stationary experiment for two rotations of the grain fallow crop rotation (2007–2020). During these years, the fertilization systems according to the experimental variants did not change, the Knopa wheat variety was sown, and the rotation of crops in crop rotations was constant. Winter wheat was sown according to the following predecessors: black pair, sideral pair, wheat after sideral pair and winter rapeseed.

The soil was southern low-humus heavy-loamy chernozem on loess. Fertilizer options were given in the presentation of the results.

Agrotechnical efficiency was calculated as the amount of additional grain yield per unit of applied fertilizers (Instructions and standards…, 1987). To characterize the economic efficiency, it was determined the net income per 1 $ of the costs associated with the use of fertilizers. At the same time, the cost of the crop increase obtained from fertilizers and the costs of their acquisition and application were taken into account. The actual volume of work performed was taken into account on the basis of technological maps at prices at the end of 2020 (Mazorenko D. I. *et al*., 2006; Monitoring of prices…, 2020; Company "Marker Group"…, 2020; Agricultural sales…, 2020). If necessary, it was used the official data of the State Statistics Committee (Agriculture of Ukraine, 2020).

The energy efficiency of fertilizer systems was carried out through the energy efficiency coefficient (Cee), that is, the ratio of the amount of renewable energy accumulated in the increase in yield to the total cost of anthropogenic energy for the formation of this increase (Medvedovsky O. K. *et al*., 1988).

As an indicator of aridity, the hydrothermal coefficient by G. T. Selyaninov was used, which was the ratio between the amount of precipitation for the period when the air temperature was above 10ºC and the sum of active temperatures for the same period, reduced by 10 times. Climate scientists established the following criteria for characterizing drought: HTC<0,4 it was very severe drought; from 0,4 up to 0,5 it was severe drought; from 0,5 up to 0,6 it was average drought; HTC from 0,7 up to 0,9 it was mild drought; from 1,0 up to 1,5 it was fairly wet, HTC>1,5 it was excessively wet (Kulbida M. I. *et al*., 2009).

The results were processed statistically using the Microsoft Excel software package for personal computers. The arithmetic mean and standard error were determined. The significance of the differences between the control and experimental variants was evaluated according to the Student's criterion and the lightest significant difference (LSD) was considered significant differences, where P<0.05 (Dospekhov B. A., 1971; Ushkarenko V. O. *et al*., 1997; Ushkarenko V. O. *et al*., 2008).

The analysis of the precipitation regime during 2007–2020 is presented in Table 1. The average amount of precipitation for the agricultural year was 443,3 mm. The number of cases when this indicator was out of range ($m_{average}$ +σ) was equal to the number of cases located in the range ($m_{average}$ -σ), which, with almost no asymmetry (-0,16), indicated a uniform distribution of data relative to the average, the coefficient of variability was 28,3%.

Table 1. Characteristics of the precipitation regime during the research period

Indicator	**Precipitation, mm**				**The number of days with precipitation**							
					in total				**less than 5 mm, % of the total Indicator**			
	1*	2*	3*	4*	1*	2*	3*	4*	1*	2*	3*	4*
Average	443,3	145,9	128,7	95,8	52,5	18,4	11,5	16,6	47,3	43,5	45,1	55,6
Standard error	33,5	20,5	18,4	11,3	4,3	2,1	1,0	2,0	4,2	6,4	6,6	5,9
Standard deviation	125,4	76,7	68,9	42,2	15,9	7,8	3,8	7,5	15,6	24,0	24,6	22,2
Kurtosis	-0,76	-1,37	0,59	-0,26	-0,99	1,1	-0,06	5,0	0,53	-0,52	0,96	0,39
Asymmetry	-0,16	0,46	0,5	0,37	0,32	1,17	0,73	1,65	0,59	0,71	0,64	0,14
Minimum value	232,5	56,0	12,4	32,7	30	9	6	5	21,1	13,4	3	11,1
Maximum value	616,1	262,8	280	180	82	37	19	38	81,7	90	100	94,4
Coefficient of variation	28,3	52,6	55,3	44,1	30,3	42,5	33,2	45,5	33,0	55,1	54,6	39,9

** 1 – agricultural year; 2 – the period of spring-summer vegetation before harvesting; 3 – autumn; 4 – winter.*

RESULTS

Calculations carried out for each of the predecessors showed that at different levels of yield, in the increments according to the norms of fertilizers, the pattern was not determined by the predecessor, but only by weather conditions, doses and the ratio of nutrients in the fertilizer systems. Therefore, we considered it was appropriate to continue to operate with data averaged over the predecessors. Table 2 shows the average yield of wheat by fertilizer options for the years of the study. In the non-fertilized variant, the winter wheat grain yield was average of 3,32 t/ha over 14 years, the difference with the fertilization systems ranged from +1,00 t/ha up to +2,24 t/ha, which was mathematically reliable since $LSD_{0,95}$=0,64.
The variability of yield over the years was great: from 44,4% down to 26,7%, but the most dependent one on the conditions of the year was the option without fertilization (44,4%) and the option where only phosphorus – potassium fertilizers were applied during all the years of research (36,6%). The degree of variation in the yield of winter wheat also depended on the rate of nitrogen fertilizer.
Thus, in the fertilizer block, where the nitrogen dose was 60 kg/ha, the average coefficient of variation was 32,3% with a variation from 30,4 up to 33,8%; with N_{120} it was 29,0% (28,5–29,4%); with N_{180} it was 27,9% with an interval from 26,7% up to 29,0%. Thus, there was a tendency to reduce the dependence of the yield level on the growing conditions when applying fertilizers in general, and there was a small, but still present, decrease in the coefficient of variation with an increase in the dose of mineral fertilizers.

Table 2. Winter wheat yield by fertilizer system options, t/ha, 2007–2020

Variant	Years														Average
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	
control	3,58	5,53	4,18	4,19	3,37	3,40	4,20	2,95	2,10	5,55	2,77	1,39	2,17	1,13	3,32
$P_{60}K_{60}$	4,36	6,91	5,90	5,29	4,71	3,85	510	3,60	3,60	5,94	3,75	2,41	2,70	2,36	4,32
N_{60}	4,64	7,13	5,23	5,25	4,92	4,40	5,25	3,65	2,53	5,79	3,50	3,06	3,37	2,20	4,35
$N_{60}P_{60}$	4,31	7,19	5,75	5,69	5,25	4,49	5,64	3,66	3,19	6,21	4,03	3,02	2,89	1,85	4,51
$N_{60}K_{60}$	4,68	6,36	5,77	5,59	5,25	4,76	5,58	3,67	3,08	6,06	3,98	2,26	3,22	2,40	4,48
$N_{60}P_{30}K_{30}$	4,53	7,19	5,47	5,58	5,46	4,36	5,25	3,99	3,04	6,64	3,88	2,95	3,35	2,44	4,58
$N_{60}P_{60}K_{60}$	4,24	7,41	5,65	5,98	5,43	5,10	5,76	3,86	3,41	6,71	4,38	3,53	3,39	2,11	4,78
N_{120}	4,41	7,22	5,92	6,10	6,21	5,03	5,83	3,96	3,70	7,13	4,55	3,78	4,11	2,27	5,02
$N_{120}P_{30}K_{30}$	4,35	7,15	5,73	6,05	5,88	4,67	5,91	4,22	3,56	7,36	5,32	3,61	3,92	2,70	5,03
$N_{120}P_{30}K_{60}$	4,39	7,15	5,71	6,49	6,05	4,80	5,90	4,02	3,58	7,10	5,83	3,64	3,84	2,71	5,09
$N_{120}P_{60}K_{30}$	4,70	7,33	5,98	6,87	6,11	4,89	5,90	3,94	3,60	7,40	6,17	4,04	4,02	2,97	5,28
$N_{120}P_{60}K_{60}$	4,36	7,41	5,85	6,64	6,06	5,19	5,89	4,09	3,74	7,52	5,90	3,84	4,24	2,18	5,21
N_{180}	3,63	6,87	5,53	6,60	6,26	5,77	6,03	4,34	4,05	7,99	5,37	4,60	3,68	2,92	5,26
$N_{180}P_{60}$	4,48	7,08	5,67	6,56	6,07	5,66	5,76	4,06	3,56	6,98	4,49	4,02	4,08	2,87	5,10
$N_{180}K_{60}$	4,08	6,94	6,25	6,17	6,00	5,38	5,77	4,09	3,56	7,58	4,71	4,15	4,09	3,05	5,13
$N_{180}P_{30}K_{30}$	4,42	7,36	6,21	6,67	6,42	4,45	6,29	4,02	3,94	7,83	6,18	4,45	3,87	2,92	5,36
$N_{180}P_{60}K_{60}$	4,00	7,69	5,99	7,23	6,54	5,82	6,37	4,15	4,10	8,38	6,32	4,26	4,09	2,96	5,56
$LSD_{0,95}$															0,64

The average yield of winter wheat for fertilizer options ranged from 7,15 t/ha (2007) up to 2,56 t/ha (2020). Among the 14 years, we identified years with similar yield levels, which were presented in Table 3. During the study period, only two years (14,3%) were marked by a high level of yield (7,00 t/ha) and one year the grain yield was the lowest as 2,56 t/ha. A relatively high agronomic efficiency was observed at the average yield level for the fertilizer variants (5,88 t/ha) and amounted to 10,5 kg of grain per 1 kg of d. v. NPK, the lowest was at the level of 2,56 t/ha as 7,9 kg/ha (or by 24,8% less). With an average grain yield on the fertilized variants of 7,10 t/ha, 4,72 and 3,69 t/ha, the agronomic efficiency was 8,7; 8,2 and 8,6 kg/ha, that is, it differed slightly from each other (within a 5 percent error), and from the maximum was, respectively, 82,9%, 78,1% and 81,9%.

The average agronomic efficiency of fertilizers for 2007–2020 was shown in Table 4, and the individual elements of nutrition in Fig. 1 (payback of mineral nitrogen) and Fig. 2 (payback of phosphorus and potassium).

Table 3. Structure of yield years for the period 2007–2020. According to the stationary field experience

Yield, t/ha		**Years**	**Number of years**		**Average yield on the option without fertilizers**
average	**range of fluctuations**		**in total**	**% of the total number of years**	
7,10	7,04–7,15	2008, 2016	2	14,3	5,54
5,88	5,76–6,17	2009, 2010, 2011, 2013	4	28,6	3,99
4,72	4,35–4,91	2007, 2012, 2017	3	21,4	3,25
3,69	3,52–3,96	2014, 2015, 2018, 2019	4	28,6	2,15
2,56	-	2020	1	7,1	1,13
in total			14	100	-

**the average amount of NPK=180 kg/ha for the fertilizer variants with the ratio (1,9:0,6:0,6), if 1=60 kg/ha.*

From the data in Table 4, it could be seen that the payback of a unit of winter wheat growth depends on both the rate of application of mineral fertilizer and the ratio of nutrients in it. If it is considered fertilizer blocks with different nitrogen application doses, the following trends are observed: such as the agrotechnical efficiency of a complete mineral fertilizer is higher, and at half the rate of PK (10,5 kg/ha for $N_{60}P_{30}K_{30}$), it is higher than when applying phosphorus-potassium (8,3 kg/ha), nitrogen-phosphorus (9,9 for $N_{60}P_{60}$) and nitrogen – potassium fertilizers (9,7 for $N_{60}K_{60}$). With an increase in the nitrogen rate, the payback of a unit of the active substance NPK at the same rate of PK decreases (at $N_{180}P_{30}K_{30}$ as 81,0% of $N_{60}P_{30}K_{30}$, at $N_{120}P_{30}K_{30}$ as 90,5%, with the introduction of $N_{180}P_{60}K_{60}$, the decrease is 7,4% against the dose of $N_{60}P_{60}K_{60}$, and at N_{120} against the same background PK – 2,5%.

According to the data of M. S. Shevchenko, A. V. Polenok and S. M. Shevchenko, increasing the dose of fertilizers for winter wheat from $N_{60}P_{30}$ to $N_{80}P_{40}$ even under irrigation conditions on chestnut soils of the Kherson region was impractical, since the increase was at the level of 0,06–0,12 t/ha and it did not justify itself economically (Shevchenko M. S *et al*., 2011). According to the standards of the FAO (Food and Agriculture Organization of the United Nations), the optimal payback is 10 kg of grain per 1 kg of NPK.

The average payback of mineral nitrogen over 14 years of observations naturally decreases with an increase in the application dose from 60 kg/ha up to 180 kg/ha (Fig. 1), as and at the same dose the agrotechnical efficiency of pure nitrogen is higher than that of nitrogen in the composition of a complete mineral fertilizer: such as by 2,2 times, 1,9 times and 1,6 times, respectively, the norms of 60, 120 and 180 kg/ha.

Table 4. Agronomic efficiency of fertilizer systems depending on the application dose and the ratio of nutrients

Fertilizer System	Sum NPK	N:P:K 1= 60 kg/ha	kg of grain growth per 1 kg of mineral fertilizers
$P_{60}K_{60}$	120	0:1:1	8,3
$N_{60}P_{60}$	120	1:1:0	9,9
$N_{60}K_{60}$	120	1:0:1	9,7
$N_{60}P_{30}K_{30}$	120	1:0,5:0,5	10,5
$N_{60}P_{60}K_{60}$	180	1:1:1	8,1
$N_{120}P_{30}K_{30}$	180	2:0,5:0,5	9,5
$N_{120}P_{30}K_{60}$	210	2:0,5:1	9,8
$N_{120}P_{60}K_{30}$	210	2:1:0.5	9,3
$N_{120}P_{60}K_{60}$	240	2:1:1	7,9
$N_{180}P_{60}$	240	3:1:0	7,4
$N_{180}K_{60}$	240	3:0:1	7,5
$N_{180}P_{30}K_{30}$	240	3:0,5:0,5	8,5
$N_{180}P_{60}K_{60}$	300	3:1:1	7,5

The average efficiency of phosphorus and potassium over a 14-year period (Fig. 2) at the rate of their application of 60 kg/ha was directly dependent on the dose of mineral nitrogen (r=0.98) and with a nitrogen dose of 60 kg/ha it was 5,0–4,5 kg/ha, and at 180 kg/ha it was 7,2–7,7 kg/ha.

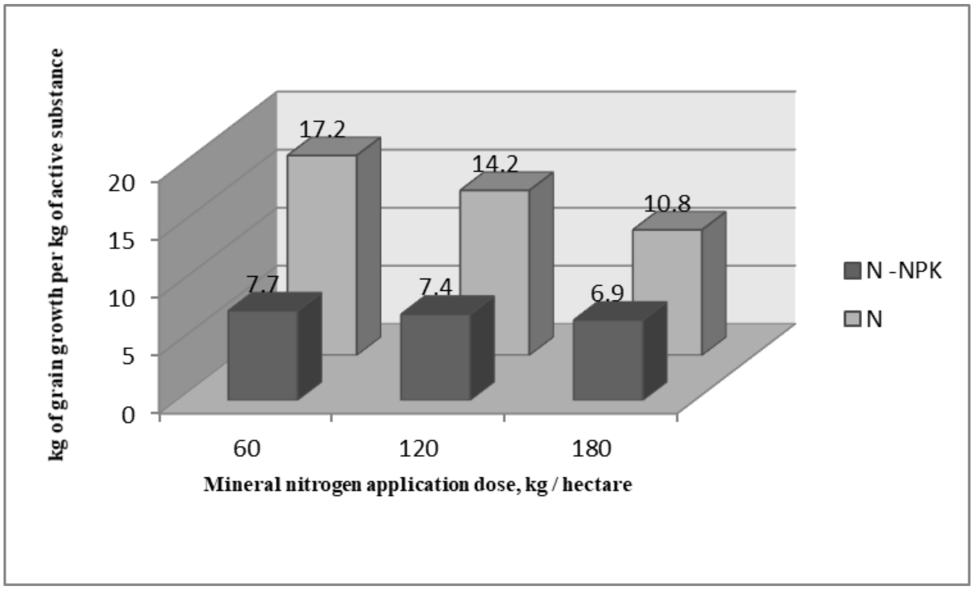

Figure 1. Agrotechnical efficiency of mineral nitrogen with separate application and as part of a complete mineral fertilizer, average for 2007–2020

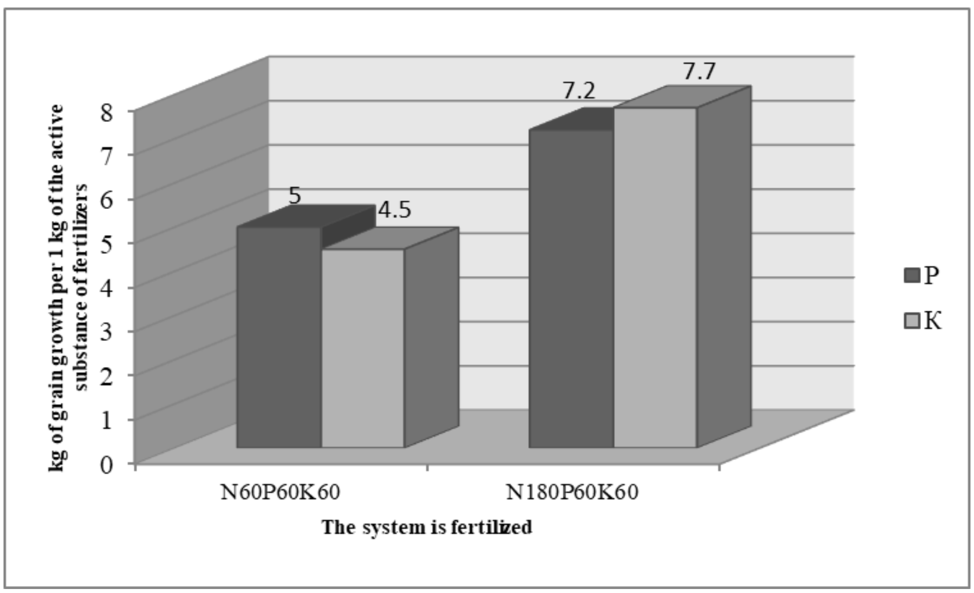

Figure 2. Agrotechnical efficiency of phosphorus and potassium at different nitrogen doses, average for 2007–2020

Assessment of the energy efficiency of winter wheat cultivation according to different predecessors (Table 5) showed that the total energy costs differed little in all variants and they ranged from 18,45 GJ/ha (the predecessor of winter rapeseed) up to 20,67 GJ/ha (the precursor is black pair). The difference was mainly due to the cost of transporting different volumes of grain from the combine and for their primary processing (cleaning of weed impurities). In addition, when growing winter wheat in re-sowing after sideral pair, there were additional costs for protective equipment (ground beetle), this option also had the smallest energy return (Cee=2.86).

Table 5. Energy efficiency of winter wheat cultivation technology depending on the predecessor, 2007–2020

Indicator	**The precursor of**				
	pair			**winter rapeseed**	**winter wheat**
	black	**sideral**			
		vetch winter	**mustard**		
Average yield by fertilizer systems, t/ha	5,89	5,52	3,98	4,36	3,32
Energy yield with yield, GJ/ha	96,90	90,81	65,48	71,73	54,62
Total energy consumption, GJ/ha	20,67	19,38	17,32	18,45	19,10
Energy Efficiency Coefficient (Cee)	4,69	4,68	3,78	3,89	2,86

The maximum coefficient of energy efficiency was observed when growing winter wheat on black pair (4,69) and it was almost the same when it was placed on the sideral pair, where winter vetch was used for sideration (4,68). The recoupment of energy in the cultivation of winter wheat after cruciferous crops occupied an average position, regardless of whether a representative of this genus was used for sideration (mustard, Cee=3,78) or as an independent crop, such as winter rapeseed (Cee=3,89).
The economic and energy efficiency of fertilizer systems was determined by the amount of increase in winter wheat yield, which they provided. Table 6 shows the efficiency parameters generalized by the blocks of mineral nitrogen application doses. If fertilizer systems with an energy efficiency coefficient (Cee) ≥2,0 are considered resource-saving (Methods of bioenergy…, 2000), then the use of N_{60} at different ratios of batteries for all predecessors has a Cee from 2,47 up to 6,93; at the same time, it is economically justified provided that it provides crop gains from 1,0 t/ha up to 2,5 t/ha and with a net profit of 69 cents to 2,92 $ per dollar of costs. The probability of obtaining such increases reaches 75–80% when growing wheat for sideral pair and winter rapeseed, and it reaches 67,9–51,6% for black pair and winter wheat, which went after sideration; for the first two predecessors, fertilizer systems with N_{60} can provide a maximum yield increase of 2,5 up to 3,0 t/ha, but the frequency of such cases is low (10,7–7,5%).

Table 6. Economic and energy efficiency of fertilizers at different doses of mineral nitrogen, taking into account the precursors

Yield growth, t/ha	Average Cee values for fertilizer system blocks											
	N_{60}	N_{120}	N_{180}	N_{60}	N_{120}	N_{180}	N_{60}	N_{120}	N_{180}	N_{60}	N_{120}	N_{180}
	black pair			sidereal pair			winter rapeseed			winter wheat		
3,5–4,0	-	4,45	3,82	-	5,45	4,10	-	5,37	4,04	-	-	-
3,0–3,5	-	4,08	-	-	4,32	3,39	-	4,74	3,57	-	-	-
2,5–3,0	-	3,82	3,13	6,76	3,85	2,90	7,10	4,12	2,90	-	-	-
2,0–2,5	6,93	3,22	2,62	5,88	3,15	2,35	6,13	3,43	2,32	5,50	3,20	2,32
1,5–2,0	4,45	2,36	2,20	4,95	2,92	1,82	4,92	2,87	1,80	4,50	2,45	1,82
1,0–1,5	3,69	1,76	1,75	3,49	2,15	1,40	3,53	2,12	1,52	3,80	2,11	1,35
0,5–1,0	-	1,45	1,50	2,28	1,77	0,65	2,47	1,51	0,81	2,90	1,58	0,8
≤0,5	1,76	-	-	1,05	0,71	0,27	1,33	-	-	1,63	-	-
Average yield on the option without fertilizers, t/ha												
4,50				3,91			3,11			1,84		
Net profit, $/ha												
Yield growth, t/ha	N_{60}	N_{120}	N_{180}	N_{60}	N_{120}	N_{180}	N_{60}	N_{120}	N_{180}	N_{60}	N_{120}	N_{180}
	black pair			sideral pair			winter rapeseed			winter wheat		
3,5–4,0	-	2,36	2,04	-	2,41	2,47	-	3,21	2,43	-	-	-
3,0–3,5	-	2,20	-	-	2,34	1,95	-	2,36	1,38	-	-	-
2,5–3,0	-	1,61	1,30	3,0	1,54	1,45	2,69	1,89	1,14	-	-	-
2,0–2,5	1,74	0,93	1,15	2,0	1,62	1,34	2,92	1,19	0,80	1,41	0,92	0,97
1,5–2,0	0,78	0,78	0,51	1,20	0,93	0,83	2,10	0,52	0,47	0,87	0,39	0,40
1,0–1,5	0,69	0,30	0,14	0,80	0,66	0,46	1,36	0,36	-0,19	1,01	0,10	0,11
0,5–1,0	-	-0,16	-0,23	-0,43	-0,24	-0,28	0,55	-0,08	-0,34	0,26	-0,16	-0,44
≤0,5	0,18	-	-0,68	-0,63	-0,70	-0,78	0,18	-	-	-0,20	-	-

Fertilizer systems with N_{120} and N_{180} in 40% of cases, when placing winter wheat crops in pairs and winter rapeseed, give an increase in its grain yield from 2,5 t/ha up to 3,5 t/ha and they give a net profit from 0,8 up to 3,21 $/ha. If winter wheat is grown in repeated sowings on sideral pair, then according to fertilizer systems with $N_{120–180}$, the yield increase is 1,0–2,5 t/ha in 83,7–95,0% of cases, but the net profit is 0,92–0,97 $/ha. It is noted only at the upper limit of the increase (2,0–2,5 t/ha), which happens in three cases out of ten, and the increase in yield of is less than 2,0 t/ha provides in this case only from 10 up to 40 cents per dollar of costs. Almost all fertilizer systems and on a good predecessor are unprofitable if the increase in the yield of wheat grain when using them does not exceed 1,0 t/ha.

The economic efficiency of fertilizer systems also depended on the hydrothermal conditions of the spring vegetation of winter wheat (Fig. 3): as the higher is the degree of aridity, that is, as the lower is the hydrothermal coefficient, the lower profit receives from the use of fertilizers.

It should also be noted that when using fertilizer systems with the inclusion of $N_{120–180}$, the quality of winter wheat grain was very high and it was exceeded the requirements of the regulatory document for the first class: the content of protein ranged from 14,5 up to 17,5%, and the content of gluten was from 28 up to 40%. But this had little effect on economic efficiency, since the price difference between the third and first class did not exceed 7–11 $, and the protein content above 14% was not taken into account at all, while the cost of fertilizers was constantly growing (Serdyuk T. Yu., 2012; Statistics of the USD…, 2020). Thus, without changing the price policy of the state, the use of high rates of fertilizers would be economically impractical with increases of less than 1,0 t/ha. With fertilizer systems with N_{60}, the grain quality did not exceed the requirements of the regulatory document for the third class, sometimes, in a particularly dry period of filling, it corresponded to the second.

When choosing a fertilizer system, you should take into account the initial state of fertility and the subsequent effect of fertilizers on the parameters of soil fertility. With a low level of fertility, increased fertilizer rates provide an economically profitable increase in the productivity of winter wheat crops (from + 2,0 t/ha), and they provide a net profit of more than 1 $ per dollar of costs and a return on energy costs of more than 2 times.

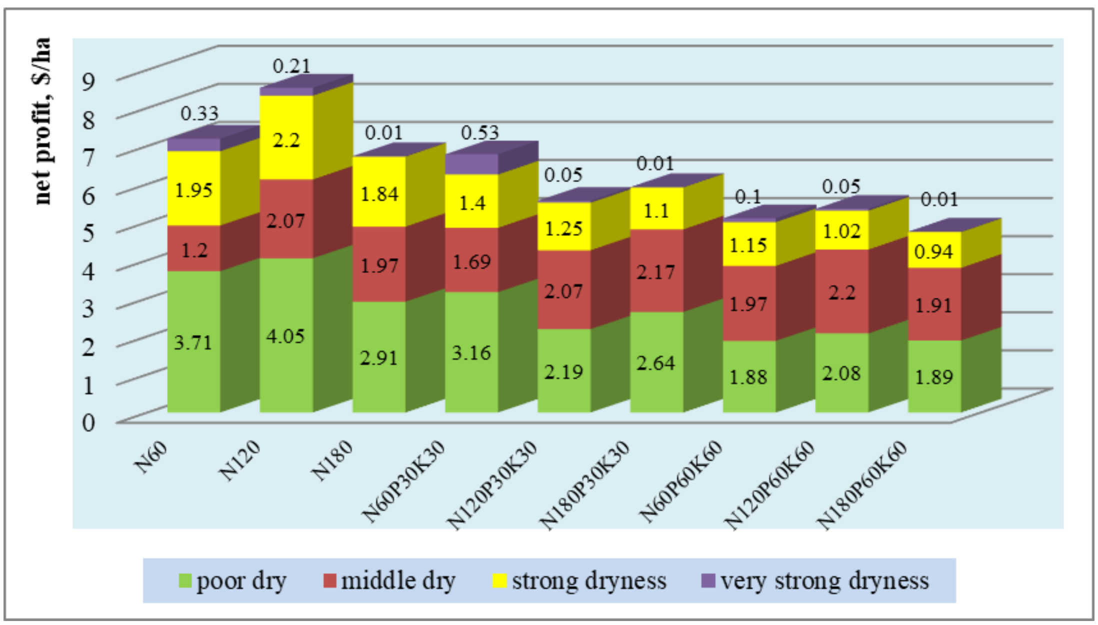

Figure 3. Payback of 1 $, invested in mineral fertilizers, $ of net profit with a dry of varying degrees in May and April

The weighted average parameters of the efficiency of fertilizer systems for growing winter wheat are shown in Table 7, from which it is obvious that with an increase in the nitrogen dose from 60 kg/ha to 180 kg/ha against the background of $P_{30–60}K_{30–60}$, crop yields increase from 1,52 t/ha up to 2,22 t/ha, but the energy efficiency coefficient decreases, although it remains within the limits that characterize the fertilizer system as resource-saving, and net profit also decreases by 1 $, expenses from 0,98 $ to 0,69 $.

Table 7. Weighted average parameters of the efficiency of mineral fertilizer systems in winter wheat crops

Fertilizer system	Efficiency		
	increase, t/ha	energy, Cee	economic, $/ha
$N_{60}P_{30–60}K_{30–60}$	1,52	3,63	0,98
$N_{120}P_{30–60}K_{30–60}$	2,04	2,41	0,79
$N_{180}P_{30–60}K_{30–60}$	2,22	2,09	0,69

The market value, and therefore economic efficiency, depends on the protein content in the grain. Generalization of data for the period 2007–2020 showed that the food properties of wheat grain are determined not only by fertilizers, but also by the quality of the predecessor (Fig. 4). In the control variant, the quality of grain was provided by the level of natural fertility and the predecessor.

Thus, the protein content in the dry matter of winter wheat grain during the transition from vapors to the stubble precursor naturally decreased from 11,82% to 11,19% and to 9,16%. The systematic use of a complete mineral fertilizer and various doses of nitrogen leads to an increase in the concentration of protein, but the above trend persists : with the deterioration of the quality of the precursor, the protein content of the grain decreases.

The correlation and regression analysis showed a high degree of influence of the precursor on the process of protein formation: R^2=0.97 for non-maneuverable variants, 0.76 for fertilizer variants.

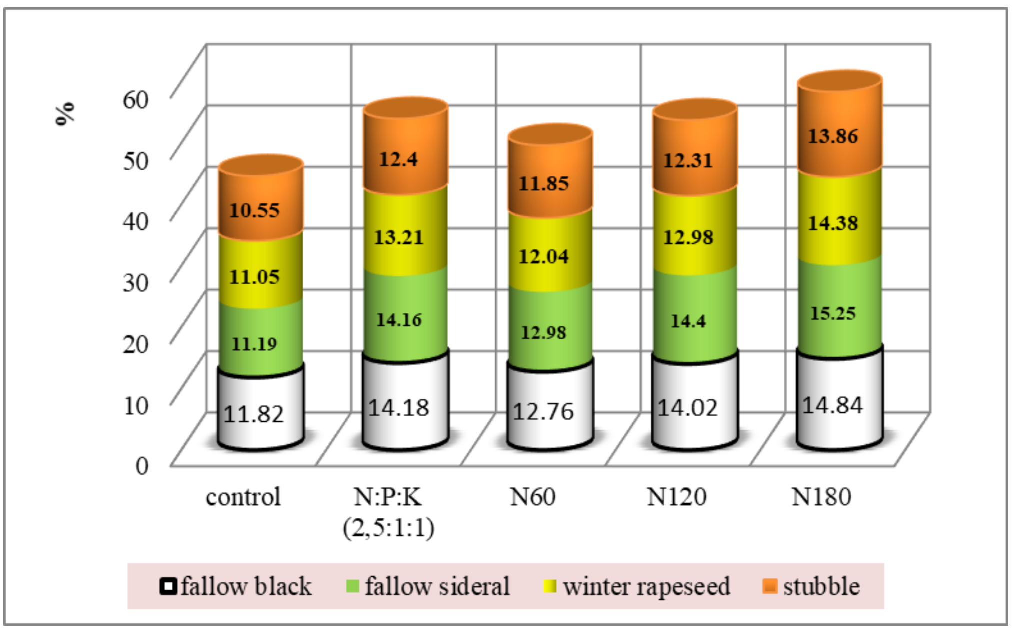

Figure 4. Protein content depending on the precursor and the dose of fertilizer application

One of the important indicators of the efficiency of fertilizers in winter wheat crops is their payback by increasing the protein content in the grain. The provision of a unit of mineral nitrogen with protein increments within each dose tended to increase with a deterioration in the quality of the precursor (Fig. 5): at N_{60} – from 15,67 mg/kg d. v. (black pair) to 44,83 mg/kg d. v. (stubble precursor); at N_{120} – from 18,33 to 26,25 mg/kg d. v. and at N_{180} – from 16,78 to 26,11 mg/kg d. v.

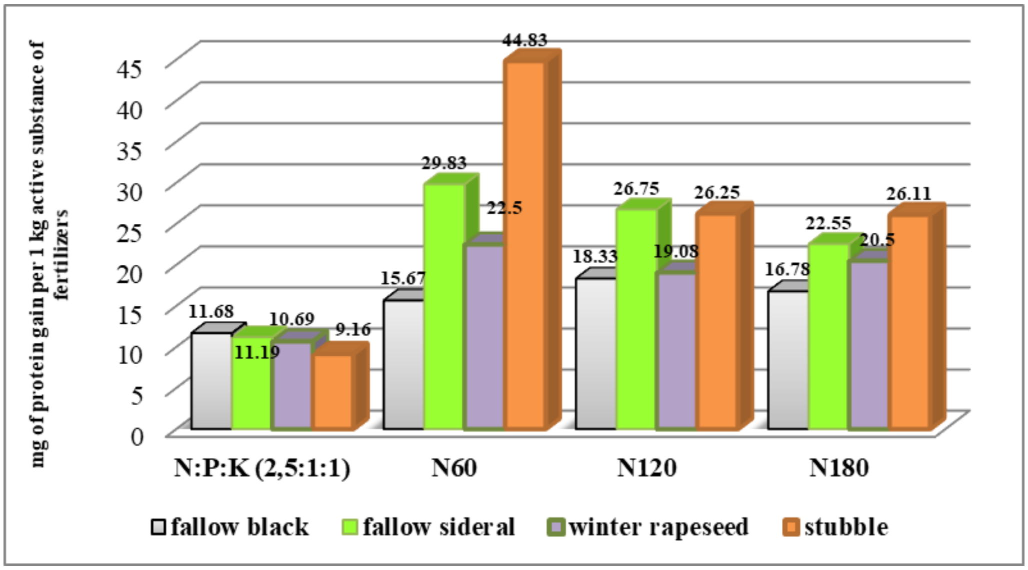

Figure 5. Payback of fertilizers by increases in protein content, average for 2007–2020

Systematic application of a complete mineral fertilizer with an average rate of 202 kg/ha and a ratio of NPK=2,5:1:1 paid off with increases in protein content from 11,68 mg/kg d. v. (black pair) up to 9,16 mg/kg d. v. (stubble precursor), that is, with the deterioration of the quality of the predecessor, this parameter decreased. It was noted that the difference between black and sideral pairs was not mathematically significant and was less than 5% (4,2%), and between black pair and two other precursors – provable: 8,5% (winter rapeseed) and 21,6% (stubble precursor).

CONCLUSIONS

Thus, the analysis of the results of the 14-year period of winter wheat cultivation showed:

- ✓ the agrotechnical efficiency of the complete mineral fertilizer is higher (10,5 kg/ha – $N_{60}P_{30}K_{30}$) for the application of phosphorus-potassium (8,3 kg/ha for $P_{60}K_{60}$), nitrogen – phosphorus (9,9 for $N_{60}P_{60}$) and nitrogen-potassium fertilizers (9,7 for $N_{60}K_{60}$);
- ✓ with an increase in the rate of application of mineral nitrogen, the payback of a unit of active substance NPK with the same rate of RC decreases: against the background of $P_{30}K_{30}$ it is from 9,5% up to 19,0%, against the background of $P_{60}K_{60}$ it is from 2,5% up to 7,4%;
- ✓ the payback of mineral nitrogen naturally decreases with an increase in the application dose from 60 kg/ha to 180 kg/ha, and at the same rate, the agronomic efficiency of pure nitrogen is higher than nitrogen in the composition of a complete mineral fertilizer: by 2,2 times, 1,9 times and 1,6 times, respectively, than the norms of 60, 120 and 180 kg/ha;
- ✓ the efficiency of phosphorus and potassium at the rate of their application of 60 kg / ha is directly dependent on the dose of mineral nitrogen (r = 0.98) and with N_{60} it is 5,0–4,5 kg/ha, and with N_{180} it is 7,2–7,7 kg/ha;
- ✓ when applying N_{60}, the energy efficiency coefficient ranges from 2,48 to 3,70, depending on the precursor; the use of this nitrogen dose in combination with phosphorus-potassium fertilizers increases the energy payback from 8,1% up to 27,0%; a similar trend is observed when using N_{120} and N_{180}, but the absolute values of the energy efficiency coefficients range from 2,41 up 3,26, and 1,82 up to 2,56, respectively;
- ✓ when growing winter wheat using sideral pair and winter rapeseed, fertilizer systems with nitrogen norms $N_{120–180}$ in 40% of cases give winter wheat grain yield increases from 2,5 t/ha up to 3,5 t/ha and they give net profit from 0,8 up to 3,21 $/ha;

- ✓ in repeated sowings of winter wheat on the sideral pair, the net profit of 0,92–0,97 $/ha is noted only at the upper limit of the increase (2,0–2,5 t/ha), which happens in three cases out of ten, in all other cases it is less than 40 cents per dollar;
- ✓ with the current price policy, almost all systems of fertilizing winter wheat, even when it is grown according to a good predecessor, are unprofitable if the increase in grain yield is less than one ton per hectare;
- ✓ weighted average indicators of fertilizer efficiency on winter wheat crops are as follows: $N_{60}P_{30\text{-}60}K_{30\text{-}60}$-yield increase of 1,52 t/ha; energy efficiency coefficient is of 3,63; net profit is of 0,98 $/ha; $N_{120}P_{30–60}K_{30–60}$-yield increase of 2,04 t/ha; energy efficiency coefficient is of 2,41; net profit is of 0,79 $/ha; $N_{180}P_{30–60}K_{30–60}$-yield increase of 2,22 t/ha; energy efficiency coefficient is of 2,09; net profit is of 0,69 $/ha;
- ✓ systematic application of a complete mineral fertilizer with a total rate of 202 NPK kg/ha and a ratio of N:P:K = 2,5:1:1 for black and sideral pairs provides winter wheat grain with a protein content of 14, 18% ; winter rapeseed – 13,21% and 12,40% - for a stubble precursor;
- ✓ with a high and very high level of availability of available phosphorus and potassium in the southern chernozem, which was created in a stationary experiment during the years preceding the presented period (37 years), the maximum protein content in wheat grain is noted when N_{180} is applied: for black pair – 14,84%, for sidereal – 15,25%, for winter rapeseed – 14,38% and for stubble predecessor – 13,86%;
- ✓ for the zone of the Black Sea Steppe of Ukraine, the parameters of the payback of a unit of the active substance of mineral fertilizers are determined by the increments of the protein content in winter wheat grain, which on average amount to (mg/kg a. s.): 202 NPK kg/ha and the ratio N:P:K=2,5:1:1 – 10,68, N_{60} – 28,20, N_{120} – 28,20 and N_{180} – 21,48.

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Conflict of interests. The authors deny any conflict of interests.

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