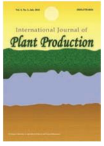

International Journal of Plant Production 10 (4), October 2016
ISSN: 1735-6814 (Print), 1735-8043 (Online)
www.ijpp.info

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Efficiency of nitrogen fertilization in spring wheat

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Received 2 February 2016; Accepted after revision 3 June 2016; Published online 10 August 2016

Abstract

An assessment of the nitrogen fertilization efficiency should not only include quantitative and qualitative yield changes, but also an analysis of formation some indicators such as: N harvest index (NHI), N use efficiency (NUE), N utilization efficiency (NUtE), N agronomic efficiency (NAE), N physiological efficiency (NPE) and N apparent recovery fraction (NRF). The objective of the study was the evaluation of spring wheat N fertilization efficiency under soil conditions of Luvic Chernozem. Factors of the experiment were: cultivar (Bombona and Tybalt) and level of N fertilization (0, 60, 90, 120 and 150 kg N ha^{-1}). The application of increasing N rates in the wheat crop raised the grain N from 56 to 92 kg N ha^{-1} and the aboveground biomass N from 70 to 123 kg N ha^{-1} and it decreased most of the efficiency indicators. The highest NHI value of 84%, PFNUE of 139.5 kg kg^{-1}, NAE of 32.7 kg kg^{-1}, NPE of 72.2 kg kg^{-1} and an NRF of 47% were observed for the lowest N rate of 60 kg N ha^{-1}. The NUtE of 92.8 kg kg^{-1}, was at the highest level on the control plot. Every increase on N rate resulted in a significant decrease in the efficiency indicators. The cultivar factor significantly affected the grain and aboveground biomass N and the NAE, NPE and NRF values. Low rainfall depths during the vegetative period favorably affected the NHI, NUtE, NAE and NPE indicators. On the other hand, excessive rainfall depths limited PFNUE, NAE, NPE and NRF.

Keywords: Wheat; Cultivar; Fertilization; Grain and biomass N yields; N effectiveness indicators.

Introduction

Optimization of N fertilization of field crops, ensuring implementation of agronomic, economic and environmental objectives still constitutes a real challenge for science and agricultural practice. Since plant production systems are usually permeable in reference to fertilization macronutrients, particularly nitrogen, numerous strategies were developed for the improvement of utilization of this nutrient by field crops. According to Zebarth et al. (2009) these strategies can be considered in two categories: optimization of fertilization and limiting the losses of nitrogen. Determination of the optimal nitrogen fertilization level is a difficult task, because it depends on numerous factors, including the genetic characteristics of the cultivar and the interactions between crop, environmental and agronomic factors. In spring wheat cultivation, in Poland, the suggested nitrogen rates remain in a wide range from 50 to 120 kg N ha^{-1} and they should not exceed 160 kg N ha^{-1} (Borkowska et al., 2002; Gąsiorowska et al., 2006; Kołodziejczyk et al., 2013; Kołodziejczyk and Szmigiel, 2014). The application of high nitrogen rates, both in mineral as well as in organic form decreases the utilization of this nutrient. Following Raun and Johnson (1999) the nitrogen utilization coefficient in cereals, including wheat, remains at a lower level than in the remaining plant groups and amounts to approximately 33%. This low level of nitrogen recovery from fertilizers implies economic and ecological results. The nitrogen that is not absorbed by arable crops or soil microorganisms is subjected to many processes and as a result its major part is lost (Mitchell et al., 1999). The studies carried so far demonstrated, that 15-66% of nitrogen is leached to the deeper soil layers and to ground waters, where it is accumulated in the form of nitrates, nitrites and organic compounds such as amines and nitrosamines, which are considered contaminants (Carranca et al., 1999; Barabasz et al., 2002; Ichir and Ismail, 2003).

The nitrogen fertilization efficiency is evaluated through the quantitative and qualitative yield changes. A more comprehensive evaluation of plant capacity to process the absorbed nitrogen per usable yield can be obtained by analyzing the following factors: N uptake, agronomic and physiologic efficiency of N, crop factor of N and N utilization from fertilizers (Novoa and Loomis, 1981; Simonis, 1988). An important issue on wheat cultivation, particularly in the reference to the environmental conditions, agricultural practices and cultivar characteristics is the understanding of the relationship between grain yield and formation of the fertilization efficiency indicators (Muurinen et al., 2007; Rahimizadeh et al., 2010).

The objective of this study was to determine the grain and aboveground biomass N yield and the nitrogen fertilization efficiency of spring wheat cultivated under soil conditions of Luvic Chernozem.

Materials and Methods

Experimental site and weather conditions

The field trials were carried in 2008-2010 near Krakow, Poland (50º 07’ N, 20º 05’ E and altitude 271 m a.s.l.) on Luvic Chernozem soil. The arable layer of soil (0-30 cm) was characterized by slightly acidic pH (pH_{KCl} 6.4), high content of absorbable phosphorus (78 mg kg^{-1}) and magnesium (102 mg kg^{-1}), average potassium content (141 mg kg^{-1}), organic C concentration 12.3 g kg^{-1} and total N 1.3 g kg^{-1}. The data used to characterize the local weather conditions were recorded from 1977 to 2007, in an automatic meteorological station located within the experimental field. The average air temperature from April to July in this region is 14.1 ^{o}C and the average cumulative precipitation is 270 mm. For the study years the average air temperature during the wheat vegetative period were 1 ^{o}C higher and the thermal sum in degree-days was 115-149 ^{o}C higher (Figure 1a). The rainfall conditions were more variable than thermal conditions. In 2008, the rainfall was 40 mm lower and in 2009 and 2010 it was higher by 65 and 312 mm, respectively, than in the analogous time of the many years (Figure 1b). It was observed an unfavorable weather condition for the development of spring wheat, stemming from the deficiency of rainfall occurred in May and June of 2008, coinciding with the stem elongation, heading and flowering periods and in April of 2009, i.e. in the germination phase. On the other hand, an excessive rainfall was recorded in June 2009 and from May to July of 2010.

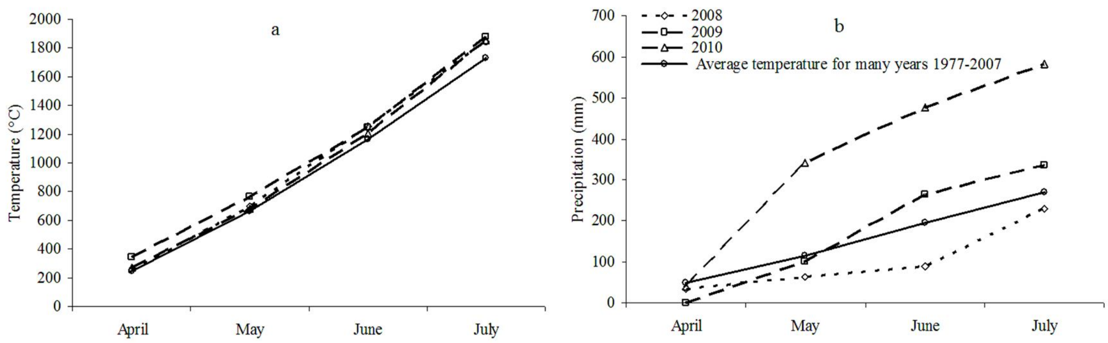

Figure 1. Cumulative sum of temperatures (a) and of rainfall (b) from 2008 to 2010 and for many years.

Experimental design

The field experiment was set up in a split–plot design with four replications. The factors were: cultivar (Bombona and Tybalt) and the level of nitrogen fertilization in kg of N ha^{-1} (0, 60, 90 (60 + 30), 120 (60 + 30 + 30) and 150 (90 + 30 + 30)). For N rates higher than 60 kg of N ha^{-1} the amount of fertilizer was split in two or three times: prior to sowing, at the stem elongation stage (BBCH 30-32) and at the beginning of heading (BBCH 50-52). Nitrogen fertilizer used was ammonium nitrate. Phosphorus and potassium were applied before sowing at rates of 60 kg of P_2O_5 ha^{-1} and 80 kg of K_2O ha^{-1}. The plot area for harvest was 16.5 m^2. The preceding crop was oats. Wheat was sown in mid-April, sowing rate was 450 pcs. of grains per m^2. Weed presence was controlled using the herbicides dicamba + triasulfuron (98.9 + 6.2 g a.i. ha^{-1}). In order to protect the plants against fungal diseases the crop was sprayed with tebukonazol + spiroksamin + triadimenol (134 + 200 + 34 g a.i. ha^{-1}) and propikonazol + cyprokonazol (125 + 40 g a.i. ha^{-1}), whereas pest were controlled using lambda – cyhalotrin (7.5 g a.i. ha^{-1}).

Nitrogen concentration determination and calculations

The nitrogen content in plant material (grain and aboveground biomass) was determined by the Kjeldahl method. Nitrogen uptake was calculated from the N concentration in the grain and in the aboveground biomass, both expressed as dry matter per unit area (kg ha^{-1}). Additional relations were determined as follows: grain N (GNY), aboveground biomass N (BNY), N harvest index (NHI), partial factor N use efficiency (PFNUE), N utilization efficiency (NUtE), N agronomic efficiency (NAE), N physiological efficiency (NPE) and N apparent recovery fraction (NRF) (Sinebo et al., 2004; López-Bellido et al., 2005; Neugschwandtner et al., 2015c).

$$NHI\ (\%) = GNY \times \frac{100}{BNY}$$

$$PFNUE\ (kg\ kg^{-1}) = \frac{YLD}{N_f}$$

$$NUtE\ (kg\ kg^{-1}) = \frac{YLD}{BNY}$$

$$NAE\ (kg\ kg^{-1}) = \frac{YLD_f - YLD_0}{N_f}$$

$$NPE\ (kg\ kg^{-1}) = \frac{YLD_f - YLD_0}{BNY_f - BNY_0}$$

$$NRF\ (\%) = (BNY_f - BNY_0) \times \frac{100}{N_f}$$

where YLD is the grain yield expressed as dry matter (kg ha^{-1}); N_f is the level of N fertilizer (kg ha^{-1}); GNY is the grain N (kg ha^{-1}); BNY is the aboveground biomass N (kg ha^{-1}).

Statistics

A variance analysis was applied to the results by using the Statistica 10.0 software. Honestly significant difference (HSD) for the nitrogen removed by the wheat grain and aboveground biomass, harvest index and N-efficiency parameters were verified using the Tukey's test at significance level P=0.05.

Results and Discussion

Grain N, aboveground biomass N, HI and NHI

The grain and aboveground biomass N were significantly depended on the cultivar, level of nitrogen fertilization, weather conditions during wheat vegetative phase and on the interaction of these factors (Table 1). Increasing the nitrogen fertilization level from 0 to 150 kg ha^{-1} raised the grain N from 56 to 92 kg N ha^{-1} and the aboveground biomass N from 70 to 123 kg N ha^{-1} but decreased the nitrogen harvest index (NHI) from 84% for the control plot to 79% for the N rate of 150 kg N ha^{-1} (Figures 2a, b, d). A considerably higher N uptake, varying from 65 to 149 kg N ha^{-1} for grain N and from 78 to 184 kg N ha^{-1}, for aboveground biomass N of spring wheat, fertilized with 0 to 160 kg N ha^{-1} was reported by Kołodziejczyk et al. (2013).

In the present study, the lowest grain and aboveground biomass N and the highest nitrogen harvest index was observed in 2008, when the rainfall was at its lowest level among the three–year study period. Also Neugschwandtner et al. (2015a) have shown that drought conditions significantly modifies of grain and aboveground biomass N. The weather conditions favoring uptake and accumulation of nitrogen in the grain, especially in the aboveground biomass occurred in 2009, as confirmed by the low NHI. The dependency of spring wheat yield on the rainfall conditions was corroborated by the work of Dmowski and Dzieżyc (2009). By using a regression model, the authors demonstrated the lack of influence of rainfall in May, the highest rainfall requirements in June (approx. 100 mm) and the decreasing dependency of crop yield on precipitation in July. The grain and aboveground biomass N successively increased in response to all N fertilization levels in 2008 and 2009, whereas in 2010, the maximum response was achieved at the 120 kg N ha^{-1} level (Figures 3a, b). The interactions of weather conditions and rates and splitting of nitrogen fertilization on the wheat aboveground biomass N was also demonstrated by the results of Velasco et al. (2012). The cultivars differed in the grain size and in the aboveground biomass N and also responded differently to weather conditions and to the level of nitrogen fertilization. In general, grain N higher than 6 kg N ha^{-1} and aboveground biomass N higher than 3 kg N ha^{-1} was a characteristic of the Tybalt wheat cultivar (Figures 2a, b), but in 2008 higher grain and aboveground biomass N was observed for the Bombona cultivar (Figures 3c, d). Moreover, the results showed that the cultivar Bombona exhibited a weaker response to N rates higher than 90 kg N ha^{-1} as compared to the Tybalt cultivar (Figures 3e, f). Regarding the NHI, no differences between the cultivars was statistically confirmed (Table 1). Statistical difference between cultivars was observed in the harvest index (HI) (Figure 2c). When studying the response of a dozen of wheat cultivars to nitrogen fertilization levels, Ehdaie and Waines (2001), reported significant influence of these factors on both HI and NHI. Moreover, these authors indicated that an increment of 1% in HI was followed by an increase of 0.84% in NHI This relationship was not corroborated in the present study.

Table 1. Analysis of variance results for grain and aboveground biomass N, harvest index (HI), nitrogen harvest index (NHI), partial factor N use efficiency (PFNUE), nitrogen utilization efficiency (NUtE), N agronomic efficiency (NAE), N physiological efficiency (NPE) and N apparent recovery fraction (NRF).

Variance source	N		HI	NHI	PFNUE	NUtE	NAE	NPE	NRF
	grain	biomass							
Fertilization (F)	***	***		***	***	***	***	***	***
Cultivar (C)	***	*	***				***	**	***
Year (Y)	***	***		***	*	***	*	*	*
F×C	*	***							
F×Y	***	***			***	**	**		***
C×Y	***	***			*				
F×C×Y	*	*							*

Significant effects at P<0.05 (*), P<0.01 (**) and P<0.001 (***). Blank values indicate no significant effect (P>0.05).

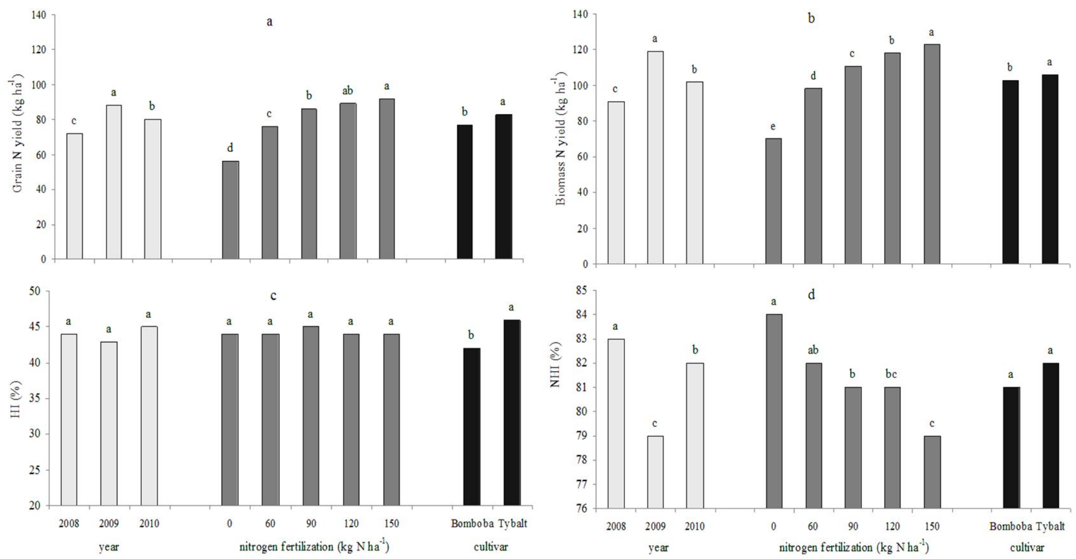

Figure 2. Grain N (a), aboveground biomass N (b), harvest index (c) and nitrogen harvest index (d), as affected by year, nitrogen fertilization level and cultivar. Different letters indicate significant differences between means (P<0.05).

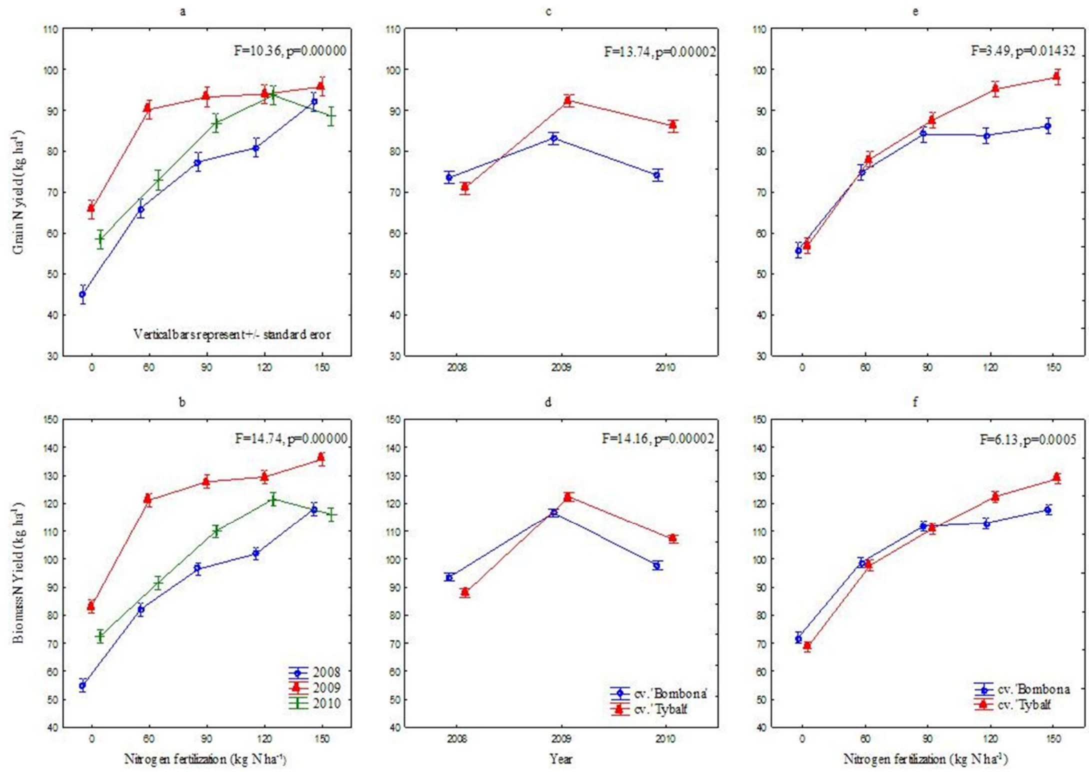

Figure 3. Grain N yield and biomass N yield as affected by the interactions of year × nitrogen fertilization (a, b), year × cultivar (c, d) and nitrogen fertilization × cultivar (e, f).

N effectiveness indicators: PFNUE, NUtE, NAE, NPE and NRF

PFNUE was influenced by the nitrogen rate and weather conditions during the spring wheat vegetative period (Table 2, Figure 4a). The highest value of this coefficient with a mean of 139.5 kg kg^{-1}, was obtained with the rate of 60 kg N ha^{-1}. Each increment on the nitrogen fertilization level resulted in a significant decrease in PFNUE. For the highest nitrogen rate of 150 kg N ha^{-1} to the PFNUE value represented only 41% of the PFNUE value determined for the 60 kg N ha^{-1} rate. Furthermore, a significantly lower nitrogen utilization efficiency was observed in years with low, as well as excessive precipitation. The effect was particularly visible for Tybalt cultivar (Figure 4b). According to some authors, the decrease of NUtE in response to increasing nitrogen rates stems from the fact of a slower grain filling rate even under high N supply (Limon-Ortega et al., 2000; López-Bellido and López-Bellido, 2001; Zhao et al., 2006; Kołodziejczyk et al., 2013).

The NUtE, expressed as grain yield per unit of aboveground biomass N, ranged from 70.7 to 92.8 kg kg^{-1}. The highest nitrogen utilization efficiency was observed in the treatment with 0 N application. Increasing the N rate from 0 to 150 kg ha^{-1} decreased NUtE by 22.1 kg kg^{-1}. The weather conditions and the interactions with N rates were important factors affecting NUtE. NUtE attained the highest value in 2008 and the lowest in 2009, for the cultivar Tybalt. In all study years a decrease in the N utilization efficiency followed an increase in nitrogen rates, but the magnitude of changes was variable (Figure 4c). In 2008, NUtE ranged from 80 to 103 kg kg^{-1}, in 2009 from 66 to 80 kg kg^{-1}, whereas in 2010 it ranged from 66 to 96 kg kg^{-1}. The results of our study are corroborated by the reports of Delogu et al. (1998), López-Bellido and López-Bellido (2001) and Neugschwandtner and Kaul (2015b), who also demonstrated decreasing in N utilization efficiency as a consequence of increasing N rates. On the other hand, in the study of Kołodziejczyk et al. (2013), carried in similar soil conditions, indicated that the highest NUtE was observed with rate of 40 kg N ha^{-1}, whereas it was significantly lower on treatments fertilized with higher nitrogen rates and on the control site. Moreover, the authors observed almost two times lower N utilization efficiency.

The N agronomic efficiency (NAE) was significantly influenced by the weather conditions, level of nitrogen fertilization and interactions of these factors, but also by the wheat cultivar characteristics (Table 1). Depending on the level of N fertilization and of the year of study the NAE, ranged from 4.7 to 43.4 kg kg^{-1} (Figure 5a). NAE was significantly higher in years with lower rainfall amounts, i.e. in 2008 and 2009 as compared to 2010, when excessive rainfall was recorded during the entire vegetative period of spring wheat. The highest N agronomic efficiency, of 32.7 kg kg^{-1} was observed for the rate of 60 kg N ha^{-1} (Table 2). Increasing the nitrogen rate to 120 and to 150 kg N ha^{-1} resulted in a decrease of NAE by 39 and 54%, respectively. Regarding the cultivars, Tybalt was more efficient in the use of mineral N as compared to Bombona; it produced more grain per kilogram of nitrogen derived from the fertilizers. A significantly higher N physiological efficiency (NPE), calculated as the grain yield increase per unit of aboveground biomass N, of 60.7 kg kg^{-1}, was determined, for the Tybalt cultivar as compared to 48.4 kg kg^{-1} observed for the Bombona cultivar. The NPE decreased the N rate increased. The highest NPE was observed for the 60 kg N ha^{-1} rate. The use of higher N rates (120 and 150 kg N ha^{-1}) resulted in significant decrease of this factor. NPE attained the highest value in 2008 and the lowest in 2010. López-Bellido and López-Bellido (2001) did not observed significant influence of the nitrogen fertilization rates ranging from 50 to 150 kg N ha^{-1} on the NPE. However, these authors reported a significant influence of N fertilization rates on the NAE; Considerably lower NAE values, ranging from 4.9 to 7.2 kg kg^{-1} was reported. NAE and NPE several times lower were also determined by Delogu et al. (1998) and López-Bellido et al. (2005).

The N apparent recovery fraction (NRF) fluctuated between 29 to 64% (Figure 5b). The nitrogen from the mineral fertilizer was best utilized by wheat when rates of 60 and 90 kg N ha^{-1} were used (Table 2). The lowest NRF value was determined for the rate of 150 kg N ha^{-1}. These results corroborate the widely known negative relationship the increasing level of N fertilization with NRF. The mean NRF of 42% observed in our study was similar to that presented by Chen et al. (2008), lower than the valued reported by Kirda et al. (2001) and higher than that indicated by Carranca et al. (1999). Regardless of the nitrogen fertilization level, a higher NRF was observed for the Tybalt cultivar. Weather conditions had significant influence on NRF. The excessive rainfall during vegetative period of the spring wheat in 2010 negatively affected the crop nitrogen utilization. Furthermore, the study demonstrated an interaction between weather conditions and the fertilization level (Figure 5b). In 2008, the NRF remained in a comparatively narrow range from 39 to 46% and the changes of this factor for individual fertilization rates were not unambiguous. In 2009, each nitrogen rate applied in the range of 0 to 120 kg N ha^{-1} resulted in a decrease of NRF. On the other hand, in 2010, the NRF decreased for N rates higher than 90 kg N ha^{-1}. The existence of strong relationship between weather conditions and N recovery from fertilizers was also demonstrated by Pilbeam (1996). However, the author determined that the higher precipitation-evaporation quotient value, the higher is the N recovery.

Table 2. PFNUE, NUtE, NAE, NPE and NRF at harvest as affected by year, nitrogen fertilization and cultivar.

Factor	PFNUE (kg kg^{-1})	NUtE (kg kg^{-1})	NAE (kg kg^{-1})	NPE (kg kg^{-1})	NRF (%)
Year					
2008	90.7 ^{b}	91.0 ^{a}	30.5 ^{a}	70.7 ^{a}	43 ^{a}
2009	97.9 ^{a}	72.8 ^{c}	26.8 ^{a}	55.1 ^{b}	47 ^{a}
2010	87.3 ^{b}	79.5 ^{b}	13.1 ^{b}	37.7 ^{c}	36 ^{b}
Nitrogen fertilization (kg N ha^{-1})					
0	-	92.8 ^{a}	-	-	-
60	139.5 ^{a}	86.7 ^{b}	32.7 ^{a}	72.2 ^{a}	47 ^{a}
90	97.2 ^{b}	79.4 ^{c}	26.0 ^{ab}	57.2 ^{ab}	46 ^{ab}
120	73.4 ^{c}	75.8 ^{cd}	20.0 ^{bc}	50.1 ^{bc}	39 ^{bc}
150	57.8 ^{d}	70.7 ^{d}	15.1 ^{c}	38.5 ^{c}	35 ^{c}
Cultivar					
Bombona	91.8 ^{a}	82.1 ^{a}	19.8 ^{b}	48.4 ^{b}	38 ^{b}
Tybalt	92.1 ^{a}	80.1 ^{a}	27.1 ^{a}	60.7 ^{a}	45 ^{a}

Different letters indicate significant differences between means (P<0.05).

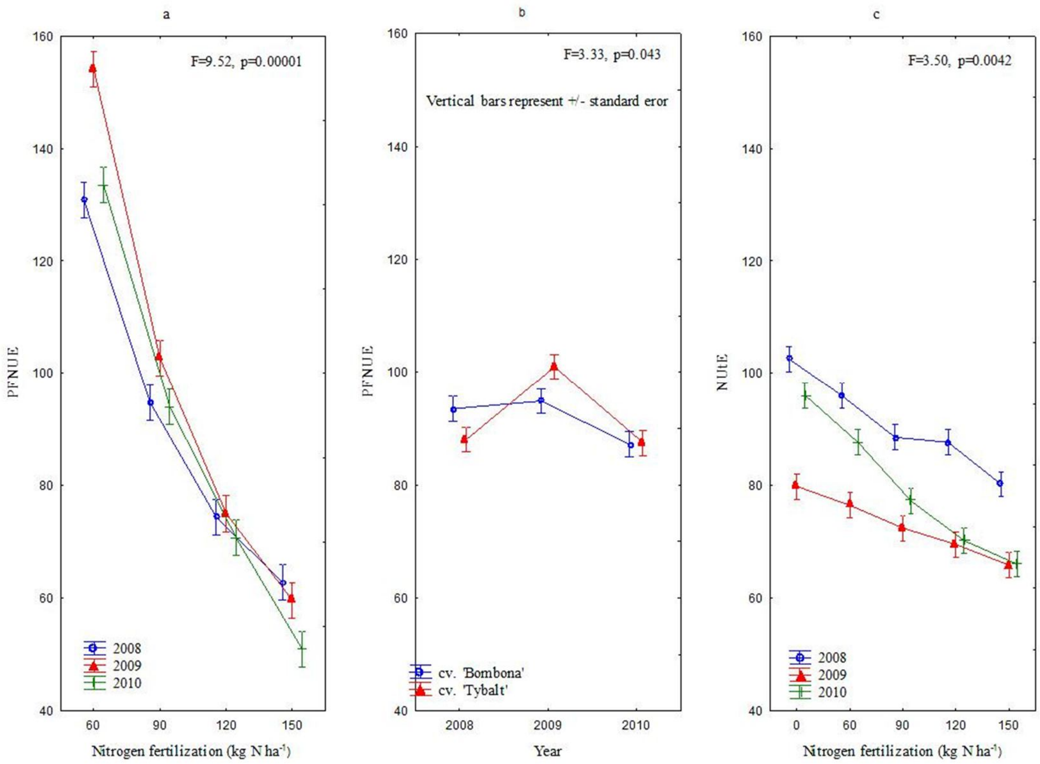

Figure 4. Partial factor N use efficiency (PFNUE) as affected by the interactions of year × nitrogen fertilization (a), year × cultivar (b) and nitrogen utilization efficiency (NUtE) as affected by the interactions of year × nitrogen fertilization (c).

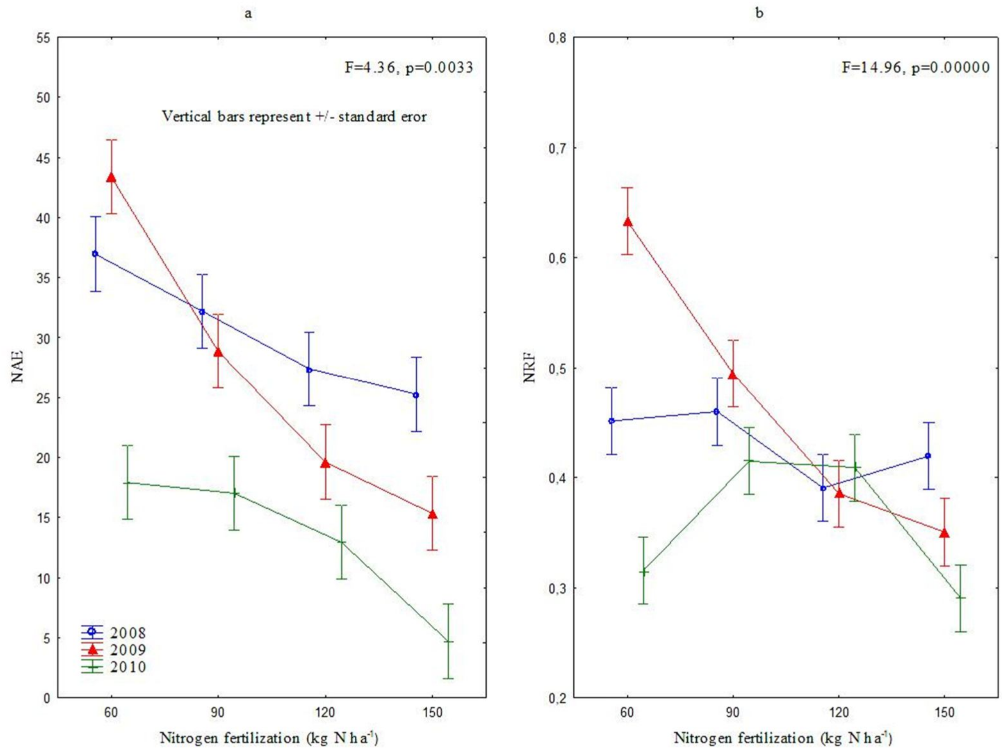

Figure 5. N agronomic efficiency (NAE), (a) and N apparent recovery fraction (NRF), (b) as affected by the interactions of year × nitrogen fertilization level.

Conclusions

Successively higher nitrogen fertilizer rates applied to spring wheat results in an increase of grain and aboveground biomass N and in a decrease of the N effectiveness indicators. The limiting factor on the effectiveness of high nitrogen rate in wheat was the natural soil fertility, which was demonstrated by the values of the efficiency indicators, specially NRF. Thus, an excessive intensification of spring wheat fertilization cultivated in soil conditions of the Luvic Chernozem may be economically unjustified. Moreover, the study demonstrated diversified capacity of the wheat cultivars for N accumulation in the aboveground biomass and also in converting the absorbed nitrogen into grain. Therefore, an individual adjust to the fertilization needs of each cultivar is necessary. The effectiveness of the nitrogen fertilization was also significantly affected by the weather conditions during spring wheat vegetative period. The N effectiveness indicators was affected to a greater extent by both excessive and limited rainfall depths. In order to improve the effectiveness of the use of high nitrogen rates (150 kg N ha^{-1}) under the conditions of excessive rainfall, a correction in fertilization program during the crop vegetative period is suggested.

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