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EFFICIENCY OF NITROGEN FERTILIZATION IN WHEAT AND BARLEY GROWN UNDER DIFFERENT FERTILIZATION SYSTEMS

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Abstract

Agronomic efficiency and Partial factor productivity of N were studied in wheat and barley grown in a long-term fertilizer trial and fertilization systems: Control, $N_{300}P_{400}K_{600}$+18 t vetch-oat mixture/ha, $N_{600}P_{400}K_{600}$ (stock fertilization), $N_{900}P_{400}K_{600}$, $N_{600}P_{400}K_{600}$+30 t manure/ha, $N_{600}P_{400}K_{600}$+4 t straw/ha, $N_{600}P_{400}K_{600}$ (annual fertilization) (I-IV crop rotations); Control, $N_{300}P_{300}K_{400}$, $N_{600}P_{300}K_{400}$, $N_{900}P_{300}K_{400}$, $N_{600}P_{300}K_{400}$+40 t manure/ha, $N_{600}P_{0}K_{400}$, $N_{600}P_{300}K_{0}$ (V-VII rotations); Control, $N_{250}P_{300}K_{200}$, $N_{500}P_{300}K_{200}$, $N_{750}P_{300}K_{200}$, $N_{250}P_{150}K_{0}$+60 t manure/ha, $N_{500}P_{0}K_{200}$, $N_{500}P_{300}K_{0}$ (VIII rotation). The studied rates were N_{60}, N_{120}, N_{180} (wheat) and N_{40}, N_{80}, N_{120} (barley). A high efficiency of N_{60} and N_{40} was found when N was incorporated into organo-mineral fertilization systems. Appling of 18 t vetch-oat mixture·ha or 60 t manure·ha increased Agronomic Efficiency of N (AE-N) and Partial Factor Productivity of N (PFP-N) to 54.5-71.3 and 81.8-112.8, respectively. The prolonged exclusion of phosphorus fertilization in the crop rotation strongly decreased AE-N and PFP-N up to 0.7-13.7.

***Key words**: AE-N, cereals, fertilization system, PFP-N.*

INTRODUCTION

Sustainable agriculture focuses on systems that ensure stable or increasing yields over an extended period of time and preserve natural resources, including the soil as the primary means of production (Alexander et al., 2015; Pradhan et al., 2015). The basis of this is the results of long-term stationary experiments carried out in different regions of the world with certain cultures, some of which are more than 100 years old (Merbach & Deubel, 2008). In Rothamsted, England is the oldest permanent fertilizer trail in the world, established in 1843. Cereal crops are studied in this experiment and it continues till present days (Edmeades, 2003). The different fertilizer loads of the soil and agroecosystems, as well as the long-term cultivation of crops without fertilization, allow studying the regulatory functions of fertilization and its absence on the state of soil fertility and the productivity of the studied crops (Foulkes, 2009). The long-term field fertilizer experiments are the unique basis for developing of modern farming systems, for managing the productivity and quality of crops according to the requirements for balanced nutrition and fertilization, for rational use of the land and preservation of soil qualities, and protection of agro-ecosystems as a whole from pollution (Babulicova, 2008).

Nitrogen is easily mobile and its improper use can cause environmental pollution (Mikkelsen et al., 2012; Fixen et al., 2015; Valcheva et al., 2015). The efficient use of N is important from an economic and ecological point of view and must be considered in the best agricultural practices (Almaliev, 2013; Fixen, 2009). Agroecosystems with efficient nitrogen use are associated with increased yields, economically optimal nutrition and fertilization, minimal losses of soil nutrients and sustainable soil fertility (Dobermann, 2005). Nitrogen fertilization of cereals is one of the main management practices affected grain yields (Das & Harikrishnan, 2015; Kismányoky & Tóth, 2010; Lopez-Bellido et al., 2005). Its efficiency in field crops is most often within limits 14 - 59% (Baligar et al., 2001; Melaj et al., 2003; Romheld, 2006). Nitrogen Use Efficiency (NUE) describes the efficiency of N fertilizer utilization in crop production (Johnston & Poulton, 2009). Yield of cereals and NUE depend on many factors such as soil properties, climate conditions, environment, grown cultivars and etc. (Zhu et al., 2011). Different agronomic, physiological and economic indicators are used for evaluation of

Nitrogen use efficiency (Rao, 2007). Most often in the agronomic research, two indexes are used Partial factor productivity and Agronomic efficiency of the applied nutrient, which determine the productive efficiency, where income is the main output (Snyder, 2009). Partial factor productivity PFP-N answers the question of what is the productivity of the system compared to nitrogen input. This index is the simplest form of the yield efficiency and is calculated in units of crop yield per unit of nutrient input. It is used as a long-term trend indicator (Fixen, 2009). Higher than typical levels indicate a higher intake of the nutrient, while lower levels indicate a productivity-limiting deficiency. Typical PFP-N values are 40-80 $kg \cdot kg^{-1}$; higher than 60 $kg \cdot kg^{-1}$ are in good practice systems, with low nitrogen rates or low soil nitrogen supply. PFP-N changed from higher values at application of low N rates to lower values when N rates were increased. Globally, PFP-N for cereals productivity has declined from 245 kg $grain \cdot kg^{-1}$ applied N in 1961-1965 to 52 $kg \cdot kg^{-1}$ in 1981-1985 and currently averages about 44 $kg \cdot kg^{-1}$ (Snyder & Bruulsema, 2007). The reason for the decline is the yields increase in parallel with an increase of nitrogen fertilization. In a number of developed countries, cereal yields have continued to increase over the past 20 years without significant changes in fertilization. The PFP-N has been steadily increasing in Western Europe, North America, and Japan since the mid-1980s. At present, average cereal yields in these regions are 60 to 100% higher than those of the world at nitrogen rates only 30 to 60% higher than world rates (Dobermann & Cassman, 2006). High yields and high PFP-N values are the result of fertile soils, favorable climatic conditions and excellent agricultural techniques. Since 1960, improved nitrogen use efficiency has led to a sharp decline in the PFP-N index by an average of 1-2% per year in developing countries (Dobermann, 2007). Too high values of this indicator in Africa (122 $kg \cdot kg^{-1}$ applied N), in Eastern Europe and Central Asia (84 $kg \cdot kg^{-1}$) are indicators of unsustainable soil use due to low nitrogen rates. PFP-N is the most important indicator for grain producers because it integrates the efficiency of use of soil nutrients and applied fertilizers (Doberman, 2007; Hawkesford, 2012; Snyder & Bruulsema, 2007).

Agronomic efficiency answers the question of what increase in yields is obtained as a result of applying the nutrient. Agronomic efficiency is calculated as increased yield per unit of nutrient input and more closely reflects the impact of applied fertilization. AE-N is used as a short-term indicator of N effects on productivity (Moll et al., 1982). Prevailing AE-N values for wheat are 10-30 $kg \cdot kg^{-1}$. Lower than typical levels suggest that management changes can increase productivity. Higher values of 25 $kg \cdot kg^{-1}$ are measured in the best practice systems, with low nitrogen use rates or low soil nitrogen supply. AE-N is the result of the return of N from applied fertilizer and the efficiency with which the plant uses each additional unit of nitrogen (Hawkesford, 2012; Snyder & Bruulsema, 2007). This index characterizes the ability of plants to increase yield in response to nitrogen fertilization (Craswell & Gowdin, 1984) and for wheat and barley are most dependent on nitrogen fertilization and climatic conditions (Delogua et al., 1998). AE-N is also often used for economic evaluation of fertilization and usually decreases with increasing fertilizer rates (Kostadinova, 2003; Fageria, 2008; Roberts, 2008). PFP-N is easily calculated for any farm that records inputs and revenues. Determining AE-N required a plot without fertilization or including research plots on the farm.

The aim of the study was to analyze the main parameters of the effectiveness of nitrogen fertilization, AE-N and PFP-N, in wheat and barley grown in field crop rotation under conditions of long-term fertilizer trial and different levels of soil stocking with nutrients created as a result of systemic mineral and organic-mineral fertilization.

MATERIALS AND METHODS

Data from the long-term field fertilizer trail of the Department of Agrochemistry and Soil Science at the Agricultural University of Plovdiv, Bulgaria for the period 1959-2013 were analyzed. Wheat and barley were grown in a field crops rotations after the corn as a predecessor crop. In the period of I-IV crops rotations, the following fertilization systems were studied: Control; $N_{300}P_{400}K_{600}$+18 t vetch-oat mixture·ha^{-1}; $N_{600}P_{400}K_{600}$ (stock fertilization); $N_{900}P_{400}K_{600}$; $N_{600}P_{400}K_{600}$+30 t manure·ha^{-1}; $N_{600}P_{400}K_{600}$+4 t straw·ha^{-1}; $N_{600}P_{400}K_{600}$ (annual fertilization). The variants of fertilization during the next three (V-VII) crops rotations were as follows: Control; $N_{300}P_{300}K_{400}$; $N_{600}P_{300}K_{400}$; $N_{900}P_{300}K_{400}$; $N_{600}P_{300}K_{400}$+40 t manure·ha^{-1}; $N_{600}P_{0}K_{400}$; $N_{600}P_{300}K_{0}$. The following systems of fertilization: Control; $N_{250}P_{300}K_{200}$; $_{500}P_{300}K_{200}$; $N_{750}P_{300}K_{200}$; $N_{250}P_{150}K_{0}$+60 t manure·ha^{-1}; $N_{500}P_{0}K_{200}$; $N_{500}P_{300}K_{0}$ were studied within the eighth crops rotation. The applied nitrogen rates were as follows: 60, 120 and 180 kg N·ha^{-1} (wheat), and 40, 80 and 120 kg N·ha^{-1} (barley). The trail was carried out in four replications and the size of the experimental plots of 150 m^{2}. Mineral fertilizers triple superphosphate and potassium chloride were applied at the corn, which, together with the manure, were plowed with the deep autumn plowing (25-30 cm). The predecessor crop corn was fertilized twice with 1/2 of the N rate as a pre-sowing fertilization, and the rest of N was applied in the 5-6 leaf growth stage. The nitrogen fertilization of the wheat and barley was done in parts: half of the ammonium nitrate as pre-sowing fertilization, and the rest of N rate as winter-spring fertilization.

The soil type of the experimental field was alluvial-meadow (Mollic Fluvisols) (FAO, 2004) it was slightly saline, sandy-clay texture, and soil reaction in water extraction was 7.5. Groundwater was located at a depth of 100-200 cm. The content of more important agrochemical parameters of the soil were: 3.72% of humus, 0.28% of total nitrogen, 0.32% of total phosphorus, and 2.81% of total potassium. Horizon A1 was up to 28 cm deep, brown-black, loose, with a well-defined powdery-granular structure, richly pierced by roots and worm courses. The content of physical clay in the upper horizons reached 50% (in horizon A was 33%). The soil contained a small amount of calcium carbonate (1.63-3.00%), which gives it favorable physico-chemical and water properties.

The climate in the educational and experimental base of the Agricultural university of Plovdiv was typical for the Plovdiv region - transitional-continental. It was relatively soft, due to the transfer of air masses from the Atlantic Ocean and the Mediterranean Sea. The winter was mild with more frequent warming, and the snow cover was small and short-lived. Summer was long, dry and hot, and autumn was long and warm. The average annual air temperature in the Plovdiv region was 12°C. In the month of July was the temperature maximum (average monthly temperature 23.2°C), and in the month of January - the minimum (average monthly temperature -0.4°C). The average annual amount of precipitation was 512 l/m^{2} and is one of the lowest in the country. Characteristic of the region was the uneven distribution of the rainfall and prolonged drought, which covered almost the entire growing season of agricultural crops. A large part of the autumn precipitation replenished underground water reserves and increased soil moisture. Another, equally large part of them evaporated due to the high temperatures. The region was also characterized by frequent spring droughts, which subsequently develop into summer and autumn ones.

The main indexes of nitrogen efficiency Partial Factor Productivity and Agronomic Efficiency were determined according to Dobermann (2007).

The partial factor productivity of applied nitrogen (PFP-N) was calculated as the ratio of grain yield to applied nitrogen (kg grain per kg fertilizer nitrogen):

PFP-N = Grain yield/Nitrogen rate (kg grain/kg N);

Agronomic efficiency of nitrogen AE-N was defined as the ratio of the difference (grain yield with fertilization – grain yield without fertilization) to the fertilizer rate of N; (kg increase in grain yield per kg nitrogen input):

AE-N = (Grain yield with N - Grain yield without N)/N rate

The data was analyzed with the ANOVA procedure and Duncan's multiple range test to find significant differences among the average values of PFP-N and AE-N. Only differences at α=0.95 were accepted as proven.

RESULTS AND DISCUSSIONS

The content of available forms of the main nutrients in the soil after VIII crops rotation in the long-term fertilizer experiment indicated close values in the content of mineral nitrogen (Table 1). It had been proven that the content of available phosphates in the soil was lower in the non-fertilized control, in the variant without phosphorus fertilization since 1988 and in the variant with higher mineral fertilization in the crop rotation.

Table 1. Content of available forms of nitrogen, phosphorus and potassium in the soil ($mg \cdot kg^{-1}$) after VIII crop rotation

Fertilizing systems	N min.	Available P_2O_5	Available K_2O
Control	26.5 b	58 c	337 c
N_1PK	43.6 a	89 a	392 ab
N_2PK	26.9 b	68 bc	351 bc
N_3PK	27.3 b	48 c	337 c
NPK+manure	43.9 a	81 ab	415 a
N_2P_0K	30.1 b	50 c	347 bc
N_2PK_0	34.0 ab	93 a	346 bc
Average	*33.2*	*70*	*361*

*Values in each column followed by the same lowercase letters are not significantly different at $p<0.05$.

The content of available potassium in the soil had been proven to be the highest after systemic organic-mineral fertilization. The average content of mineral nitrogen, mobile phosphorus and absorbable potassium showed that the soil is characterized as poorly stocked with respect to nitrogen and phosphorus, and well stocked with respect to potassium. This was explainable due to the naturally good supply of the soil from the experimental field with available potassium.

The lowest productivity of wheat and barley was obtained when both crops were grown without fertilization (Table 2). The average yields of wheat grain were in the range of 1190-1610 $kg \cdot ha^{-1}$. In the controls without fertilization, the barley yields varied from 920 $kg \cdot ha^{-1}$ (V-VII crop rotations) to 1660 $kg \cdot ha^{-1}$ in VIII crop rotation. The highest average grain productivity of 4910 $kg \cdot ha^{-1}$ for wheat and 4510 $kg \cdot ha^{-1}$ for barley was found in the period of VIII crops rotation upon application of organic-mineral fertilization $N_{250}P_{150}K_0$+60 t manure$\cdot ha^{-1}$ in the field crop rotation. Since 1988, fertilizing variants have been included in the crop rotation in which phosphorus and potassium were excluded from the fertilizer combination.

Table 2. Grain yields of wheat and barley depending on the fertilization systems and applied nitrogen rates

Fertilization systems	N rate of wheat/barley	Wheat $kg \cdot ha^{-1}$	Barley $kg \cdot ha^{-1}$
I-IV crops rotations			
Control	N_0	1610	1270
$N_{300}P_{400}K_{600}$+18 t vetch-oat mixture$\cdot ha^{-1}$	N_{60}/N_{40}	4880	3500
$N_{600}P_{400}K_{600}$ (PK stock fertilization)	N_{120}/N_{80}	4670	3240
$N_{900}P_{400}K_{600}$	N_{180}/N_{120}	4550	3290
$N_{600}P_{400}K_{600}$+30 t manure$\cdot ha^{-1}$	N_{120}/N_{80}	4600	3200
$N_{600}P_{400}K_{600}$+4 t straw$\cdot ha^{-1}$	N_{120}/N_{80}	4950	2920
$N_{600}P_{400}K_{600}$ (PK annual fertilization)	N_{120}/N_{80}	4340	2720
Average		*4229*	*2877*
V-VII crops rotations			
Control	N_0	1190	920
$N_{300}P_{300}K_{400}$	N_{60}/N_{40}	3680	3000
$N_{600}P_{300}K_{400}$	N_{120}/N_{80}	3540	3190
$N_{900}P_{300}K_{400}$	N_{180}/N_{120}	3850	3380
$N_{600}P_{300}K_{400}$+40 t manure$\cdot ha^{-1}$	N_{120}/N_{80}	3590	3070
$N_{600}P_0K_{400}$	N_{120}/N_{80}	2240	1740
$N_{600}P_{300}K_0$	N_{120}/N_{80}	3680	3360
Average		*3110*	*2666*
VIII crops rotation			
Control	N_0	1560	1660
$N_{250}P_{300}K_{200}$	N_{60}/N_{40}	3520	3160
$N_{500}P_{300}K_{200}$	N_{120}/N_{80}	4540	3900
$N_{750}P_{300}K_{200}$	N_{180}/N_{120}	4340	4210
$N_{250}P_{150}K_0$ + 60 t manure.ha^{-1}	N_{60}/N_{40}	4910	4510
$N_{500}P_0K_{200}$	N_{120}/N_{80}	1640	2600
$N_{500}P_{300}K_0$	N_{120}/N_{80}	4160	4240
Average		*3524*	*3469*

The long-term exclusion of the fertilizer phosphorus from the mineral fertilization system $N_{600}P_0K_{400}$ (V-VII crops rotations) and $N_{500}P_0K_{400}$ (VIII crops rotation) demonstrated a strong negative effect on the grain productivity of both cereals. As a result, the lowest average yields were obtained compared to all the fertilized variants. The yield decreased was by 1300-2900 $kg \cdot ha^{-1}$ for wheat and 1300-1450 $kg \cdot ha^{-1}$ for barley, compared to the obtained grain under application of the triple fertilizer combination $N_{600}P_{300}K_{400}$ and $N_{500}P_{300}K_{400}$. The long-term exclusion of the fertilizer potassium and a negative balance of this nutrient in the soil had a slight effect on the productivity of wheat and barley when the soil was well supplied with available potassium.

The obtained average values of PFP-N in the period of I-IV crops rotations were similar in both crops 43.5-44.3 $kg \cdot kg^{-1}$ (Table 3). In the next four rotations, they were in the range of 31.9-41.8 and 40.9-60.2 kg·kg^{-1}, for wheat and barley, respectively. The analysis of the data for the studied period indicated increased values of PFP-N when both crops were grown under organic-mineral fertilization systems and low N_{60}/N_{40} rates. Within the study, the plowing of 6 t manure per hectare ($N_{250}P_{150}K_0$+60 t manure·ha^{-1}) resulted in the highest partial nitrogen productivity of 81.8-112.8 kg·kg^{-1}, for wheat and barley, respectively.

Table 3. Partial Factor Productivity of nitrogen in wheat and barley depending on the fertilization systems and applied nitrogen rates

Fertilization systems	N rate of wheat/barley	PFP-N wheat	PFP-N barley
I-IV crops rotations			
$N_{300}P_{400}K_{600}$+18 t vetch-oat mixture·ha^{-1}	N_{60}/N_{40}	81.3	87.5
$N_{600}P_{400}K_{600}$ (PK stock fertilization)	N_{120}/N_{80}	38.9	40.5
$N_{900}P_{400}K_{600}$	N_{180}/N_{120}	25.3	27.4
$N_{600}P_{400}K_{600}$+30 t manure·ha^{-1}	N_{120}/N_{80}	38.3	40.0
$N_{600}P_{400}K_{600}$+4 t straw·ha^{-1}	N_{120}/N_{80}	41.3	36.5
$N_{600}P_{400}K_{600}$ (PK annual fertilization)	N_{120}/N_{80}	36.2	34.0
Average		*43.5*	*44.3*
V-VII crops rotations			
$N_{300}P_{300}K_{400}$	N_{60}/N_{40}	61.3	75.0
$N_{600}P_{300}K_{400}$	N_{120}/N_{80}	29.5	39.9
$N_{900}P_{300}K_{400}$	N_{180}/N_{120}	21.4	28.2
$N_{600}P_{300}K_{400}$+40 t manure·ha^{-1}	N_{120}/N_{80}	29.9	38.4
$N_{600}P_0K_{400}$	N_{120}/N_{80}	18.7	21.8
$N_{600}P_{300}K_0$	N_{120}/N_{80}	30.7	42.0
Average		*31.9*	*40.9*
VIII crops rotation			
$N_{250}P_{300}K_{200}$	N_{60}/N_{40}	58.7	79.0
$N_{500}P_{300}K_{200}$	N_{120}/N_{80}	37.8	48.8
$N_{750}P_{300}K_{200}$	N_{180}/N_{120}	24.1	35.1
$N_{250}P_{150}K_0$+60 t manure·ha^{-1}	N_{60}/N_{40}	81.8	112.8
$N_{500}P_0K_{200}$	N_{120}/N_{80}	13.7	32.5
$N_{500}P_{300}K_0$	N_{120}/N_{80}	34.7	53.0
Average		*41.8*	*60.2*

A strong positive effect on PFP-N was found when green manure was included in the fertilizer combination ($N_{300}P_{400}K_{600}$+18 t vetch-oat mixture·ha^{-1}) where 81.3-87.5 kg of grain were obtained for each kilogram of applied mineral nitrogen. This demonstrated that wheat and barley made the most efficient use of fertilizer and soil nitrogen under fertilization systems using organic-mineral fertilization. The values of PFP-N in the fertilized variant $N_{250}P_{150}K_0$+60 t manure·ha^{-1} (VIII crops rotation) exceeded the obtained PFP-N under mineral fertilization $N_{250}P_{300}K_{200}$ by 39.4 and 42.8%, respectively, for wheat and barley. Within I-IV crops rotations, it had been demonstrated that moderate nitrogen fertilization N_{120}/N_{80} of wheat and barley under stock [$N_{600}P_{400}K_{600}$ (stock fertilization)] or annual [$N_{600}P_{400}K_{600}$ (annual fertilization] application of phosphorus and potassium into the crop rotation, as well as, organic-mineral fertilization ($N_{600}P_{400}K_{600}$+30 t manure·ha^{-1} and $N_{600}P_{400}K_{600}$+4 t straw·ha^{-1}) slightly changed PFP-N. Reduced potassium fertilization systems ($N_{600}P_{300}K_0$ and $N_{500}P_{300}K_0$) studied in V-VIII crops rotations showed slight effect on the PFP-N in both crops. The obtained grain per kilogram of fertilizer nitrogen in these variants (30.7-50.3) was close to the values of PFP-N under the analogous mineral systems with included potassium. Prolonged exclusion of the fertilizer phosphorus from the mineral fertilization system $N_{600}P_0K_{400}$ (V-VII crops rotations) and $N_{500}P_0K_{400}$ (VIII crops rotation) strongly reduced PFP-N and it was correspond-ded with the effect of its exclusion on the wheat and barley grain yields.

The lowest values of PFP-N (13.7-21.8 kg·kg^{-1}) were obtained for both crops within the studied period. They were 3.4-4.2 times lower in comparison with the triple fertilizer combinations $N_{600}P_{300}K_{400}$ and $N_{500}P_{300}K_{400}$. The agronomic efficiency of nitrogen widely varied from 0.7 to 55.8 kg·kg^{-1} (wheat) and from 10.3 to 71.3 kg·kg^{-1} (barley) over the studied period (Table 4). However, close average values were found for the wheat and barley of 24.9 and 29.5 kg·kg^{-1}, respectively. The highest AE-N was found at application of low N_{60}/N_{40} rates under organic-mineral fertilization system ($N_{250}P_{150}K_0$+60 t manure·ha^{-1}) in which the manure was plowed at the beginning of the crop rotation. This demonstrated the need of manure fertilization of field crops in the crop rotations. Higher values of AE-N were also established under used mineral plus green fertilization ($N_{300}P_{400}K_{600}$+18 t vetch-oat mixture·ha^{-1}) within I-IV crops rotations. The exclusion of phosphorus from the fertilizer combination had an extremely unfavorable effect on the agronomic efficiency of nitrogen. The AE-N values obtained were very low 0.7-8.8 kg·kg^{-1} for wheat and 10.3-11.8 kg·kg^{-1} for barley. The results of VIII crop rotation indicated that 35 times less additional yield of wheat grain per kilogram of nitrogen fertilizer was obtained, compared to the analogous fertilization system, but provided with fertilizer phosphorus. The reduction of additional yield as a result of nitrogen fertilization was 2.4 times for barley. Therefore, in cereal crops, phosphorus fertilization should be a mandatory practice. The exclusion of potassium from the fertilizer combination of the crop rotation in soils well stocked with available potassium had little effect on the AE-N in wheat and barley.

Table 4. Agronomic efficiency of nitrogen in wheat and barley depending on the fertilization systems and applied nitrogen rates

Fertilization systems	N rate of wheat/barley	AE-N wheat	AE-N barley
I-IV crops rotations			
$N_{300}P_{400}K_{600}$+18 t vetch-oat mixture·ha^{-1}	N_{60}/N_{40}	54.5	55.8
$N_{600}P_{400}K_{600}$ (PK stock fertilization)	N_{120}/N_{80}	25.5	24.6
$N_{900}P_{400}K_{600}$	N_{180}/N_{120}	16.3	16.8
$N_{600}P_{400}K_{600}$+30 t manure·ha^{-1}	N_{120}/N_{80}	24.9	24.1
$N_{600}P_{400}K_{600}$+4 t straw·ha^{-1}	N_{120}/N_{80}	27.8	20.6
$N_{600}P_{400}K_{600}$ (PK annual fertilization)	N_{120}/N_{80}	22.8	18.1
Average		*28.6*	*26.7*
V-VII crops rotations			
$N_{300}P_{300}K_{400}$	N_{60}/N_{40}	41.5	52.0
$N_{600}P_{300}K_{400}$	N_{120}/N_{80}	19.6	28.4
$N_{900}P_{300}K_{400}$	N_{180}/N_{120}	14.8	20.5
$N_{600}P_{300}K_{400}$+40 t manure·ha^{-1}	N_{120}/N_{80}	20.0	26.9
$N_{600}P_{0}K_{400}$	N_{120}/N_{80}	8.8	10.3
$N_{600}P_{300}K_{0}$	N_{120}/N_{80}	20.8	30.5
Average		*20.9*	*28.1*
VIII crops rotation			
$N_{250}P_{300}K_{200}$	N_{60}/N_{40}	32.7	37.5
$N_{500}P_{300}K_{200}$	N_{120}/N_{80}	24.8	28.0
$N_{750}P_{300}K_{200}$	N_{180}/N_{120}	15.4	21.3
$N_{250}P_{150}K_{0}$+60 t manure·ha^{-1}	N_{60}/N_{40}	55.8	71.3
$N_{500}P_{0}K_{200}$	N_{120}/N_{80}	0.70	11.8
$N_{500}P_{300}K_{0}$	N_{120}/N_{80}	21.7	32.3
Average		*25.2*	*33.7*

The average values of PFP-N and AE-N within the period of eight crops rotations decreased in parallel with the increase of the nitrogen rates combined with mineral PK fertilization (Table 5). The highest grain yield of wheat (67.1) and barley (80.5) per kilogram of fertilizer nitrogen had been demonstrated when using the low N_{60}/N_{40} rates. Doubling (N_{120}/N_{80}) or tripling (N_{180}/N_{120}) the applied fertilizer nitrogen resulted in obtaining of 31.7-43.5 kg less grain of wheat and 37.5-50.3 kg of barley for 1 kg of applied nitrogen. A high AE-N of 42.9-48.4 kg·kg^{-1} was found as a result of N_{60}/N_{40} fertilization for both crops. Moderate N_{120}/N_{80} and high N_{180}/N_{120} rates had been shown to lower AE-N by 44.2-45.7% and by 59.7-63.8%, respectively, compared to N_{60}/N_{40} rates.

Table 5. Effect of nitrogen rate on the Agronomic efficiency and Partial Factor Productivity of nitrogen in wheat and barley

Crop	N rate	PFP-N	AE-N
Wheat	N_{60}	67.1 a	42.9 a*
	N_{120}	35.4 b	23.3 b
	N_{180}	23.6 c	15.5 b
Barley	N_{40}	80.5 a	48.4 a
	N_{80}	43.1 b	27.0 b
	N_{120}	30.2 c	19.5 b

*Values in each column followed by the same lowercase letters are not significantly different at $p<0.05$.

Despite lower AE-N values at high nitrogen fertilization, differences were not mathematically proven with obtained AE-N under the moderate N_{120}/N_{80} rates. A negative linear relationship was established between the amount of fertilizer nitrogen and the PFP-N and AE-N indicators of wheat and barley (Table 6).

Table 6. Relationship between nitrogen rate and AE-N and PFP-N in wheat and barley

Index	Equation	R^2
PFP-N Wheat	$y = -0.362x + 85.5$	0.935
AE-N Wheat	$y = -0.228x + 54.6$	0.941
PFP-N Barley	$y = -0.628x + 101.5$	0.926
AE-N Barley	$y = -0.361x + 60.5$	0.928

The high values of the coefficient of determination R^2 of 0.926 - 0.941 was found, as well. Each kilogram of mineral nitrogen in rates N_{60}-N_{120} decreased PFP-N and AE-N values in wheat by 0.362 and 0.228 kg.kg^{-1}, respectively. The fall of PFP-N and AE-N for barley was 0.628 and 0.361 kg·kg^{-1}, respectively.

CONCLUSIONS

Values of PFP-N changed in the range of 13.7-81.8 (wheat) and of 21.8-112.8 (barley) over a period of eight crops rotations. The agronomic efficiency of nitrogen in dependence of fertilization varied within limits 0.7-55.8 kg·kg^{-1} (wheat) and 10.3 - 71.3 kg·kg^{-1} (barley). A high efficiency of N_{60} and N_{40} was found when N was incorporated into organic-mineral fertilization systems. Appling of 18 t vetch-oat mixture·ha^{-1} or 60 t manure·ha^{-1} increased AE-N and PFP-N to 54.5-71.3 and 81.8-112.8, respectively. The long-term exclusion of the fertilizer phosphorus from the mineral fertilization system $N_{600}P_0K_{400}$ (V-VII crops rotations) and $N_{500}P_0K_{400}$ (VIII crops rotation) decreased the grain yields by 1300-2900 kg·ha^{-1} for wheat and 1300-1450 kg·ha^{-1} for barley, compared to the triple fertilizer combination $N_{600}P_{300}K_{400}$ and $N_{500}P_{300}K_{400}$. As a result, PFP-N was reduced by 3.4-4.2 times and values of AE-N were very low: 0.7-8.8 kg·kg^{-1} (wheat) and 10.3-11.8 kg·kg^{-1} (barley).

Each kilogram of mineral nitrogen in rates N_{60}-N_{120} decreased PFP-N and AE-N values in wheat by 0.362 and 0.228 kg·kg^{-1}, respectively. The fall of PFP-N and AE-N for barley was 0.628 and 0.361 kg·kg^{-1}, respectively.

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