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Efficiency of Precision Fertilization System in Grain-Grass Crop Rotation

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Abstract: The purpose of a comprehensive field experiment was to evaluate the agronomic efficiency of a precise organomineral fertilizer system based on a uniform and differentiated application of mineral and organic fertilizers. The methodological basis of the study was a two-factor landscape field experiment with grain-grass crop rotation, established within the sloping agricultural landscape of a gently undulating glaciolacustrine plain. It was determined, that soil and agrochemical conditions and a stable soil water regime were of decisive importance in the effectiveness of fertilizers within the agrolandscape. The level increase in yield from the differentiated application of peat-dung compost (once in a bare fallow) and mineral fertilizers relative to the uniform application was 7–12% for winter wheat, 5–11% for oats, 3–8% for perennial grasses, and in the entire crop rotation—5–8%. It regularly decreased during the mineralization of the applied organic fertilizers. Among the three variants of the precise fertilization system studied, the best result was achieved in the option, where organic and mineral fertilizers were applied differentially. In this case, the absolute increase in crop rotation productivity relative to the unfertilized variant reached 16.39 t ha^{-1} of cereal units or 116%, and relative to the uniform fertilizer system—2.27 t ha^{-1} of cereal units or 8%.

Keywords: agricultural landscape; soil; precise fertilization system; efficiency

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1. Introduction

One of the leading parts of modern precision farming is a precise fertilization system based on spatial databases on the state of soils and agrocenoses and differentiated management of their agrochemical state and production process using appropriate information and analytical systems and technological equipment [1,2]. They have a significant potential for effective management of soil fertility, agrocenosis productivity, crop production quality, nutrient losses, greenhouse gas emissions, weather and climate risks, etc. [2–4].

The fundamental property of all open thermodynamic systems—the spatio-temporal heterogeneity of the components of an agricultural landscape is the main factor in the successful implementation of precise fertilizer systems. It has an almost ubiquitous distribution, with a certain regional formation specificity [5–7]. In the Nonchernozem zone of Russia on arable land, it has a complex natural and anthropogenic origin [2,8] associated with the heterogeneity of glacial soil-forming rocks, a pronounced meso- and microrelief, and the uneven use of ameliorants and fertilizers [8–10]. But even under conditions of pronounced soil heterogeneity, it is not always possible to achieve a significant increase in efficiency relative to the common technologies [11–13]. Among the many reasons, one often has to deal with the limiting effect of the agrophysical properties and water regime of the soil [13,14], the different responsiveness of crops to the precise use of fertilizers [15,16], and spatial and temporal heterogeneity of landscape-ecological conditions [17–19].

The complex of landscape-ecological conditions is one of the main factors of soil cover heterogeneity, which determines the geochemical regimes of matter migration in the agricultural landscape and its stability [19,20]. The geophysical mapping of these conditions creates quite obvious theoretical prospects for the practice of differentiated application of fertilizers [8,21,22]. Often, the contribution of the current specifics of landscape and ecological conditions to the variability of crop yields is higher than that of soil heterogeneity or the most effective nitrogen fertilizers [23,24]. In some cases, this circumstance, along with the risks of loss of geochemical stability, serves as a basis for refusing the intensive use of fertilizers [25].

Under conditions of favourable moisture supply, typical for the Nonchernozem zone of Russia, a significant effect of the geochemical regimes of drained agricultural microlandscapes on the efficiency of precise fertilizer systems has not yet been established [2,13]. In the presence of confirmed information on the significant dependence of the spatial distribution of microbiological activity and the soil nutrient regime on the relief and microclimatic differentiation of agricultural landscapes [23,26,27], the precision application of organic fertilizers has not received the scientific justification required [2,8]. The obvious lack of field experimental data in this direction was pointed out earlier [28]. The rather contradictory nature of the available assessments of the responsiveness of individual grain crops [29–31] and perennial grasses [32–34] to the specifics of landscape-ecological and agrochemical conditions complicates the problem.

Since organomineral fertilizer systems have the best prospects for a set of assessment indicators [2,13,35], the purpose of a comprehensive field study for the first time was to assess the agronomic efficiency of a precise fertilizer system based on the uniform and differentiated use of mineral and organic fertilizers, taking into account the spatial distribution of landscape-ecological conditions and geochemical regimes. The new experimental data and knowledge obtained in it will allow developing of the scientific foundations for precision control of the production process of field crops, increasing the payback of fertilizers and reducing environmental risks.

2. Materials and Methods

2.1. Location of the Study

The methodological basis of the study was a landscape field experiment, laid out in 2013 at the Menkovsky branch of the Agrophysical Institute in the Gatchina district of the Leningrad region within the sloping agricultural landscape of a gently undulating glaciolacustrine plain (Figure 1).

Figure 1. Location of the study (AML 1–5 are agricultural microlandscapes 1–5 within the landscape experiment).

This experiment is included in the multilevel system of field experiments of the Agrophysical Institute [36]. Its geographic position is 59°25′ N, 39°0′ E in the northwest of the East European Plain. The climate is moderately continental with signs of a maritime one with an average annual air temperature of 4.2 °C and total precipitation of 720 mm. With annual evaporation of moisture of 400–420 mm, it has a humid character, forming a leaching and stagnant-leaching water regime of the soil. Automorphic and semihydromorphic soils of the soddy-podzolic type, or Albic Retisols, dominate on agricultural lands [37].

2.2. Objects of the Study

The object of the study is represented by a historically established agricultural landscape on a gentle slope of western and northwestern exposure (height difference from 102 to 89 m) within the hole 'Krivoe Koleno' with a total area of 53.64 hectares. Currently, 47.3 hectares of land are arable, and 6.34 hectares are hayfields. A more complete agricultural development of the territory dates back to the second half of the 18th century. Land reclamation and intensive soil cultivation were carried out in the 70–80s of the 20th century. Two decades prior to the start of the experiment, the land was extensively used in crop rotation against the background of a low (34 kg ha^{-1}) average annual level of fertilizer application with a balance deficit of N—61 kg ha^{-1}, P—12 kg ha^{-1}, and K—62 kg ha^{-1}.

The contrasting and complex structure of the soil cover is formed by small contour complexes of light and medium loamy soddy-podzolic gleyic soils (Gleyic Albic Retisols). The soil-forming rock is heavy loamy and clayey, carbonate and carbonate-free moraine with a thickness of 70–130 cm, underlain by glaciolacustrine sand. After a precision survey of the agricultural landscape using 38 soil profiles [38], 5 key areas were selected for the experiment, representing agricultural microlandscapes (AML), differing in lithogenic basis and geochemical regimes. AML 1 is eluvial (17% S, altitude is 102 m) on soddy-weakly podzolic gleyic medium loamy soil formed on the thin and medium thick heavy loamy moraine. AML 2 is eluvial-accumulative (8% S, altitude is 97 m) on soddy-weakly podzolic light loamy soil formed on medium-thick clay moraine. AML 3 is transit-eluvial (49% S, altitude is 92 m) on soddy-weakly podzolic gleyic light loamy eroded soil formed on the thin and medium-thick clayey moraine. AML 4 is accumulative (18% S, altitude 95 m) on soddy-weakly podzolic gleyic residual-calcareous medium loamy soil formed on thin clayey carbonate moraine. AML 5 is accumulative (8% S, altitude 94 m) on soddy-podzolic gley medium loamy soil formed on the thin clayey moraine. Their agrophysical and agrochemical properties within the arable layer are presented in Table 1.

Table 1. Agrophysical and agrochemical soil properties in the experiment.

Soil Properties, Units	Agromicrolandscapes					Agrolands-Capes		Field Experiment	
	No 1	No 2	No 3	No 4	No 5	m_{med}	Cv, %	m_{med}	Cv, %
Physical clay, %	33.4	28.1	28.7	31.6	32.9	30.3	8	30.9	8
Maximum water capacity, %	39.8	34.4	29.7	36.7	38.2	33.7	13	35.8	11
Share of aggregates 0.25–10 mm, %	56.8	54.7	61.0	83.5	74.6	64.9	19	66.1	19
Water resistance of aggregates, %	49.4	53.1	35.7	46.6	50.9	42.6	16	47.1	14
pH_{KCl}	6.01	5.50	5.37	5.54	4.86	5.48	7	5.46	8
Ha *, cmol(eq) kg^{-1}	2.75	3.27	2.80	2.41	3.51	2.82	16	2.95	15
Ca^{2+}+Mg^{2+}, cmol(eq) kg^{-1}	3.88	3.85	4.08	4.67	3.68	4.10	11	4.03	10
Organic matter, %	4.01	3.04	2.39	3.36	3.27	2.96	18	3.21	18
N mobile, mg kg^{-1}	18	16	13	26	23	17	28	19	27
P mobile, mg kg^{-1}	127	130	110	75	77	106	25	104	26
K mobile, mg kg^{-1}	102	72	55	63	96	69	28	78	26

* Ha—hydrolytic acidity.

During the cultivation process, the spatial variability of agrochemical properties decreased 2.6 times (from 36 to 14%) [38]. However, according to individual indicators, its level exceeded 25%, and according to the exchange acidity of the soil, expressed as an indicator of the active concentration of H^+ ions, it actually reached 101%. Soils of AML 1, AML 2 and AML 4 have an average level of cultivation, while those of AML 3 and AML 5 have a low level of cultivation according to a set of indicators. Soils of dominant AML 3 affected by erosion have a low supply of organic matter and mobile potassium, and AML 5 soils have increased acidity.

The main objects of the study also included crops of the field crop rotation 'bare fallow—winter wheat—oats + perennial grasses—perennial grasses of the 1st–4th years of use'. They were represented by the following varieties: winter wheat (*Triticum aestivum* L.) *Moskovskaya 56* (Moscow Research Institute of Agriculture "Nemchinovka", Russia); oats

(*Avéna sativa* L.) *Borrus* (Leningrad Research Institute of Agriculture "Belogorka", a branch of the Lorch Federal Research Center for Potato, Russia); perennial grasses (mixture): timothy grass (*Phleum pratense* L.) *Leningradskaya 204* (Leningrad Research Institute of Agriculture 'Belogorka', a branch of the Lorch Federal Research Center for Potato, Russia) and Festulolium *VIK-90* (All-Russian Williams Fodder Research Institute, Russia).

Ammonium nitrate and azophoska (Akron, Russia), potassium chloride (Uralkali, Russia), as well as local fertilizer—peat-dung compost (PDC), were used as fertilizer materials to ensure the mineral nutrition of plants in the experiment. Ammonium nitrate and azophoska met the requirements of GOST. PDC had a moisture content of 66.6%, an ash content of 46.7%, a pH_{water} value of 7.5 units; nitrogen content was 0.35%, phosphorus—0.52%, potassium—0.72%, calcium—1.36%.

2.3. Methodology of the Study

The landscape field experiment had a two-factor design. According to factor A (landscape-ecological conditions), it included 5 variants of agricultural microlandscapes described above. According to factor B (fertilization system), it was represented by the control (without fertilizers) and 4 variants of the organomineral fertilization system. They included a variant of the uniform fertilization system (UFS), in which the optimal dose of organic and mineral fertilizers was set according to the average soil parameters of the agricultural landscape.

In the variants of the precise fertilization system (PFS), the fertilizer doses were adjusted for the agricultural microlandscapes, taking into account the geochemical regimes prevailing in them. At the same time, it was taken into account that in eluvial AMLs there are the best conditions for the mineralization of organic matter and the unproductive loss of nutrients. In accumulative AMLs, due to the lack of heat at the beginning of the growing season, there is reduced microbiological activity, which negatively affects the availability of nutrients from organic fertilizers for plants. In addition, they form natural geochemical barriers for vertical and horizontal migration of biogenic elements. This served as a theoretical basis for the spatial redistribution between doses of organic and mineral fertilizers. In the PFS 1 variant, only organic fertilizer was differentiated in space, increasing its doses by 30–45% in eluvial AMLs and decreasing by 38% in accumulative AMLs, while mineral fertilizers were applied uniformly. In the PFS 2 variant, the doses of mineral fertilizers were differentiated with the opposite adjustment for AMLs, and the organic fertilizer was applied uniformly. In the PFS 3 variant, the doses of both organic and mineral fertilizers were differentiated (in the eluvial AMLs, the total dose of NPK increased by 12%, while in the accumulative AMLs, it decreased by 14%). The actual distribution of fertilizers by rotation options and crops is presented in Table 2.

This fertilization scheme was implemented by placing small-plot field experiments in the selected key areas of agricultural microlandscapes. The distribution of options is systematic, the replication is three-fold. The total area of the plot was 20 m^2, the accounting area was 10.5 m^2. The observations and counts were carried out using generally accepted and standardized methods, as well as verified equipment.

Before applying mineral fertilizers, soil was sampled with a reed drill to the depth of the arable layer (0–22 cm) 1 day before sowing crops. The average sample from the experimental plot was made up of 25 individual samples. In the Agrophysical Institute testing laboratory, we examined the average samples for the contents of mobile compounds of nitrogen ($N\text{-}NO_3^-$ + $N\text{-}NH_4^+$), phosphorus and potassium in triplicate analytical replication. The content of $N\text{-}NO_3^-$ was determined ionometrically in the extract of a 1% solution of aluminum potassium sulphate at the ratio of soil to solution of 1:2.5 with HI 2216 (HANNA Instruments Deutschland GmbH, Germany). The content of exchange ammonium was determined in a 1 M KCl extract at the soil to solution ratio of 1:2.5 photocolorimetrically using Spekol 1300 (Analytik Jena AG, Jena, Germany). Mobile compounds of phosphorus and potassium were determined in an extract of 0.2 M HCl at the soil to solution ratio of 1:5. Quantitative determination of phosphorus was carried out photocolorimetrically using Spekol 1300 (Analytik Jena AG, Jena, Germany), and potassium was determined by a flame photometric method using FPA-2-01 (JSC Zagorsk Optical and Mechanical Plant, Moscow, Russia).

Table 2. Fertilizer doses for crops and variants of the landscape experiment.

Fertilization System	**Dose of PDC (t ha^{-1}) and Mineral Fertilizers (kg ha^{-1} a.i.) for Agro-Microlandscapes**				
	AML 1	**AML 2**	**AML 3**	**AML 4**	**AML 5**
Bare fallow					
Control—0	0	0	0	0	0
UFS	PDC,40 + K67	PDC,40 + K67	PDC,40 + K67	PDC,40 + K67	PDC,40 + K67
PFS 1	PDC,52 + K67	PDC,40 + K67	PDC,58 + K67	PDC,30 + K67	PDC,20 + K67
PFS 2	PDC,40 + K50	PDC,40 + K58	PDC,40 + K92	PDC,40 + K83	PDC,40 + K50
PFS 3	PDC,52 + K50	PDC,40 + K58	PDC,58 + K92	PDC,30 + K83	PDC,20 + K50
Winter wheat					
Control—0	0	0	0	0	0
UFS	N80	N80	N80	N80	N80
PFS 1	N80	N80	N80	N80	N80
PFS 2	N50	N90	N100	N100	N60
PFS 3	N50	N90	N100	N100	N60
Oats + perennial grasses					
Control—0	0	0	0	0	0
UFS	N100P22K92	N100P22K92	N100P22K92	N100P22K92	N100P22K92
PFS 1	N100P22K92	N100P22K92	N100P22K92	N100P22K92	N100P22K92
PFS 2	N90P18K67	N100P22K75	N110P27K108	N110P22K100	N90P22K100
PFS 3	N70P18K67	N90P22K75	N120P27K108	N110P22K100	N110P22K100
Perennial grasses of the 1st–4th year of use					
Control—0	0	0	0	0	0
UFS	N80K75	N80K75	N80K75	N80K75	N80K75
PFS 1	N80K75	N80K75	N80K75	N80K75	N80K75
PFS 2	N70K50	N80K58	N90K92	N90K83	N70K92
PFS 3	N50K50	N70K58	N100K92	N90K83	N90K92

Harvesting in the experiment was carried out by a continuous weight method. It was preceded by accounting of the structure of crop productivity on 5 test plots with an area of 1 m^2 within each plot of the experiment. Plants were harvested manually using a sickle. The grain was threshed with a sheaf threshing machine MPSU-500 (Machine-Building Plant for Experimental Designs of VIM, Moscow, Russia).

2.4. Agricultural Technology

In the experiment, approved zonal crop cultivation technologies were used with standardized technological equipment. Technological operations were carried out in optimal terms with the quality specified by the technical requirements for individual elements of the technology.

The main tillage included fallow ploughing 3 weeks before sowing winter wheat and autumn ploughing after harvesting it to a depth of 23 cm. Pre-sowing tillage and sowing were carried out with a combined sowing machine Lemken Compact Solitair 9 HD (Lemken GmbH & Co. KG, Alpen, Germany). Soil cultivation after sowing included early spring harrowing of winter wheat and perennial grasses with a harrow evener.

Fertilizers in the experiment were applied manually: PDC—before fallow ploughing, the main mineral fertilizer—before pre-sowing tillage, and mineral top dressing—in the phase of the beginning of spring regrowth of winter wheat and perennial grasses. In the rest of the agricultural landscape, PRT-7A body spreader (Bobruiskagromash, Babruysk, Belarus) was used for the application of PDC, and Amazone Z-AM 1500 mounted spreader (AMAZONE H. Dreyer GmbH & Co. KG., Hasbergen, Germany) was used for mineral fertilizers. To control weeds in winter wheat, the herbicide Lintur, WDG (Syngenta AG, Switzerland) was applied by Amazone 800 BU mounted sprayer (AMAZONE H. Dreyer GmbH & Co. KG., Germany).

Grain harvesting was carried out using Claas Dominator 130 combine (CLAAS KGaA GmbH, Herzebrock-Clarholz, Germany). Perennial grasses were cut once for hay in the phase of the beginning of the anthurus heading of timothy grass using technological production equipment.

2.5. Weather and Climate Conditions

The weather and climate conditions of the test plot are favourable for the effective use of fertilizers. The best indicators of crop productivity are ensured in years with parameters of heat and moisture supply close to the average with a slight deviation towards an increase in heat supply and aridity [8]. During the years of research, due to global climate change, the heat supply for the growing season increased by 13% compared to the average long-term data (Figure 2).

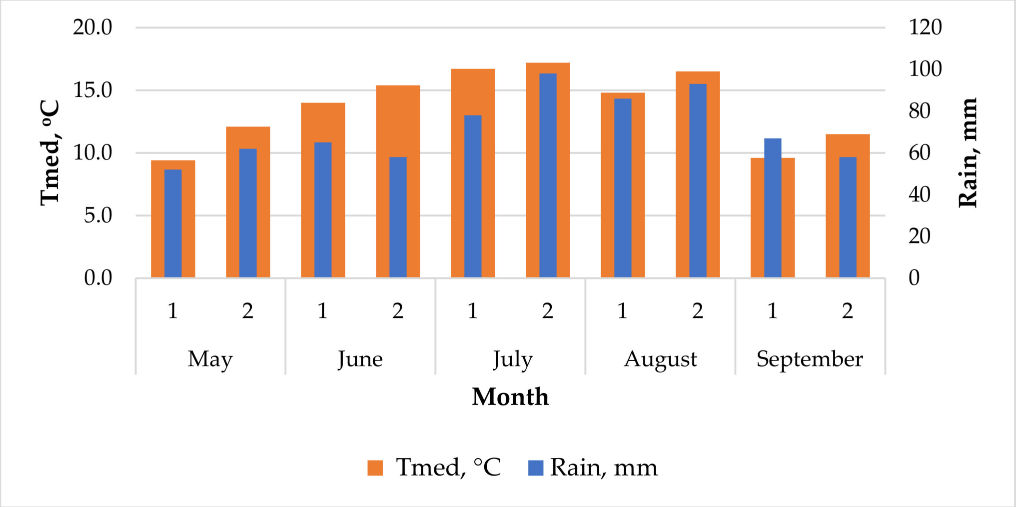

Figure 2. Average monthly air temperature and precipitation (1—average long-term data; 2—data of the period 2013–2019).

The average daily air temperature of the growing season increased from 12.9 to 14.6 °C while maintaining good parameters (368 mm) of precipitation. However, at the same time, the risks of various anomalies and the instability of weather and climatic conditions significantly (1.3–2 times) increased [8]. The variability of the hydrothermal coefficient (HTC according to Selyaninov) increased during the experiment 1.3 times and reached C_v values of 75–83%. The average daily air temperature varied within 8.6–14.6 °C in May, 12.9–17.8 °C in June, 15.0–20.2 °C in July, 15.8–17.5 °C in August, 10.5–12.6 °C in September. Similar indicators of precipitation amounted to 17–121, 9–95, 24–173, 36–157, 27–125 mm, respectively.

The greatest damage to the production process of field crops during the years of research was caused by late spring-early summer droughts and cold waves, characteristic of the region, which were the most severe in 2015–2018. The weather and climatic conditions of the winter wheat growing season were generally very favourable, however, the thinning of the crops in the accumulative AMLs was associated with slow snow melting. Oats suffered from a long wave of cold in May—early June, perennial grasses—from droughts at the same time. The most severe manifestations of drought were recorded in 2018, when it continued throughout May and June, and the HTC during this period amounted to 0.4–0.5, with long-term average values of 1.5–1.7 units. The complete loss of the perennial grasses crops was prevented by excessive soil moistening in the previous period.

2.6. Statistical Analysis

The responsiveness of the research objects to the factors studied in the landscape experiment was judged by the average (m_{med}), minimum (m_{min}) and maximum (m_{max}) values of the estimated indicator, standard deviation (σ) and coefficient of variation (C_v, %). Crop rotation productivity is calculated in cereal units (CU) using a conversion factor for a specific type of main product: wheat grain—1.0, oat grain—0.8, winter wheat straw—0.2, oat straw—0.25, green mass of perennial grasses—0.18. The significance of differences in the variants of the field experiment was assessed at a 5% significance level according to

Fisher's criterion. The results of accounting for individual indicators of crop productivity after checking compliance with the normal distribution law according to Pearson's criterion were processed by the analysis of variance using the Statistica 7.0 software package (StatSoft, Inc., Tulsa, OK, USA). The results of observations and counts on the figures are presented as mean values and confidence intervals in the form of their standard deviations.

3. Results

3.1. Efficiency of Fertilization Systems in Winter Wheat

The weather and climatic conditions of 2013 were characterized by increased and stable parameters of heat and moisture supply, making it possible, under bare fallow conditions, to form a nutrient regime that is quite satisfactory for winter wheat within the arable layer in all AMLs (Table 3).

Table 3. Nutrient regime of the soil before sowing winter wheat.

Option	Nutrition Parameters, mg kg^{-1}														
	Nmob					Pmob					Kmob				
	m_{min}	m_{max}	m_{med}	s	C_v, %	m_{min}	m_{max}	m_{med}	s	C_v, %	m_{min}	m_{max}	m_{med}	s	C_v, %
0	24	69	43	14	32	73	136	105	25	24	54	105	78	19	25
UFS	51	90	68	13	19	94	155	125	24	19	109	144	125	10	8
PFS 1	64	91	74	9	12	87	158	127	31	24	109	160	128	16	13
PFS 2	52	89	67	12	18	96	155	127	22	17	111	142	125	9	7
PFS 3	64	81	72	6	8	89	160	129	29	22	106	155	127	16	13

When using the organomineral fertilizer system, the content of mobile compounds of nitrogen, phosphorus and potassium in the arable layer of the soil increased on average by 69%, 21% and 63%, respectively. At the same time, their spatial variability decreased from 23–25 to 9–21%. As a result, the field germination of crop seeds (94–96%) practically did not depend on landscape and ecological conditions or the variant of the soil fertilization system. The best biometric indicators of sowing by the beginning of the winter season were formed in the fertilized variants of the experiment.

The overwintering conditions of the culture were unsatisfactory. As a result of the damping-out (death) of wheat plants under snow cover and damage caused by snow mold, the plant density decreased by 37–42% in the control and by 28–34% in the fertilized variants. The summer drought also played a negative role, which affected the crops of eluvial AMLs more severely. At the time of full ripeness, the difference in plant density between favourable AML 4 and unfavourable AML 5 reached on average ($p \leq 0.05$) (Figure 3).

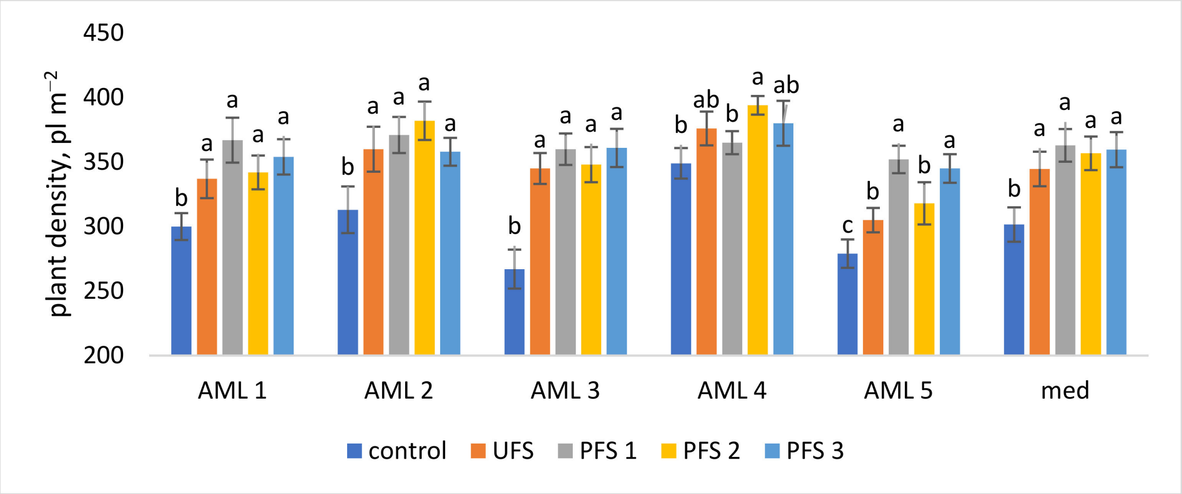

Figure 3. Plant density of winter wheat crops in the phase of full ripeness.

The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value (n = 15). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

By optimizing the nutrient regime of the soil, the average plant density for agricultural microlandscapes increased by 18% (from 302 to 356 plants m^{-2}) ($p \leq 0.05$). Precise fertilization systems, showing positive results in individual AMLs, did not provide a stable reliable superiority over the UFS. The spatial variability of crop density decreased from 11% in the control to 8% in the UFS and 5% in the PFS.

The arid weather and climatic conditions at the beginning of the growing season in 2014 limited the tillering process of plants and the use of top-dressing nitrogen by them in the eluvial facies. This negatively affected the indicators of productive tillering of winter wheat (Figure 4).

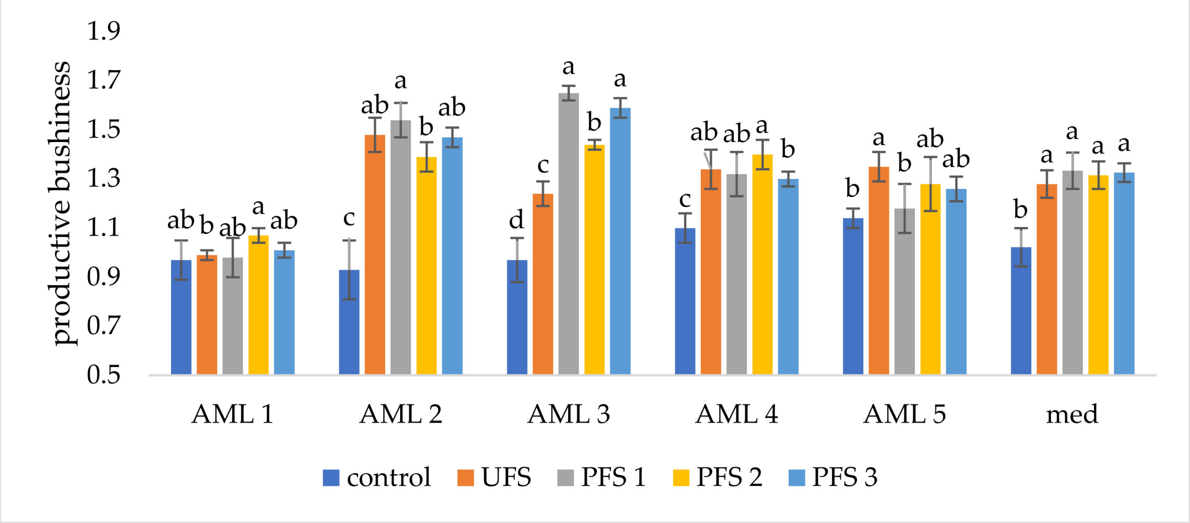

Figure 4. Productive bushiness of winter wheat plants in the experiment.

In eluvial AMLs, they turned out to be less than unity. The positive effect of fertilizers on the productive tillering of plants was manifested in AMLs with better moisture conditions, located in the lower parts of the relief. The exception to this rule was AML 5 with acid soil. On average over the experimental variants, due to the use of fertilizers, this important indicator increased by 29% (from 1.02 to 1.32 units) ($p \leq 0.05$).

The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value (n = 15). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

Precise fertilization systems, having provided a tendency to increase the tillering of winter wheat plants, did not achieve a sustainable superiority over the UFS. Only in AML

3 with eroded soil, a differentiated redistribution of fertilizers made it possible to increase productive tillering by 7–10% ($p \leq 0.05$). The spatial variability of productive tillering under the action of fertilizers under conditions of different soil moisture content in AMLs increased from 9% in the control to 14% in the UFS and 16% in the PFSes.

The initiation of wheat generative organs took place under more favourable weather conditions, which made it possible to increase the number of grains per ear in eluvial AMLs under the action of fertilizers (Figure 5). In the accumulative AML 4, where the natural conditions for initiation and forming grains were the best, fertilizers had almost no effect on the number of grains per ear. On the contrary, the maximum effect from the use of organomineral fertilizer systems was obtained in AML 3, where this indicator increased by 34% (from 14.8 to 19.8 grains) ($p \leq 0.05$). On average over the studied AML variants, due to the use of fertilizers, the grain content per ear increased by 10% (from 18.1 to 20.0 grains) ($p \leq 0.05$). Precise fertilization systems have not achieved sustainable superiority over the UFS.

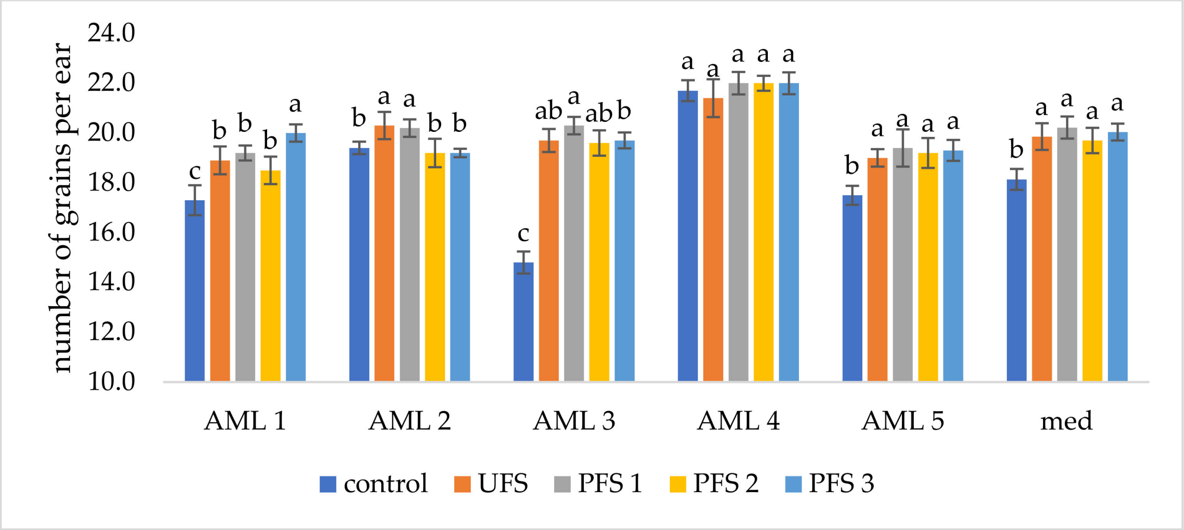

Figure 5. The number of grains per ear of winter wheat in the experiment. The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value ($n = 15$). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

Winter wheat grain formation took place under arid conditions (HTC in July was 0.6 units), which reduced the positive effect of the fertilizer systems studied in the experiment on an important indicator of grain crop productivity—the weight of 1000 grains (Figure 6). The best parameters of fertilizer efficiency were obtained in AML 3 and AML 4, where they increased the weight of 1000 grains by 4%. On average over the fertilized variants of the experiment, this indicator increased by 2% (from 49.3 to 50.3 g) and more significantly (by 3%) ($p \leq 0.05$) in the PFS 3 variant. The maximum positive effect of 5% ($p \leq 0.05$) was achieved in PFS 3 variant in AML 1 and the PFS 2 variant in AML 4. Variants of the UFS and PFS 3 under the landscape-ecological conditions of AML 5 caused a reduction in the weight of 1000 grains by 4% ($p \leq 0.05$).

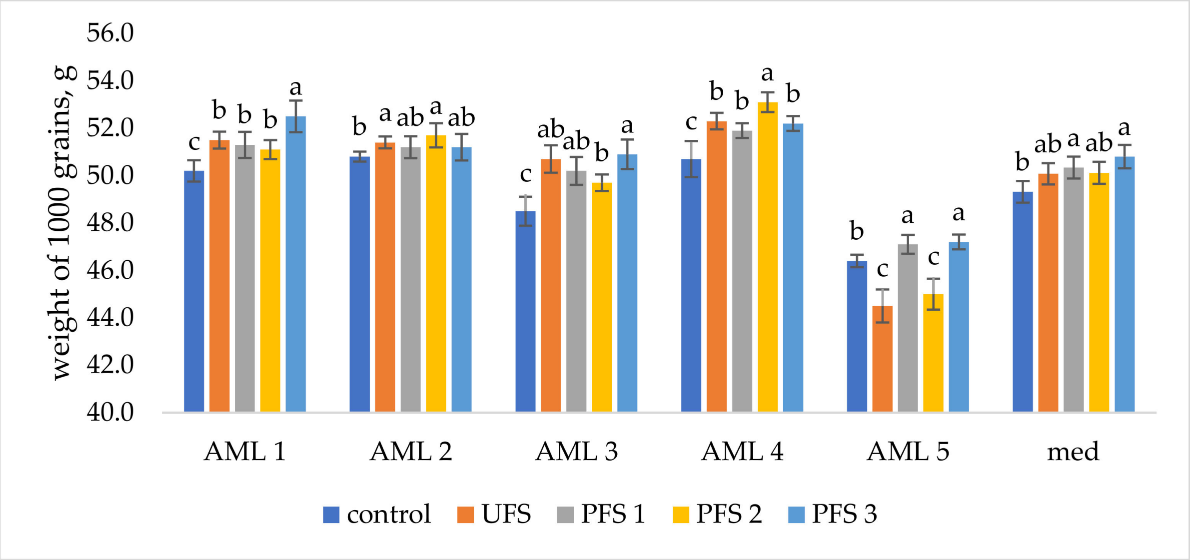

Figure 6. Weight of 1000 grains of winter wheat in the experiment.

The results of continuous weight accounting of winter wheat grain yield at standard humidity (14%) confirmed that the best soil-agrochemical and landscape-ecological conditions for the crop were formed in accumulative AML 4.

The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value (n = 15). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers conditions for the crop were formed in accumulative AML 4 (Table 4).

The yield of grain was higher than the average one for the agricultural landscape by 48% ($p \leq 0.05$), %, and of straw—by 39% ($p \leq 0.05$). The worst conditions for the growth and development of winter wheat were formed in the transit-eluvial AML, which dominated in the agrolandscape, where grain and straw yields decreased by 33% relative to the average values ($p \leq 0.05$).

The best conditions for the manifestation of a positive effect from the studied organomineral fertilizer systems were formed in AML 2 and AML 3, where the average level of grain yield increase reached 2.48 and 3.00 t ha^{-1}. A stable significant superiority of 12 and 9% in grain productivity of all PFS variants over the UFS ($p \leq 0.05$) was provided in AML 3 and AML 5, which have a complex of the most unfavourable soil-agrophysical and agrochemical conditions.

Due to the dominance of AML 3 within the agricultural landscape, the yield of winter wheat grain with differentiated fertilization increased by 96–105% ($p \leq 0.05$) relative to the control and by 7–12% ($p \leq 0.05$) relative to the UFS variant. Slightly better indicators were recorded in variants with the differentiated application of PDC. The spatial variability of the grain yield decreased from 23% in the control and 22% in the UFS variant to 16–20% in the PFS variants.

The average yield of straw virtually had no significant differences over the variants of the fertilizer system. Naturally, the best conditions for its formation were formed in accumulative AMLs, and the worst ones—were in transit-eluvial AML 3.

Table 4. Effect of AML conditions and fertilizer systems on winter wheat productivity.

Fertilization System (Factor B)	**Productivity, t ha^{-1}**			**Yield Increase**					
	Grain	**Straw**	**Total CU**	**Grain**		**Straw**		**Total**	
				t ha^{-1}	**%**	**t ha^{-1}**	**%**	**t ha^{-1} CU**	**%**
AML 1									
Control-0	2.66 c	4.40 c	3.54 c	-	-	-	-	-	-
UFS	3.66 b	5.30 b	4.72 b	1.00	38	0.90	20	1.18	33
PFS 1	3.89 ab	5.40 b	4.97 b	1.23	46	1.00	23	1.43	40
PFS 2	3.70 b	5.30 b	4.76 b	1.04	39	0.90	20	1.22	34
PFS 3	4.07 a	6.24 a	5.32 a	1.41	53	1.84	42	1.78	50
AML 2									
Control-0	2.88 c	5.05 c	3.54 c	-	-	-	-	-	-
UFS	5.34 b	6.18 a	4.72 b	2.46	85	1.13	22	2.69	69
PFS 1	5.65 a	6.09 a	4.97 b	2.77	96	1.04	21	2.98	77
PFS 2	5.26 b	5.54 b	4.76 b	2.38	83	0.49	10	2.48	64
PFS 3	5.19 b	5.83 b	5.32 a	2.31	80	0.78	15	2.47	63
AML 3									
Control-0	1.83 c	1.87 c	2.20 d	-	-	-	-	-	-
UFS	4.26 b	5.69 a	5.40 c	2.43	133	3.82	204	3.2	145
PFS 1	5.13 a	5.63 a	6.26 a	3.30	180	3.76	201	4.06	184
PFS 2	5.01 a	5.58 a	6.13 ab	3.18	174	3.71	198	3.93	178
PFS 3	4.90 a	5.23 b	5.95 b	3.07	168	3.36	180	3.75	170
AML 4									
Control-0	3.59 c	4.44 d	4.48 c	-	-	-	-	-	-
UFS	5.72 a	6.05 b	6.93 a	2.13	59	1.61	36	2.45	55
PFS 1	5.76 a	6.24 ab	7.01 a	2.17	60	1.80	41	2.53	56
PFS 2	5.34 b	5.60 c	6.46 b	1.75	49	1.16	26	1.98	44
PFS 3	5.68 a	6.40 a	6.96 a	2.09	58	1.96	44	2.48	55
AML 5									
Control-0	2.57 c	4.14 c	3.40 c	-	-	-	-	-	-
UFS	3.49 b	4.75 ab	4.44 b	0.92	36	0.61	15	1.04	31
PFS 1	3.78 ab	4.69 b	4.72 ab	1.21	47	0.55	13	1.32	39
PFS 2	3.62 b	5.02 a	4.62 b	1.05	41	0.88	21	1.22	36
PFS 3	3.95 a	4.90 ab	4.93 a	1.38	54	0.76	18	1.53	45
Agricultural landscape – factor A									
Control-0	2.43 c	3.20 b	3.07 c	-	-	-	-	-	-
UFS	4.45 b	5.65 a	5.58 b	2.02	83	2.45	77	2.51	82
PFS 1	4.97 a	5.66 a	6.10 a	2.54	105	2.46	77	3.03	99
PFS 2	4.76 a	5.49 a	5.86 a	2.33	96	2.29	72	2.79	91
PFS 3	4.85 a	5.63 a	5.98 a	2.42	100	2.43	76	2.91	95
LSD_{05} factor A	0.43	0.55	0.54						
factor B	0.24	0.30	0.30						
interaction	0.53	0.68	0.68						

Note: AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers. Different lowercase letters in each row indicate significant differences ($p \leq 0.05$) between options of fertilizer application using least significant difference (LSD).

3.2. *Efficiency of Fertilization Systems in Oats*

Weather and climate conditions in 2015 had close to the average long-term indicators of heat supply and reduced indicators of moisture supply. Dry periods occurred in the first half of May and June. The lower temperature background of the spring drought sharply limited the microbiological activity of the soil. As a result, the mobile nitrogen content in the topsoil before fertilization was low and amounted to 13–18 mg kg^{-1}, and in the variants fertilized with PDC, it varied within 24–33 mg kg^{-1}. A sharp waterlogging in the third decade of May, when the weakened oat plants started the tillering stage, caused the rapid development of the red-brown spot pathogen. The spread of the disease showed a pronounced landscape-ecological and agrochemical confinement (Figure 7). Infection of oat plants was minimal in the warmest AML 1. It significantly increased in AML 2—by 23%, AML 3—by 158%, AML 4—by 68%, and AML 5—by 146% ($p \leq 0.05$). The organomineral fertilization systems studied in the experiment increased the immunity of oat plants and reduced the infestation of the crop with red-brown spot pathogen from 33.1 to 17.9%. The differentiated use of fertilizers did not provide a significant additional effect on the development of the disease.

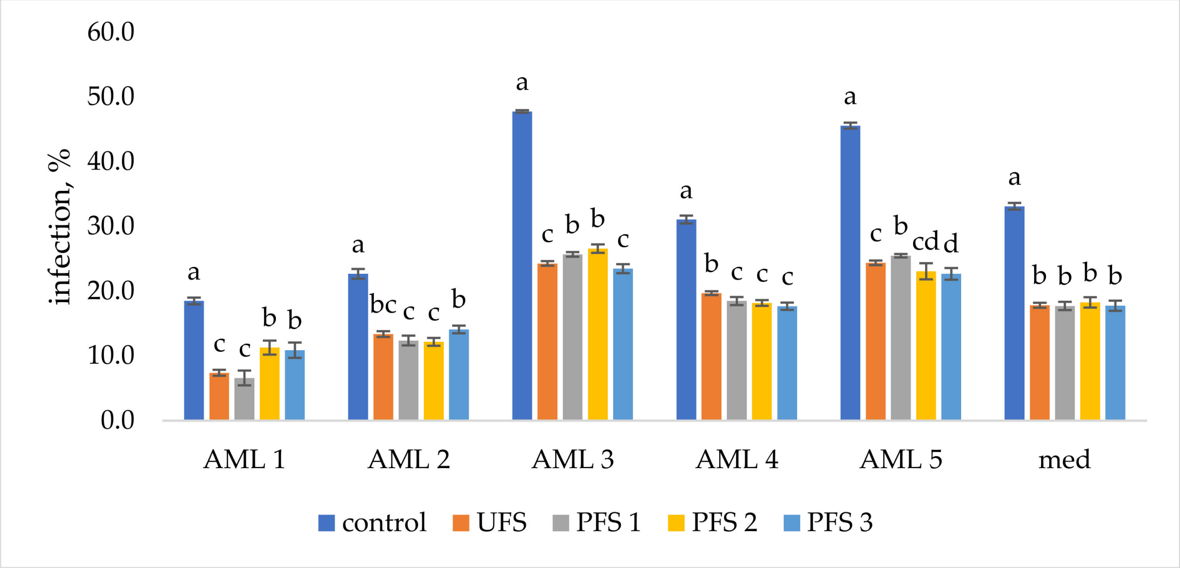

Figure 7. Oat infection with red-brown spot pathogen. The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value (n = 15). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

The noticeable damage to oats by red-brown spot in combination with very unfavourable weather and climate conditions negatively affected the survival of the plants in the phase of full ripeness, which varied between 56 and 85%. Its minimum values were characteristic of AML 5. Here, the planting density of oats turned out to be lower than in the most favourable AML 1 on average over the variants of factor B by 24% ($p \leq 0.05$) (Figure 8). The residual effect of organic fertilizers and the application of mineral ones increased the sowing density by 13% on average for the variants (from 324 to 367 plants m^{-2}) ($p \leq 0.05$). Precise fertilization systems, as in the winter wheat crops, did not form a stable significant superiority over the UFS. The best effect was achieved from PFS 2 in AML 3 and AML 5, which were unfavourable in terms of a set of indicators. The spatial variability of plant density decreased slightly: from 11% in the control to 10% in the UFS and 9% in the PFSes.

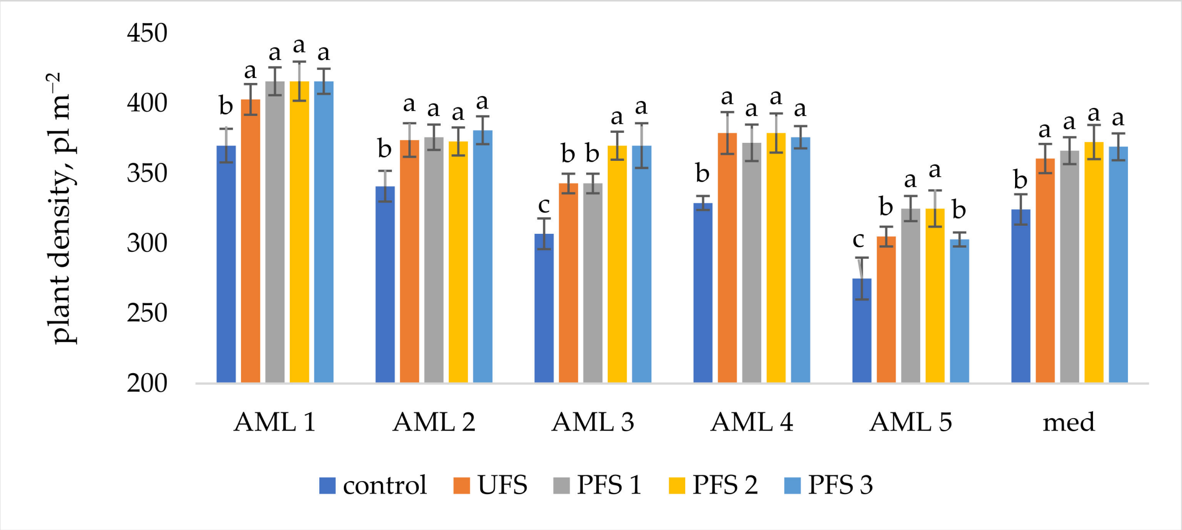

Figure 8. Oat plant density of oat plants in the phase of full ripeness.

The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value (n = 15). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

The injury of oats by the causative agent of red-brown spot in the tillering phase negatively affected the general and productive tillering of its plants. Productive tillering in the variants of the landscape field experiment varied within 0.86–1.40 units (Figure 9).

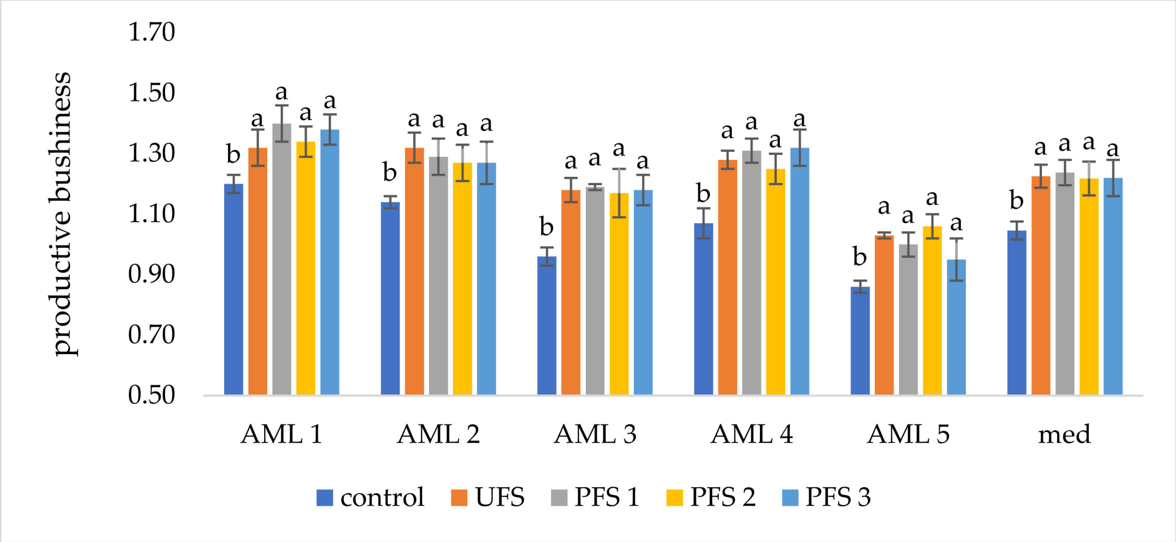

Figure 9. Productive bushiness of oat plants in the experiment.

The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value (n = 15). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

Unlike winter wheat, the minimum values of productive bushiness (0.86 units) of oats were characteristic of AML 5 with the most unfavourable combination of soil properties. Here, even in fertilized variants, the productive business reached only 1.01 units, and in eluvial AMLs, it was lower than 1. As in wheat, the positive effect of fertilizers on this indicator in oats was more significant in AMLs with better moisture conditions, located in lower parts of the relief. On average over the experimental options, due to the use of fertilizers, this important indicator of grain productivity increased by 17% (from 1.05 to 1.23 units) ($p \leq 0.05$). Precise fertilization systems under adverse weather, climate and phytosanitary conditions could not significantly improve the productive tillering of oats relative to the UFS option. They only slightly reduced the spatial variability of this indicator from 13% in the control to 10% in the UFS and 12% in PFSes.

The initiation of grain by oat plants occurred under relatively favourable weather conditions, so the main limiting factor was the level of soil fertility. Its minimum value in AML 3 and AML 5 predetermined the decrease in the number of grains per oat panicle relative to AML 1 by 15 and 21%, respectively ($p \leq 0.05$) (Figure 10). In these landscape-ecological conditions, the greatest recoupment (13 and 23%) ($p \leq 0.05$) was also from the studied fertilizer systems. On average in the AML variants, the increase in the number of grains per oat panicle under the fertilizer action reached 14% (UFS—12%, PFS 1–14%, PFS 2 and PFS 3–15%) ($p \leq 0.05$). Despite the absence of a significant superiority of PFSes over the UFS, their reliable advantage ($p \leq 0.05$) was manifested in PFS 1 in AML 1 and AML 5, in PFS 2 and PFS 3 in AML 3, AML 4 and AML 5.

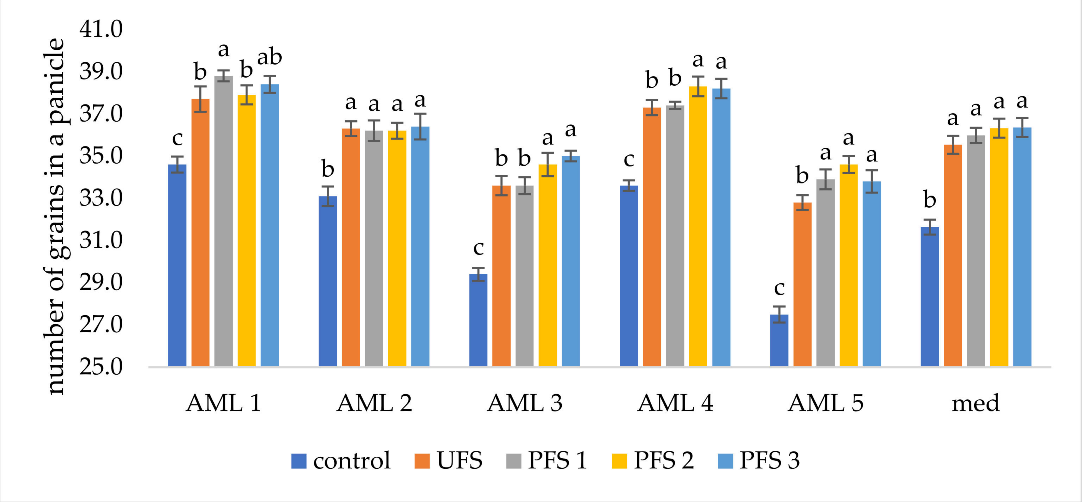

Figure 10. The number of grains per oat panicle in the experiment. The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value (n = 15). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

The formation of oat grain took place under fairly favourable weather conditions, which made it possible to realize the positive effect of fertilization systems on the nutrient regime of the soils of the experiment. Naturally, the value of the weight of 1000 grains in oats was 1.4 times lower than in winter wheat. However, it proved to be sensitive to both soil-ecological and fertilization conditions (Figure 11).

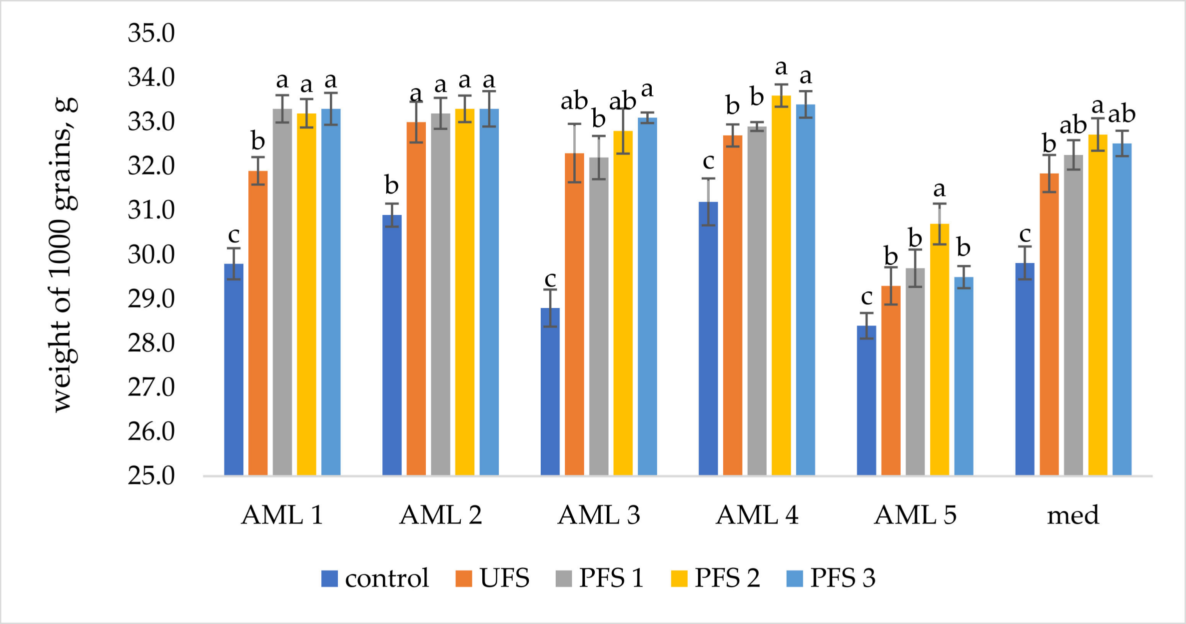

Figure 11. Weight of 1000 grains of oats in the experiment.

The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value ($n = 15$). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

Compared to favourable AML 4, its value in AML 3 and AML 5 decreased by 8 and 9%, respectively ($p \leq 0.05$). On average, the studied fertilization systems, optimizing the nutrient regime of the soil, increased the weight of 1000 grains of oats by 8% (UFS—7%, PFS 1–8%, PFS 2–10%, and PFS 3–9%) ($p \leq 0.05$). At the same time, in PFS 2, a significant superiority ($p \leq 0.05$) over the UFS was achieved, and in PFS 1 and PFS 3 variants, a pronounced trend of positive action was achieved. PFS 1 variant demonstrated significant superiority in AML 1, PFS 2—in AML 1, AML 4 and AML 5, PFS 3—in AML 1, AML 3 and AML 4 ($p \leq 0.05$).

The indicators presented above, which determine the grain productivity of oats, had a direct impact on the agronomic efficiency of the studied fertilizer systems under various landscape and ecological conditions (Table 5). Unlike drought-stricken winter wheat, the best water, nutritional, and phytosanitary regime conditions for oats in 2015 were formed in AML 1. Here, the grain yield was higher than the average for the agrolandscape by 46% ($p \leq 0.05$), and straw yield—by 48% ($p \leq 0.05$). The worst conditions for the growth and development of oats were formed in the accumulative AML 5, where the yield of grain and straw decreased relative to the average by 41 and 28%, respectively ($p \leq 0.05$).

Table 5. Effect of AML conditions and fertilizer systems on oat productivity.

Fertilization System (Factor B)	Yield, t ha^{-1}			Yield Increase					
	Grain	Straw	Total CU	Grain		Straw		Total	
				t ha^{-1}	%	t ha^{-1}	%	t ha^{-1} CU	%
AML 1									
Control-0	4.55 d	5.98 d	5.14 d	-	-	-	-	-	-
UFS	6.40 c	8.29 c	7.19 c	1.85	41	2.31	39	2.05	40
PFS 1	7.50 a	9.66 a	8.42 a	2.95	65	3.68	62	3.28	64
PFS 2	7.05 b	8.95 b	7.88 b	2.5	55	2.97	50	2.74	53
PFS 3	7.36 a	9.42 a	8.24 a	2.81	62	3.44	58	3.1	60
AML 2									
Control-0	3.97 b	5.04 c	4.44 b	-	-	-	-	-	-
UFS	5.90 a	6.55 b	6.36 a	1.93	49	1.51	30	1.92	43
PFS 1	5.84 a	7.52 a	6.55 a	1.87	47	2.48	49	2.11	48
PFS 2	5.74 a	7.35 a	6.43 a	1.77	45	2.31	46	1.99	45
PFS 3	5.84 a	7.55 a	6.51 a	1.87	47	2.51	50	2.07	47
AML 3									
Control-0	2.48 c	3.19 c	2.78 c	-	-	-	-	-	-
UFS	4.36 b	5.65 b	4.90 b	1.88	76	2.46	77	2.12	76
PFS 1	4.39 b	5.74 b	4.95 b	1.91	77	2.55	80	2.17	78
PFS 2	4.92 a	6.25 a	5.50 a	2.44	98	3.06	96	2.72	98
PFS 3	5.05 a	6.52 a	5.67 a	2.57	104	3.33	104	2.89	104
AML 4									
Control-0	3.68 c	4.62 c	4.10 c	-	-	-	-	-	-
UFS	5.90 b	7.55 b	6.61 b	2.22	60	2.93	63	2.51	61
PFS 1	6.00 b	7.80 b	6.75 b	2.32	63	3.18	69	2.65	65
PFS 2	6.10 b	7.94 ab	6.87 ab	2.42	66	3.32	72	2.77	67
PFS 3	6.31 a	8.18 a	7.09 a	2.63	71	3.56	77	2.99	73
AML 5									
Control-0	1.84 d	2.90 d	2.20 d	-	-	-	-	-	-
UFS	3.04 c	4.37 c	3.52 c	1.2	95	1.47	51	1.32	60
PFS 1	3.29 b	4.78 b	3.83 b	1.45	79	1.88	65	1.63	74
PFS 2	3.67 a	5.16 a	4.23 a	1.83	99	2.26	80	2.03	92
PFS 3	2.87 c	5.43 a	3.65 bc	1.03	56	2.53	87	1.45	66
Agrolandscape—factor A									
Control-0	3.12 d	4.05 d	3.51 d	-	-	-	-	-	-
UFS	5.00 c	6.41 c	5.60 c	1.88	60	2.36	58	2.09	60
PFS 1	5.24 b	6.84 b	5.90 b	2.12	68	2.79	69	2.39	68
PFS 2	5.46 a	7.01 ab	6.12 ab	2.34	75	2.96	73	2.61	74
PFS 3	5.56 a	7.31 a	6.28 a	2.44	78	3.26	80	2.77	79
LSD $_{05}$ factor A	0.39	0.67	0.48						
factor B	0.21	0.37	0.26						
interaction	0.48	0.83	0.59						

Note: AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers. Different lowercase letters in each row indicate significant differences ($p \leq 0.05$) between options of fertilizer application using least significant difference (LSD).

The best conditions for the manifestation of a positive effect from the aftereffect of organic fertilizers and direct action of mineral fertilizers were formed in AML 1, AML 3 and AML 4, where the average level of grain yield increase reached 2.53, 2.20, and 2.40 t ha^{-1}. The average increase in grain yield over the fertilized variants reached 2.30 t ha^{-1} or 74% ($p \leq 0.05$). A stable reliable superiority in grain productivity of all PFS variants over the UFS of 10–17% ($p \leq 0.05$) was provided in AML 1.

On average, in the agrolandscape, the yield of oats grain with differentiated fertilization increased by 68–78% ($p \leq 0.05$) relative to the control and by 5–11% ($p \leq 0.05$) relative to the UFS variant. The best indicator of agronomic efficiency was achieved in variants with the differentiated application of fertilizers directly for oats and PDC—for winter wheat. The spatial variability of the grain yield of oats decreased from 34% in the control and 27% in the UFS variant to 23–30% in the PFS variants.

The best conditions for the formation of straw, as well as grain, were formed in higher eluvial AMLs, and the worst—in accumulative AML 5. In contrast to winter wheat, in the PFS variants, significant increases in straw yield were obtained not only relative to the control (69–80%) ($p \leq 0.05$), but also relative to the UFS (7–14%) ($p \leq 0.05$).

3.3. Efficiency of Fertilization Systems in Perennial Grasses

Perennial grasses are crops that are very demanding on the water and nutrient (especially nitrogen) regime of the soil. This predetermined the effect of the factors studied in the landscape experiment on their productivity. Used quite extensively (in a single-cut mode), perennial grasses retained very satisfactory indicators of the botanical composition up to the fourth year of the study. The share of timothy grass and Festulolium varied on average by variants within 84–95% in the first year, 81–93% in the second year, 74–85% in the third year, and 68–82% in the fourth year of economic use of the crop. The best parameters of the botanical composition were in AML 1 and AML 2, the worst ones—in AML 5. The studied fertilizer systems also had a positive effect on it, increasing the share of valuable perennial grasses on average from 77% in the control to 88% in the fertilized variants.

This had a certain impact on the productivity of the culture. However, to a greater extent, it depended on the weather and climate conditions and the specifics of the water and nutrient regime of the soil in May–June (Table 6).

Table 6. Influence of AML conditions and fertilization systems on perennial grass productivity.

Fertilization System (Factor B)	Productivity Indicators by Years											
	2016			2017			2018			2019		
	Yield, t ha^{-1}	Yield Increase		Yield, t ha^{-1}	Yield Increase		Yield, t ha^{-1}	Yield Increase		Yield, t ha^{-1}	Yield Increase	
		t ha^{-1}	%		t ha^{-1}	%		t ha^{-1}	%		t ha^{-1}	%
AML 1												
Control-0	7.22 c	-	-	15.23 c	-	-	5.48 c	-	-	13.12 c	-	-
UFS	19.43 a	12.21	169	28.94 b	13.71	90	14.02 ab	8.54	156	23.53 a	10.41	79
PFS 1	20.04 a	12.82	178	30.65 a	15.42	101	14.90 a	9.42	172	23.17 a	10.05	77
PFS 2	18.24 b	11.02	153	28.08 b	12.85	84	13.53 ab	8.05	147	21.91 b	8.79	67
PFS 3	17.80 b	10.58	147	26.92 cb	11.69	77	15.11 a	9.63	176	21.72 b	8.60	66
AML 2												
Control-0	9.33 c	-	-	14.92 c	-	-	7.34 c	-	-	14.10 c	-	-
UFS	20.73 b	11.40	122	27.67 a	12.75	85	16.33 a	8.99	122	23.15 a	9.05	64
PFS 1	21.60 b	12.27	132	27.55 a	12.63	85	16.08 a	8.74	119	23.03 a	8.93	63
PFS 2	24.77 a	15.44	165	26.94 a	12.02	81	15.85 a	8.51	116	23.52 a	9.42	67
PFS 3	20.95 b	11.62	125	25.36 b	10.44	70	15.01 b	7.67	104	21.88 b	7.78	55
AML 3												
Control-0	6.40 e	-	-	11.41 c	-	-	7.11 c	-	-	10.22	-	-
UFS	22.81 d	16.41	256	26.96 ba	15.55	136	18.31 b	11.20	158	21.59 b	11.37	111
PFS 1	25.62 c	19.22	300	28.58 a	17.17	150	18.95 b	11.84	167	22.66 ab	12.14	115
PFS 2	28.84 b	22.44	351	26.36 b	14.95	131	19.07 b	11.96	168	22.17 ab	11.95	117
PFS 3	33.23 a	26.83	419	27.84 a	16.43	144	20.12 a	13.01	183	23.05 a	12.83	126
AML 4												
Control-0	13.85 c	-	-	19.22 c	-	-	12.56 c	-	-	15.37 c	-	-
UFS	30.77 b	16.92	122	31.53 b	12.31	64	25.13 b	12.57	100	29.13 b	13.76	90
PFS 1	30.11 b	16.26	117	32.02 ab	12.80	67	25.13 b	12.57	100	28.15 b	12.78	83
PFS 2	32.56 a	18.71	135	33.15 a	13.95	72	26.68 a	14.12	112	30.30 a	14.93	97
PFS 3	31.90 a	18.05	130	32.94 a	13.72	71	25.97 ab	13.41	107	29.66 ab	14.29	93
AML 5												
Control-0	10.31 c	-	-	13.12 c	-	-	9.16 d	-	-	11.95 c	-	-
UFS	28.70 a	18.39	178	25.45 b	12.33	94	23.11 b	13.05	138	25.54 b	13.59	114
PFS 1	27.43 b	17.12	166	25.31 b	12.19	93	22.72 b	13.56	143	24.63 b	12.68	106
PFS 2	28.55 ab	18.24	177	25.72 b	12.60	96	21.94 c	12.78	143	24.60 b	12.65	106
PFS 3	29.64 a	19.33	187	27.66 a	14.54	111	24.08 a	14.92	153	26.91 a	14.96	125
Agrolandscape—factor A												
Control-0	8.43 e	-	-	13.88 c	-	-	8.00 c	-	-	12.09 b	-	-
UFS	23.97 d	15.54	184	28.06 ab	14.18	102	19.03 b	11.03	138	23.72 a	11.63	96
PFS 1	25.30 c	16.87	200	29.21 a	15.33	110	19.45 ab	11.45	143	23.92 a	11.83	98
PFS 2	27.36 b	18.93	225	27.87 b	13.99	101	19.47 ab	11.47	143	23.89 a	11.80	98
PFS 3	29.10 a	20.67	245	28.39 a	14.51	105	20.23 a	12.23	153	24.23 a	12.14	100
LSD $_{05}$ factor A	2.09			2.38			1.72			1.96		
factor B	1.15			1.31			0.95			1.08		
interaction	2.61			2.97			2.16			2.45		

Note: AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the opt without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers. Different lowercase letters in each row indicate significant differences ($p \leq 0.05$) between options of fertilizer application using least significant difference (LSD).

The May droughts in 2016 and 2018, when the HTC amounted to only 0.4 units, sharply limited the production process of hydrophilous perennial grasses. As a result, the average yield in the control variant (8.22 t ha^{-1}) in these years turned out to be 1.58 times lower than in 2017 and 2019, which were favourable in terms of moisture conditions. (12.99 t ha^{-1}).

In 2016, the specifics of soil and environmental conditions led to the fact that the yield of green mass of perennial grasses in accumulative AML 4 and AML 5 (12.08 t ha^{-1}) was 1.58 times higher than in eluvial AML 1, AML 2 and AML 3 (7.65 t ha^{-1}). As a result, a decreasing series of AMLs was formed in terms of the level of favourableness for perennial grasses: AML 4 > AML 5 > AML 2 > AML 1 > AML 3. Despite the dry beginning of the growing season, the fertilization systems studied had a very high degree of efficiency. The level increase in yield was in the range of 184–245%, and its absolute value on average for the agricultural landscape reached the maximum values over the years of research at 15.54–20.67 t ha^{-1}. The maximum recoupment from the fertilization systems studied was achieved in AML 3, where the absolute level of increase in yield was higher than in AML 1, AML 2, AML 4, and AML 5 1.16, 1.67, 1.21, 1.82 times, respectively. In AML 3, a stable superiority of PFSes over the UFS was recorded. It was expressed in an increase in the yield of green mass of perennial grasses relative to the UFS variant of 2.81 t ha^{-1} (12%) ($p \leq 0.05$) in PFS 1, 6.03 t ha^{-1} (26%) ($p \leq 0.05$ in PFS 2, and 10.42 t ha^{-1} (26%) ($p \leq 0.05$) in PFS 3. Under the conditions of the spatial dominance of AML 3 (49%) in the agricultural landscape, this caused a significant superiority of the PFS variants over the UFS in the agrolandscape in general. The superiority over the UFS in terms of yield and its increase in the PFS 1 variant was 6 and 9% ($p \leq 0.05$), PFS 2–14 and 22% ($p \leq 0.05$), PFS 3–21 and 33% ($p \leq 0.05$), respectively. At the same time, the spatial variability of the yield of perennial grasses decreased from 35% in the control, to 21% in the UFS and 20% in the PFSes.

In terms of weather conditions, 2017 was the most favourable year for perennial grasses, their productivity on average over the variants of the landscape experiment was 25.58 t ha^{-1}. In the control variant, the superiority over the yield in 2016 reached 65%. At the same time, the influence of the landscape-ecological factor decreased and the influence of the soil-agrochemical factor increased. As a result, a decreasing series of AMLs was formed in terms of the level of favourableness for perennial grasses: AML 4 > AML 1 > AML 2 > AML 5 > AML 3. Against the background of favourable moisture conditions, the efficiency of the studied fertilization systems remained very high, although, in absolute (13.99–15.33 t ha^{-1}) and relative (101–110%) values, it was inferior to the indicators of 2016. A significant ($p \leq 0.05$) superiority of the PFSes over the UFS was found only in PFS 1 in AML 1 and AML 3, where it reached 1.71 and 1.62 t ha^{-1} of green mass or 6%. This was not enough to form a significant increase in productivity in the entire agricultural landscape. In the PFS 1 variant, which provided 110% superiority over the control, there was a tendency to increase the grass yield relative to the PFS variant by 4%. The spatial variability of the green mass productivity of perennial grasses caused by the action of the landscape-ecological factor decreased from 21% in the control to 8% in the UFS and 10% in the PFSes.

In 2018, when the drought continued throughout May and June, only the later dates (after optimal moistening in July) of grass harvesting made it possible to achieve satisfactory agronomic efficiency of their cultivation. The influence of the specifics of landscape-ecological conditions and the water regime of the soil on the productivity of perennial grasses was maximum. As a result, a decreasing series of AMLs was formed according to the level of favourableness for perennial grasses: AML 4 > AML 5 > AML 2 > AML 3 > AML 1. Although maintaining very high parameters of the relative increase (138–153%) in the yield of green mass of grasses, its absolute value (11.03–12.23 t ha^{-1}) decreased relative to 2016 by a factor of 1.56. A significant increase in crop productivity from the differentiated application of fertilizers was recorded in the PFS 2 variant in AML 4 and for PFS 3 in AML 1, AML 3 and AML 5. Although PFS 3 in AML 2 decreased grass yield relative to the UFS by 8%, in the entire agricultural landscape PFS 3 significantly ($p \leq 0.05$) increased this indicator by 1.20 t ha^{-1} or 6%. The spatial variability in the yield of perennial grass green mass, caused by the extreme heterogeneity of field soil moisture, decreased less noticeably than in previous years: from 34% in the control to 24% in the UFS and 25% in the PFSes.

In 2019, the early summer drought in the first half of June substituted for favourable soil moisture conditions in May and therefore did not have a significant negative impact on the production process of perennial grasses. The decreasing series of AMLs according to the level of favourable landscape and ecological conditions for perennial grasses took the following form: AML 4 > AML 2 > AML 1 > AML 5 > AML 3. The agronomic efficiency of mineral fertilization systems decreased significantly. The average absolute level of yield increase (11.85 t ha^{-1}) for the fertilized variants of the experiment turned out to be almost the same as in the dry 2018 (11.55 t ha^{-1}) and 1.52 and 1.22 times lower than in the 2016 and 2017 years respectively. At the same time, the culture reacted very sensitively to changes in the doses of nitrogen and potassium mineral fertilizers during their differentiated application. There was a significant decrease in yield with a reduction in the fertilizer dose in eluvial AML 1 and AML 2 and a yield increase with an increase in the fertilizer dose in AML 3, AML 4, and AML 5. A direct consequence of this was a weak effect of PFSes on the spatial heterogeneity of crop yield: 16% in the control, 12%—in the UFS variant and 9–14% in the PFS variants. As a result, it was not possible to achieve significant superiority over the UFS in the agricultural landscape in general, even in the most promising version of PFS 3.

On average, over 4 years of the study, a decreasing series was formed according to the level of favourable landscape-ecological conditions of individual AMLs: AML 4 > AML 2 > AML 5 > AML 1 > AML 3 (Figure 12). The efficiency of the mineral fertilization systems in all AMLs was very high, reaching an average increase in green mass yield for the fertilized options of 13.97 t ha^{-1} in absolute terms and 132% in relative terms (Table 7).

Table 7. Agronomic efficiency of fertilization systems on perennial grasses (average for 2016–2019).

Fertilization System	Yield of Green Mass, t ha^{-1}			Yield Increase		Cv Spatial, %	Cv Temporal, %
	m_{min}	m_{max}	m_{med}	t ha^{-1}	%		
Control-0	8.79	15.25	10.60	-	-	21	27
USF	21.48	29.14	23.70	13.10	124	13	16
PFS 1	22.07	28.85	24.47	13.87	131	11	16
PFS 2	20.44	30.67	24.65	14.05	133	15	16
PFS 3	20.39	30.12	25.49	14.89	140	17	16
LSD_{05}			1.13				

Note: Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

The maximum recoupment of fertilizers was achieved in the lower soils of AML 3 and AML 5, which had a more stable water and unfavourable nutritional regime. The differentiated application of mineral fertilizers in the variants of PFS 1 and PFS 2 provided only a tendency to increase the yield of grasses relative to the UFS by 3 and 4%, and in PFS 3—a significant increase by 8% ($p \leq 0.05$). At the same time, it was not possible to achieve a significant reduction in the spatial and temporal variability of crop yields relative to the UFS variant.

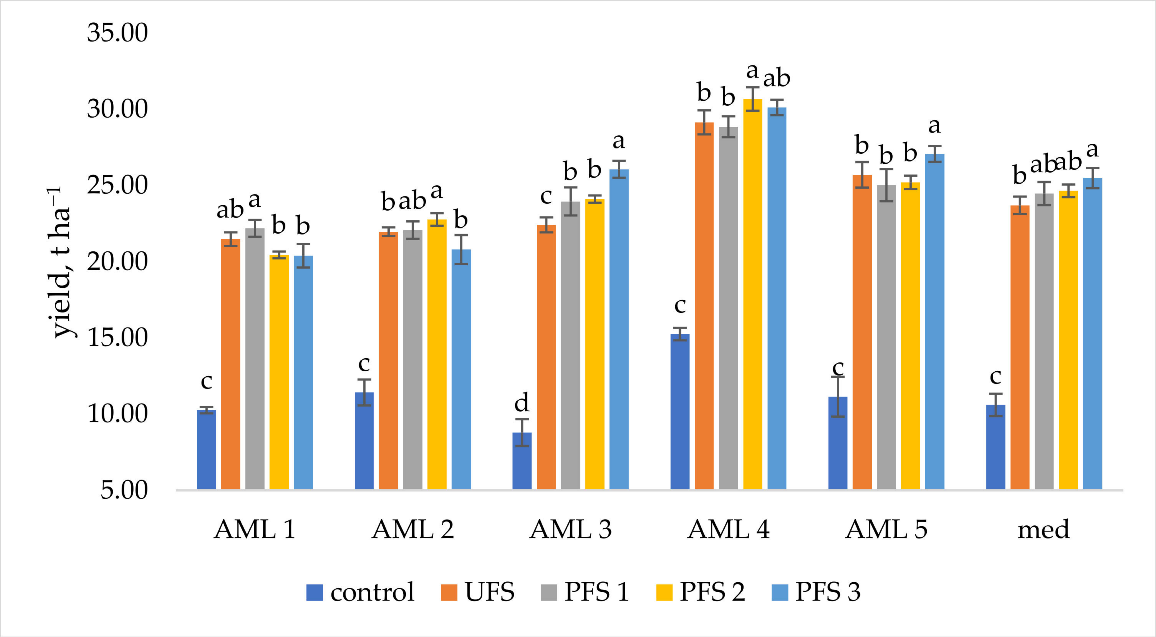

Figure 12. Influence of AML conditions and fertilization systems on the productivity of perennial grasses in 2016–2019.

The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value (n = 12). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

3.4. Efficiency of Fertilization Systems in the Crop Rotation

Calculating the efficiency of the fertilization systems studied in the crop rotation with the conversion of different types of products into cereal units confirmed the patterns previously established for individual crops. The best conditions for the production process of cultures in the crop rotation were formed in the accumulative AML 4 with favourable and stable water and nutrient regime (Table 8). The decreasing series of favourable AML conditions averaged over the grain-grass crop rotation took the following form: AML 4 > AML 1 > AML 2 > AML 5 > AML 3.

The different letters represent statistically significant ($p \leq 0.05$) differences between the tested options of fertilizer application. Error bars show the standard deviation of the mean value (n = 15). AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers.

Table 8. Efficiency of the fertilization systems in the field crop rotation.

Fertilization System (Factor B)	Application of NPK Fertilizers, kg ha^{-1}	Crop Rotation Productivity, t ha^{-1} CU	Productivity Increase		Recoupment of 1 kg of NPK, kg CU
			t ha^{-1}	%	
		AML 1			
Control-0	0	16.07 c	-	-	-
UFS	1614	27.37 b	11.30	70	7.00
PFS 1	1808	29.38 a	13.31	83	7.36
PFS 2	1393	27.32 b	11.25	70	8.08
PFS 3	1432	28.18 ab	12.11	75	8.46
		AML 2			
Control-0	0	15.55 c	-	-	-
UFS	1614	28.72 ab	13.17	85	8.16
PFS 1	1614	29.29 a	13.74	88	8.51
PFS 2	1633	29.19 ab	13.64	88	8.35
PFS 3	1483	27.90 b	12.35	79	8.33
		AML 3			
Control-0	0	11.31 d	-	-	-
UFS	1614	26.44 c	15.13	134	9.37
PFS 1	2083	28.45 b	17.14	152	8.23
PFS 2	1801	28.96 b	17.65	156	9.80
PFS 3	2317	30.36 a	19.05	168	8.22
		AML 4			
Control-0	0	19.56 b	-	-	-
UFS	1614	34.48 a	14.92	76	9.24
PFS 1	1478	34.57 a	15.01	77	10.16
PFS 2	1633	35.38 a	15.82	81	9.69
PFS 3	1584	35.78 a	16.22	83	10.24
		AML 5			
Control-0	0	13.62 b	-	-	-
UFS	1416	26.45 a	12.83	94	7.95
PFS 1	1299	26.57 a	12.95	95	9.97
PFS 2	1606	27.00 a	13.38	98	8.33
PFS 3	1308	27.08 a	13.46	99	10.29
		Agricultural landscape—factor A			
Control-0	0	14.12 c	-	-	-
UFS	1416	28.24 b	14.12	100	9.97
PFS 1	1827	29.62 a	15.50	110	8.48
PFS 2	1672	29.73 a	15.61	111	9.34
PFS 3	1887	30.51 a	16.39	116	8.69
LSD $_{05}$	factor A	2.41			
	factor B	1.31			
	interaction	2.96			

Note: AML 1 is the eluvial agricultural microlandscape, AML 2 is the eluvial-accumulative agricultural microlandscape, AML 3 is the transit-eluvial agricultural microlandscape, AML 4 is the accumulative agricultural microlandscape, AML 5 is the accumulative agricultural microlandscape. Control is the option without fertilizers, UFS is the uniform application of organic and mineral fertilizers, PFS 1 is the differentiated application of organic and uniform application of mineral fertilizers, PFS 2 is the differentiated application of mineral and uniform application of organic fertilizers, PFS 3 is the differential application organic and mineral fertilizers. Different lowercase letters in each row indicate significant differences ($p \leq 0.05$) between options of fertilizer application using least significant difference (LSD).

Return on fertilizers on average over the options for 7 years of the experiment has reached high values of 15.41 t ha^{-1} or 109% ($p \leq 0.05$). It depended on the peculiarities of landscape and ecological conditions. The average level of increase in crop rotation productivity for the variants of the fertilizer system formed a decreasing series of AMLs in terms of fertilizer efficiency: AML 3 (17.24 t ha^{-1}) > AML 4 (15.49 t ha^{-1}) > AML 2 (13.23 t ha^{-1}) ≥ AML 5 (13.15 t ha^{-1}) > AML 1 (11.99 t ha^{-1}).

The superiority of PFSes over the UFS due to the differentiated application of organic and mineral fertilizers was the following: PFS 1–1.38 t ha^{-1} (5%) ($p \leq 0.05$), PFS 2–1.49 t ha^{-1} (5%) ($p \leq 0.05$), PFS 3–2.27 t ha^{-1} (8 %) ($p \leq 0.05$). To a large extent, this effect was achieved by increasing the doses of fertilizers in the transit-eluvial AML with eroded soil. However, this circumstance did not allow to increase the natural payback of 1 kg of the active ingredient of the applied fertilizers, the level of which in the experiment reached high values of 8.48–9.97 kg of cereal units.

4. Discussion

The main causes of fluctuations in the growth and development processes of cultures in the grain-grass crop rotation were the uneven distribution of the heat and moisture resources, the spatial heterogeneity of the agrophysical and agrochemical properties of the soil, and the very unstable geochemical regimes in individual AMLs, which were previously recorded [8,24,25].

Establishing the experiment under bare fallow conditions contributed to the formation of favourable parameters of mobile nitrogen, phosphorus, and potassium. This is largely due to the activation of the mineralization of soil organic matter and PDC during the stabilization of its thermal and water regime [39,40]. As expected by the scientific hypothesis, the best effect was achieved in the nitrogen mode in the variants with the differentiated application of PDC (PFS 1 and PFS 3). Furthermore, in contrast to the results in chernozem soils [23], where, under conditions of better heat supply, mobile nitrogen accumulated in better accumulative AMLs, in our experiment, high values of 68–70 mg kg^{-1} were also achieved in eluvial AMLs. At the same time, the variability of the content of mobile nitrogen was reduced from 32 to 13%. Changes similar in direction also affected the potassium regime of the soil. This fully corresponds to the data obtained earlier in field experiments on the decrease in the spatial heterogeneity of the agrochemical properties of soddy-podzolic soil under the influence of the precise organomineral system of fertilizers, when the variability of soil supply with mobile nitrogen and potassium decreased from 40–44 and 64–67% to 14 and 8–17%, respectively [2,13].

Individual components of the cereals' productivity are formed in different stages of ontogeny. A complex combination of landscape-ecological, weather-climate and soil-agrochemical conditions in each of them forms a whole mosaic of changing limiting factors and effects [29–31]. Their negative side is associated with the death of plants, the development of pathogens, the limitation of tillering processes, the initiation of generative organs, and grain formation, which often have a pronounced landscape localization. According to Soon & Malchi [23], on the chernozems of northern China, their contribution to winter wheat crops is so significant that it exceeds the effect of nitrogen fertilizers. Under the conditions of the study region, its importance is often greater than that of the soil-agrochemical factor [24,41]. In general, it can be argued that the results obtained confirm the current idea of the critical importance of an objective assessment and operative management of the production process of crops, taking into account landscape and ecological differentiation [24–28,42].

As a result of generalizing the data of the landscape experiment, a decreasing series of preferences of individual cultures for landscape-ecological positions and their corresponding geochemical regimes were formed. Winter wheat against drought background preferred accumulative AMLs with the most fertile soils and stable water regime, and the series took the form: AML 4 > AML 2 $\geq$ AML 1 $\geq$ AML 5 > AML 3. Similar data on the spatial differentiation of grain yield by 16–32% were obtained by Spedt et. al. [29] on leached chernozems of southern Siberia and Soon & Malchi [23] on chernozems of northern China. One of the reasons for the decrease in grain yield in the upper part of slopes, according to the authors, was the reduction in the growing season duration. According to Stukalo et al. [43], winter wheat also prefers accumulative AMLs on the dark chestnut soil of southern Russia, providing a grain yield of 4.86 t ha^{-1}. In transit-accumulative AMLs it decreases to 4.22 t ha^{-1}, in eluvial AMLs with pronounced deflation it reduced to 4.12 t ha^{-1}, and in transit-eluvial AMLs with developed water erosion grain yield decreased to 3.24 t ha^{-1}. The manifestation of late spring drought in the Non-Chernozem zone, according to Ivoylov & Chernysheva [44], reduced the productivity of winter wheat by 13–23% from 3.60 to 2.78–3.12 t ha^{-1}.

Oats under specific humid weather and climatic conditions, which contributed to the predominant injury by the red-brown spot pathogen in accumulative facies, preferred the warmest and most drained eluvial AMLs: AML 1 > AML 2 > AML 4 > AML 3 > AML 5. The coefficient of variation in the yield of oats grain within the agricultural landscape in the control variant reached 34%, while for winter wheat (23%) it was 1.5 times lower. According to Ivanov, et al. [45], structural features of the agricultural landscape determined more than 80% of the variability in oat yield. At the same time, its dependence on the spatial differentiation of soil conditions was significantly higher than that of winter grain crops [30].

Perennial grasses, having some differences due to the specifics of the weather in some years, formed a decreasing series of preferences to the stability of the water and nutrient regime of the soil: AML 4 > AML 2 > AML 5 > AML 1 > AML 3. In a long-term landscape experiment, carried out by Ivanov, et al. [33], the difference in perennial grass hay yield between eluvial and accumulative AMLs on slopes reached 25% (5.2 and 6.5 t ha^{-1}, respectively). At the same time, the largest (60.7%) share of its spatial heterogeneity was determined by the features of soil hydromorphism under various microlandscape conditions.

On average, over the crop rotation, a decreasing series of responsiveness of its crops to the conditions of individual AMLs took the form: AML 4 > AML 1 > AML 2 > AML 5 > AML 3, which fully corresponds to the parameters of effective soil fertility in each of the agricultural microlandscapes presented. The data obtained confirm the well-established opinion that the preference of crops and varieties for individual landscape positions has a pronounced biological and genetic specificity [13,20,25]. According to Ivanov, et al. [34], perennial grasses (meadow timothy grass) prefer warmer elevated elements, while legumes (meadow and hybrid clover) prefer lower and cool elements of the agrolandscape. At the same time, due to the extreme instability of the weather and climate factor, such confinement cannot be stable [33,34]. This is convincingly proved by the results of this study on perennial grasses under normal (in 2017 and 2019) and dry (in 2016 and 2018) moisture regimes. The spatial variability of grass productivity increased sharply from 15–20% under normal moisture to 31–32% under dry weather and climatic conditions.

A high dependence of the productivity of perennial grasses on weather and climatic conditions in our experiment turned out to be characteristic of eluvial AMLs (C_v was 27–45%), and the minimum—to accumulative AMLs (C_v was 16–19%). The maximum average productivity of unfertilized perennial grasses of 15.25 t ha^{-1} over 4 years of the research was obtained in accumulative AML 4, while in eluvial AML 1 it was 10.26 t ha^{-1}. Similar data were obtained in the experiment of Ivanova et al. [46], where under accumulative landscape-ecological conditions the yield of grass mixture was 16–22% higher than in eluvial ones.

The results of the experiment confirmed the previously formed idea of the high payback of organomineral fertilizer systems in field crop rotations in the Nonchernozem zone of Russia [2,13,38,47]. A decreasing series of landscape-ecological conditions that are preferable for fertilizer use (AML 3 (17.24 t ha^{-1}) > AML 4 (15.49 t ha^{-1}) > AML 2 (13.23 t ha^{-1}) $\geq$ AML 5 (13.15 t ha^{-1}) > AML 1 (11.99 t ha^{-1})) confirmed the decisive role of unfavourable soil and agrochemical conditions and stable water regime of the soil in fertilizer efficiency. A similar pattern of efficiency of organic and mineral fertilizer systems was obtained in the experiment of Ivanova et al. [46], where the best indicators of grass productivity increase of 48–51% were obtained under conditions of normal moisture. In an earlier experiment in a vegetable crop rotation [16], the average annual increase in its productivity from the organomineral fertilizer system on poorly cultivated soddy-podzolic soil reached 5.70 t ha^{-1} CU (130%), and on well-cultivated soil the increase was 4.14 t ha^{-1} CU (78%). Against the background of a more stable moisture regime, its level reached 4.84 t ha^{-1} CU, while against an unstable background it was 3.80 t ha^{-1} CU.

The average annual increase in crop rotation productivity of the widely tested uniform fertilizer system studied in the experiment reached high values of 2.02 t ha^{-1} CU or 100%, which slightly exceeded the parameters (1.62 t ha^{-1} or 71%) obtained by Merzlaya in a grain-grass crop rotation [47]. In the experiment of Seraya, et al. [48] in the crop rotation with winter wheat, higher parameters of the efficiency of the organomineral fertilizer system were achieved (the yield increase was 3.70 t ha^{-1} or 100%, the payback of 1 kg of NPK was 9.7–9.9 kg CU).

Against this background, it is very difficult to achieve a significant increase in crop productivity due to the differentiated application of fertilizers [2]. The level increase in yield from the differentiated application of peat-dung compost (once in a bare fallow) and mineral fertilizers relative to the UFS was 7–12% for winter wheat, 5–11% for oats, 3–8% for perennial grasses, and crop rotation in general—5–8%. It decreased regularly during the mineralization of the differentially applied organic fertilizer. In Tcyganova's experiment [45], the increase in the yield, caused by the precise application of fertilizers, on cultivated soddy-podzolic soil relative to the UFS was 1.19 t ha^{-1} (25%) for winter wheat, 0.46 t ha^{-1} (9%) for barley, 0.22–0.28 t ha^{-1} (7–8%) for perennial grasses. This ensured an increase in crop rotation productivity of 2.23–2.41 t ha^{-1} (10–11%), comparable to that obtained in our experiment.

The maximum agronomic efficiency from the precise fertilization system was achieved in the PFS 3 variant, where both organic and mineral fertilizers were applied differentially (in accordance with the hypothesis implemented in the form of an algorithm). The absolute increase in crop rotation productivity relative to the unfertilized variant reached 16.39 t ha^{-1} of cereal units or 116%, and relative to the UFS variant—2.27 t ha^{-1} of cereal units or 8%. At the same time, the level of increase in crop rotation productivity caused by the applied fertilizers increased by 16%. However, this result was achieved largely due to an increase in the doses of fertilizers in the transit-eluvial AML with eroded soil, which ultimately did not allow increasing the payback of fertilizers. On the contrary, according to Tcyganova [49], on more fertile soils, the differentiated use of fertilizers made it possible to increase the payback of 1 kg of NPK from 9.9 to 11.6–16.2 kg CU. Higher parameters of agronomic efficiency of precise organomineral fertilizer systems were achieved earlier [16] in the vegetable crop rotation. The advantage of the PFS, based on precision soil cultivation, reached 14% with a payback of 1 kg of NPK of 14.8 kg CU.

Contrary to the previously accumulated data [1,2,4,13,16] the use of PFSes in this experiment failed to achieve a significant reduction in the spatial and temporal variability of field crop productivity relative to the UFS variant. One of the most likely reasons for this was the high sensitivity of crop rotation cultures under emerging landscape-ecological and soil-agrochemical conditions to spatial redistribution (both increase and decrease) of fertilizer doses. Significant spatial stabilization of productivity was achieved only in agrolandscapes with a larger proportion of well-cultivated soils, where individual crops may be less sensitive to lower fertilizer doses. Indirect confirmation of this fact is the data of Chen et. al. [28] on the high efficiency of precision fertilizer application strategies in comparison with excess ones on cultivated soils. In the experiments of Ivanov, et al. [2,16], the spatial variability of the crop rotation productivity decreased from 32% against the non-fertilized background to 16% for the UFS and 9% for the PFS. Similar parameters for the reduction of this indicator were also obtained in Tcyganova's experiment [49].

The results of the study confirmed one of the working hypotheses for substantiating the spatial distribution of doses of organic fertilizers within the sloping agricultural landscape according to the altitudinal principle. If there are signs of planar erosion within the agrolandscape, the application of this principle will have some features associated with the need to limit surface runoff and compensate for the negative effects of erosion using adaptive farming means, as presented in Smirnova, et al. [50].

In general, the accumulated scientific data on the issues of substantiating the differentiated use of fertilizers based not only on agrochemical conditions, but also on landscape-ecological conditions and geochemical regimes of agrolandscapes in the humid climate zone are still not enough to develop comprehensively justified strategies for precise fertilization systems. Successful solution of this important applied problem requires further refinement of scientific research in this area.

5. Conclusions

The main causes of the fluctuations in the growth and development processes of cultures in grain-grass crop rotation were the uneven distribution of heat and moisture resources, the spatial heterogeneity of the agrophysical and agrochemical properties of the soil, and very unstable geochemical regimes in certain agricultural microlandscapes.

Under changing weather and climate conditions, the landscape and ecological preferences of separate cultures are individual and cannot be constant.

The decreasing series of landscape-ecological conditions preferable for fertilizer use (AML 3 (17.24 t ha^{-1}) > AML 4 (15.49 t ha^{-1}) > AML 2 (13.23 t ha^{-1}) $\geq$ AML 5 (13.15 t ha^{-1}) > AML 1 (11.99 t ha^{-1})) confirmed the decisive role of unfavourable soil and agrochemical conditions and a stable soil water regime in the fertilizer effectiveness.

The level of increase in yield from the differentiated application of peat-dung compost (once in a bare fallow) and mineral fertilizers relative to the UFS was 7–12% for winter wheat, 5–11% for oats, 3–8% for perennial grasses, and crop rotation in general—5–8%. The best result was achieved in the variant PFS 3, where organic and mineral fertilizers were applied differentially taking into account the specifics of landscape and environmental conditions.

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