Winter wheat agronomic traits and nitrate leaching under variable nitrogen fertilization

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ABSTRACT

In the long-term field trial on an arable dystric Stagnosols, winter wheat (*Triticum aestivum* L.) grain yield, nitrogen use efficiency (NUE) and nitrate nitrogen (NO_3^--N) in lysimeter water were compared under treatments of 0, 100, 150, 200, 250 and 300 kg/ha of mineral nitrogen (N) during the growth years 1996/97, 1999/00, 2002/03 and 2005/06. Year properties significantly influenced N availability resulting in different responses of grain yield and NUE under variable treatments. Grain yield showed strong significant correlation with the rainfall accumulated from March to May ($r = 0.77$). In the case of a dry year 2003, winter wheat yield and NUE were adversely influenced by unfavourable climatic conditions. The optimal response of yield and NUE to increasing mineral N rates was found at the amount of 150–200 kg N/ha. Very strong significant correlation between the total amount of leached NO_3^--N and NUE was found for periods 1999/00 and 2005/06 where, in terms of increasing N levels, lower NUE conditioned higher NO_3^--N leaching ($r = 0.91$ and $r = 0.94$, respectively). According to the shallow depth of groundwater and installation of drainage systems, there is still a risk of freshwater contamination by nitrates if the N rates higher than 200 kg/ha were applied.

Keywords: Stagnosols; climate; water deficit; grain yield; nitrogen use efficiency

Increased nitrogen (N) fertilizer rates prompt increased yield up to a point, beyond which there is no additional response, but it also prompts greater N loss (Lopez-Bellido and Lopez-Bellido 2001). Some of the fertilizer N can be immobilised in the soil and the rest is lost by denitrification, volatilization, gaseous plant N loss, leaching and surface runoff (Raun and Johnson 1999). Depending on the method used, nitrogen use efficiency (NUE) can be less than 50% in winter wheat grain production systems (Thomason et al. 2000). Wheat yields and NUE can be low and very variable in response to irregular weather patterns and insufficient seasonal rainfall supply under rainfed conditions (Semenov et al. 2007). Average winter wheat grain yield of 4.5 t/ha for the last decade (2000–2010) in Croatia (CBS 2011) was low compared to the yield potential of currently grown cultivars. In order to improve N fertilizer recommendations, the inclusion of climate features among integration of soil and yield data seems essential to better anticipate crop growth, N uptake and N fertilization rates (Appel 1994, Samborski et al. 2009).

The objective of the paper was to investigate how variable mineral N fertilization rates affected the nitrate nitrogen (NO_3^--N) losses in lysimeter water, winter wheat grain yield and NUE during the four climatically different years on the long-term field experiment located in the Pannonia region with the purpose of determining the sustainable mineral N rates for winter wheat production.

MATERIAL AND METHODS

Research was conducted on an experimental field within hydro-ameliorated cropland in Western Pannonia sub-region of Croatia (45°33'N, 16°31'E).

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The soil type of the trial site is dystric Stagnosols. Precipitation water periodically stagnates on the illuvial horizon (52–97 cm) (Table 1), which was the reason for installing a pipeline drainage system at a depth of 120 cm across the experimental area. Other factors that limit crop yield are low soil organic matter and soil pH. The experiment was established as a block design with six mineral fertilizer treatments (N_0PK, $N_{100}PK$, $N_{150}PK$, $N_{200}PK$, $N_{250}PK$ and $N_{300}PK$, kg/ha) and four replications. The dimension of each treatment parcel was 26 × 26 m. The experimental design included the installation of zero tension pan lysimeters (after Ebermayer 1878) at a depth of 80 cm.

The field experiment included growing years 1997, 2000, 2003 and 2006 with winter wheat (*Triticum aestivum* L.) as a test crop, extracted from the crop rotation of maize/soybean-winter wheat-oilseed rape. Sowing of winter wheat was carried out on 10 October 1996 at the beginning of the experiment, after maize on 13 October 1999, after soybean on 28 October 2002, and after soybean on 26 October 2005 with four cultivars: Sana (6 MGS/ha), Žitarka (6.75 MGS/ha), Renan (4.5 MGS/ha) and Fiesta (5 MGS/ha), respectively (MGS – millions of germinating seeds).

Basic fertilization involved 2:3 of the total amount of phosphorus-potassium (PK) mineral fertilizer applied before ploughing, with the other 1:3 of the total amount, with 30% of N, applied directly before seedbed preparation. N topdressing was performed three times using calcium-ammonium-nitrate (CAN): I. 25%; II. 25%, and III. 20%. The first topdressing was applied at the beginning of spring tillering, and the second and third during stem extension. Fertilizer for winter wheat amounted to 500 kg of complex mineral fertilizer NPK 10-30-20 in case of 200 kg N/ha, as for all treatments with higher amounts of mineral N. With 500 kg NPK 10-30-20 applied, soil was treated with 50 kg N, 150 kg P and 100 kg K, which was the reason for applying 334 kg of triple superphosphate and 170 kg of 60% potassium chloride for the treatments II. N_0PK, III. $N_{100}PK$ and IV. $N_{150}PK$.

Grain yields (t/ha, 14% moisture content) were compared between the vegetation periods. Nitrate separation in lysimeter water samples was performed on Doinex ICS-1000 system (ion chromatography method) according to the ISO 10304-1 (1998). NUE was calculated according to Craswell and Godwin (1984):

$$\text{NUE} = (\text{grain yield}_F - \text{grain yield}_C)/\text{fertilizer N applied (kg/kg)}$$

Where: F – fertilized crop; C – unfertilized control.

The significance test for overall statistics (ANOVA) was performed at a probability level of $P < 0.05$ (SAS Institute Inc., Cary, USA).

RESULTS AND DISCUSSION

Experimental years were characterised by high inter-annual variability and intra-annual distribution of rainfall amounts. Water balance (according to Thornthwaite 1948) indicated different agroecological conditions during the investigated periods (Figure 1). The driest year was 2003, as presented by significant water deficit during the late spring and summer months. High intra-annual variability of water balance was found in the year 2000. Water supply from January to April was high enough to compensate for water deficit in June and July. The most optimal conditions were recorded in the vegetation periods of the years 1997 and 2006 where water surplus in winter and early spring did not exceed cumulative amount of 95 mm, while water deficit appeared only in July.

Table 1. Soil physical and chemical properties

Depth (cm)	Soil particles (ø mm, %)				Soil texture	pH_{KCl}	C_{org} (%)	Nutrient amount (mg/100 g)		$CaCO_3$ (%)
	2–0.2	0.2–0.02	0.02 –0.002	< 0.002				$P\text{-}P_2O_5$	$K\text{-}K_2O$	
0–32	0.36	55.24	30.30	14.10	loam	4.84	0.587	7.73	8.67	–
32–52	0.40	50.60	32.00	17.00	loam	5.12	0.529	2.27	5.94	–
52–97	0.05	55.10	38.00	6.85	sandy clay loam	6.02	0.203	3.35	5.34	0.62
97–116	1.22	60.93	32.70	5.15	sandy loam	7.41	0.128	3.33	4.11	2.08
> 116	0.04	85.91	8.75	5.30	sandy loam	7.18	0.076	1.26	3.24	0.83

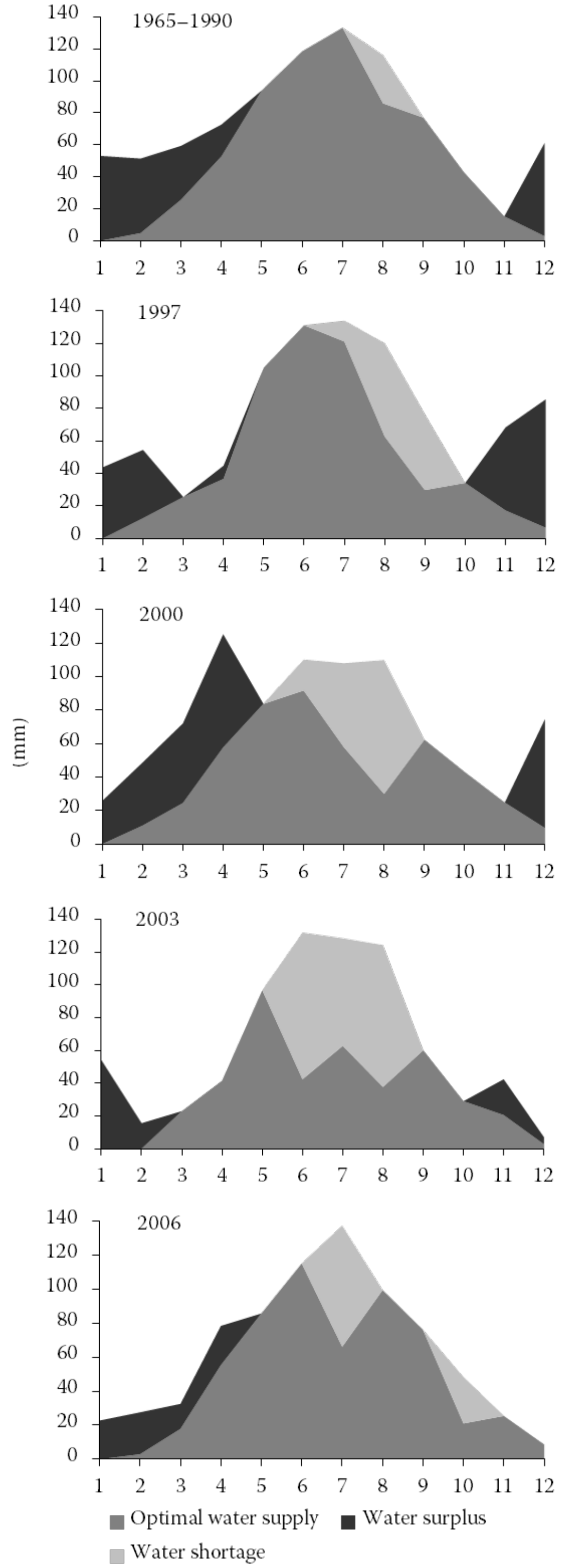

Figure 1. Water balance according to Thornthwaite for the reference period (1965–1990) and years 1997, 2000, 2003 and 2006 (rainfall data measured at the field; temperature data measured at the meteorological station Sisak)

Water deficit in the vegetation period was 13, 69, 155 and 71 mm for the years 1997, 2000, 2003 and 2006, respectively.

Climatic differences were statistically significant for both variables and N fertilization was the key factor that influenced both yield and NUE (Table 2). A significant year × treatment interaction was found for both grain yield and NUE, which means that growing conditions influenced N availability resulting in different responses of measured traits under variable N treatments. Olfs et al. (2005) gave a comprehensive review on the relation between grain yield and economic optimum N rate and concluded considerable variation of these parameters between fields and years. In the example from Rothamsted, the optimum N fertilizer rate for winter wheat varied between 176 and 240 kg N/ha (Broadbalk Experiment, 1990–2001; adopted from Brentrup and Link 2004). Results presented in this paper show grain yield ranging from 1.26 t/ha (1997, N_0) to 7.48 t/ha (2006, N_{300}) with the average value across four growing seasons and all fertilization treatments of 4.40 t/ha, and NUE in grain yield from 8.3 kg/kg (2003, N_{250}) to 28.8 kg/kg (2000, N_{100}) with an average of 16.5 kg/kg (Table 3). Winter wheat yields in 1997 and 2000 were realised under almost optimal water regime, while year 2003 was extremely dry and hot during the vegetation period, mostly between the stem elongation and the anthesis growth stage (Figure 1), which adversely influenced yield and NUE (Figure 2).

Average grain yields showed a strong significant correlation with the rainfall accumulated during the critical periods of wheat growth (March to May) ($r = 0.77$, $P < 0.05$; Figure 3). According to Lalic et al. (2012), high positive correlations between yield

Table 2. Analysis of variance for winter wheat yield and nitrogen use efficiency (NUE) for overall effect

Results of ANOVA[†]	Yield	NUE
CV	11.60	19.53
R^2	0.94	0.80
Model	48.14*	12.50*
Error	0.26	10.35
Year	134.39*	50.89*
Treatment	129.42*	11.53*
Year × treatment	3.80*	3.23*

[†] *MSE* and *F*-values are given for the sources of variation considered; *$P < 0.001$; *CV* – coefficient of variation

Table 3. Mean comparison for winter wheat yield and nitrogen use efficiency (NUE) between different N fertilizer treatments

Winter wheat variables	Treatment (kg N/ha)		1997	2000	2003	2006
	code	N rate				
Yield (t/ha)	I	N_0	1.26^{d}	1.37^{d}	1.48^{d}	3.1^{d}
	II	N_{100}	2.85^{c}	4.24^{c}	2.41^{cd}	5.51^{c}
	III	N_{150}	3.87^{b}	4.92^{bc}	3.18^{bc}	6.26^{b}
	IV	N_{200}	5.40^{a}	5.83^{ab}	3.32^{abc}	6.34^{b}
	V	N_{250}	5.46^{a}	5.83^{ab}	3.54^{ab}	6.67^{b}
	VI	N_{300}	5.03^{a}	6.08^{a}	4.24^{a}	7.48^{a}
NUE (kg/kg)	I	N_0	–	–	–	–
	II	N_{100}	15.9^{bc}	28.8^{a}	9.3^{a}	24.1^{a}
	III	N_{150}	17.4^{ab}	23.7^{ab}	11.3^{a}	21.1^{a}
	IV	N_{200}	20.7^{a}	22.3^{b}	9.2^{a}	16.2^{b}
	V	N_{250}	16.8^{ab}	17.9^{bc}	8.3^{a}	14.3^{b}
	VI	N_{300}	12.6^{c}	15.7^{c}	9.2^{a}	14.6^{b}

Means followed by the same letter within a column for each year are not significantly different at the $P < 0.05$ level by the Duncan's Multiple Range test

and accumulated rainfall for the April–June period indicated that water will remain a major limiting factor for growing winter wheat in the Pannonian lowland region. Similar results were reported by Ducsay and Ložek (2004) where different weather conditions significantly influenced winter wheat grain yield in individual experimental years. They recorded yield depression in the season 1999/2000 when low precipitation and high temperature in April and May negatively affected the final grain production. Lopez-Bellido et al. (1996) showed, from a long-term experiment, the wheat response to fertilizer N rates in dry years (with rainfall below 450 mm during growing season) to be low or nonexistent.

Favourable climatic conditions during winter wheat growth recorded in 2006 positively affected yield, which was the highest at all treatments compared to the previous vegetation years. With regard to climate, the higher yield in 2006 could be affected by soybean residues in the soil (vegetation period 2004/05), which possibly provided more N in the soil available for winter wheat. This especially applies for the N_0 treatment, where high differences in yield were found between 2006 and other years (Table 3). NUE was decreased in response to increasing N fertilizer for winter wheat in the growing years 2000 and 2006, but increased up to N_{200} in 1997 and N_{150} in 2003; it had lower values in N treated plots during dry year 2003. NUE in

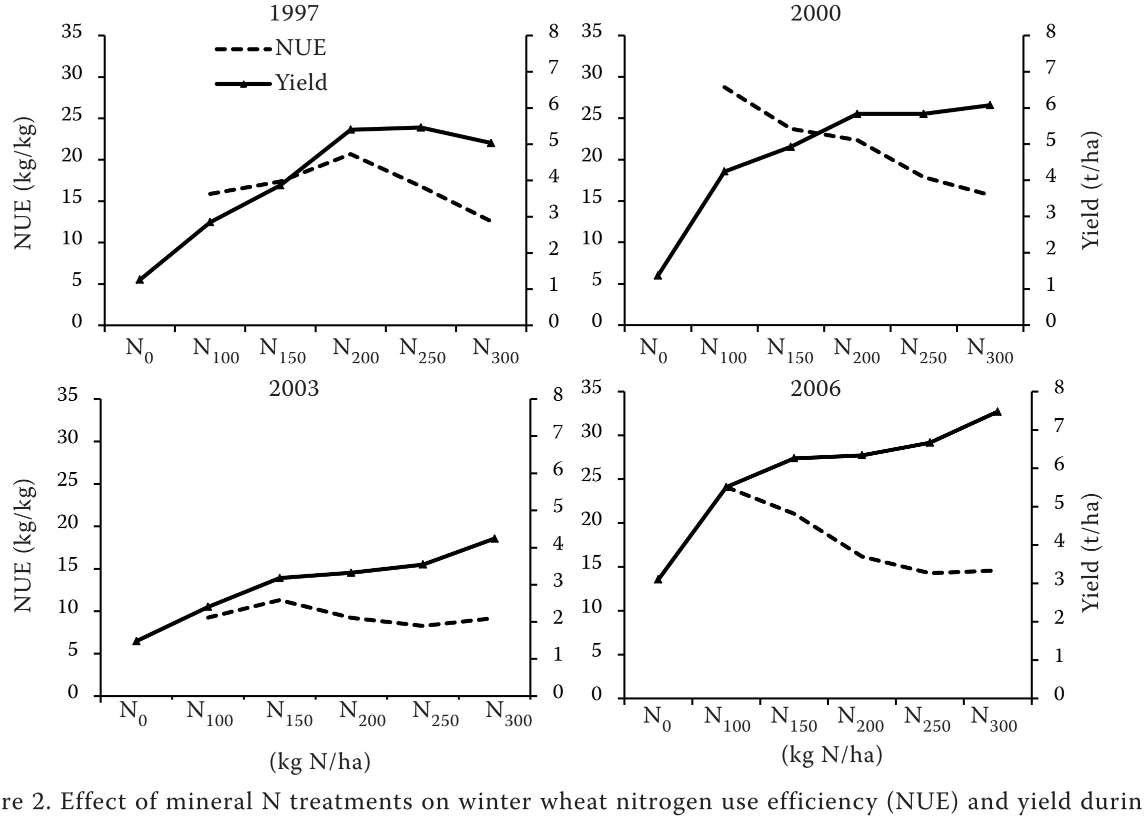

Figure 2. Effect of mineral N treatments on winter wheat nitrogen use efficiency (NUE) and yield during the four growth years

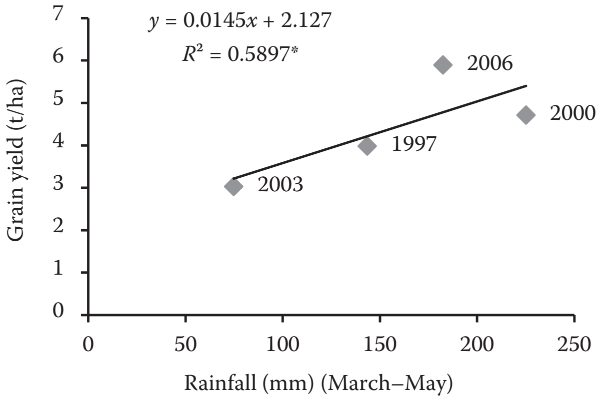

Figure 3. Relationship between winter wheat grain yield and rainfall amounts during tillering and stem extension for years 1997, 2000, 2003 and 2006. *$P < 0.05$

years 2000 and 2006 had a similar pattern, but it was lower in 2006 because of significantly higher grain yield in the control treatment (N_0). Grain yield was significantly increased by increasing N fertilizer levels in all of the investigated years. NUE was significantly affected by fertilizer levels in all years except 2003, when N uptake by crops was distorted by drought. When the results of the mean comparison between treatments per each year are studied (Table 3), yield values significantly differed up to 200 kg N/ha.

Figure 2 shows the relationship between NUE and grain yield based on response to increasing mineral N rates. The optimal response of NUE and yield was found at lower fertilizer rates (approximately 150–200 kg N/ha), with the exception of the vegetation period 2002/03 where unfavourable climatic conditions and water deficit influenced winter wheat to have a very low response to applied N. Jing et al. (2009) reported that N uptake by wheat increased with increasing N rates, while agronomic NUE (kg grain/kg N applied) declined at rates exceeding 150 kg N/ha. As investigated by Haberle et al. (2006), lower doses of applied N (100 kg N/ha) were crucial for achieving almost full depletion of available mineral N by winter wheat uptake in the soil up to the depth of 90 cm during the most of the vegetation period.

In terms of detecting N losses on the experimental plots, interesting results were gained from the analysis of nitrate leaching in relation to increasing fertilization levels and NUE. Figure 4 shows NO_3^--N concentrations in lysimeter water at each fertilizer treatment according to the measurement dates during the investigation periods. Different times of the last lysimeter water sampling in the experimental years indicate that there was no longer leaching till the end of the vegetation period which was directly related to the rainfall amounts and distribution. Absolute minimum NO_3^--N concentration was recorded during summer 1997 with 1.0 mg/L for the treatment with 150 kg N/ha, while the maximum value (61.0 mg NO_3^--N/L) was determined for a plot treated with 300 kg N/ha

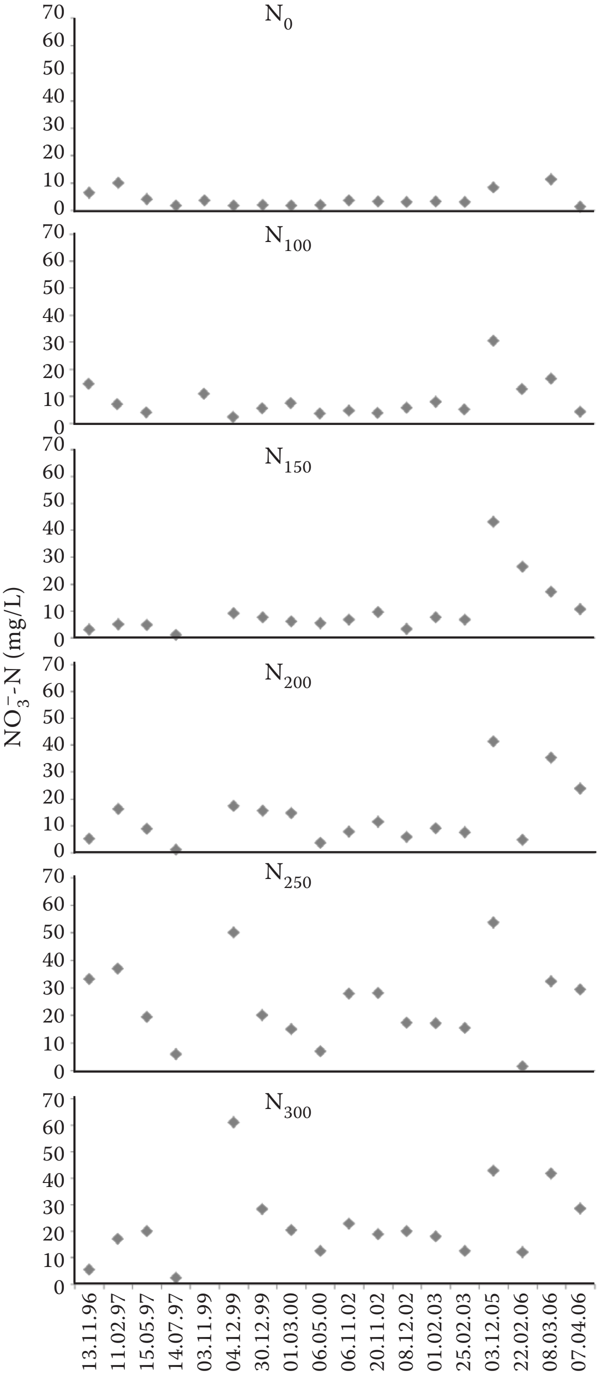

Figure 4. NO_3^--N concentration in lysimeter water at six N fertilization treatments (0, 100, 150, 200, 250 and 300 kg N/ha)

during the late autumn 1999. The obvious problem of potential groundwater contamination with NO_3^--N was found with N fertilizer rates higher than 200 kg N/ha in periods with high rainfall amounts. In treatment without N application, the NO_3^--N concentration through each vegetation period was low (2.1–5.5 mg/L). Increased N rates in the form of 200, 250 and 300 kg/ha led to higher average values of NO_3^--N concentration in leachate amounting to 7.9–26.3, 18.4–29.1 and 11.2–31.3 mg/L, respectively. In treatments of up to 150 kg N/ha, the NO_3^--N concentration in leachate was lower than the maximum allowed amount of 11.3 mg NO_3^--N/L in the freshwater (EC 1991). The study conducted by Liang et al. (2011) showed similar proportions of NO_3^--N concentrations in leachate according to different N fertilizer rates (0, 90, 180, 270 and 360 kg N/ha) applied to winter wheat fields.

Relationship between the leached NO_3^--N and NUE for each of the vegetation periods indicated effect of the year on the crop N uptake and N losses (Figure 5). Total amount of leached NO_3^--N (kg/ha) was calculated according to the following multiplication: quantity of lysimeter water (L) × NO_3^--N concentration in lysimeter water (mg/L) × 2 × 10000/1000/1000. Very strong significant correlation was found for periods 1999/00 and 2005/06 where, in terms of increasing N levels, lower NUE conditioned higher NO_3^--N leaching. As expected, at the beginning of the experiment (1996/97) this relationship was very weak. Extreme rainfall and temperature path of the dry year 2003 resulted in very low NUE and nitrate leaching higher only for the fertilizer rates of 250 and 300 kg N/ha.

In the case of a dry year, winter wheat production could not be maintained at satisfactory level. NUE was also lowered, which increases the probability of N loss to ecosystems and negative economic results in winter wheat production. According to the shallow depth of groundwater (about 2 m) and drainage systems installed on intensively managed arable Stagnosols, there is still a risk of contamination of freshwater by nitrates if the N rates higher than 200 kg N/ha were applied. Further work implies the use of model-based decision support tools to find the optimum strategies for achieving maximum NUE in cereal crops and minimum N losses to the environment.

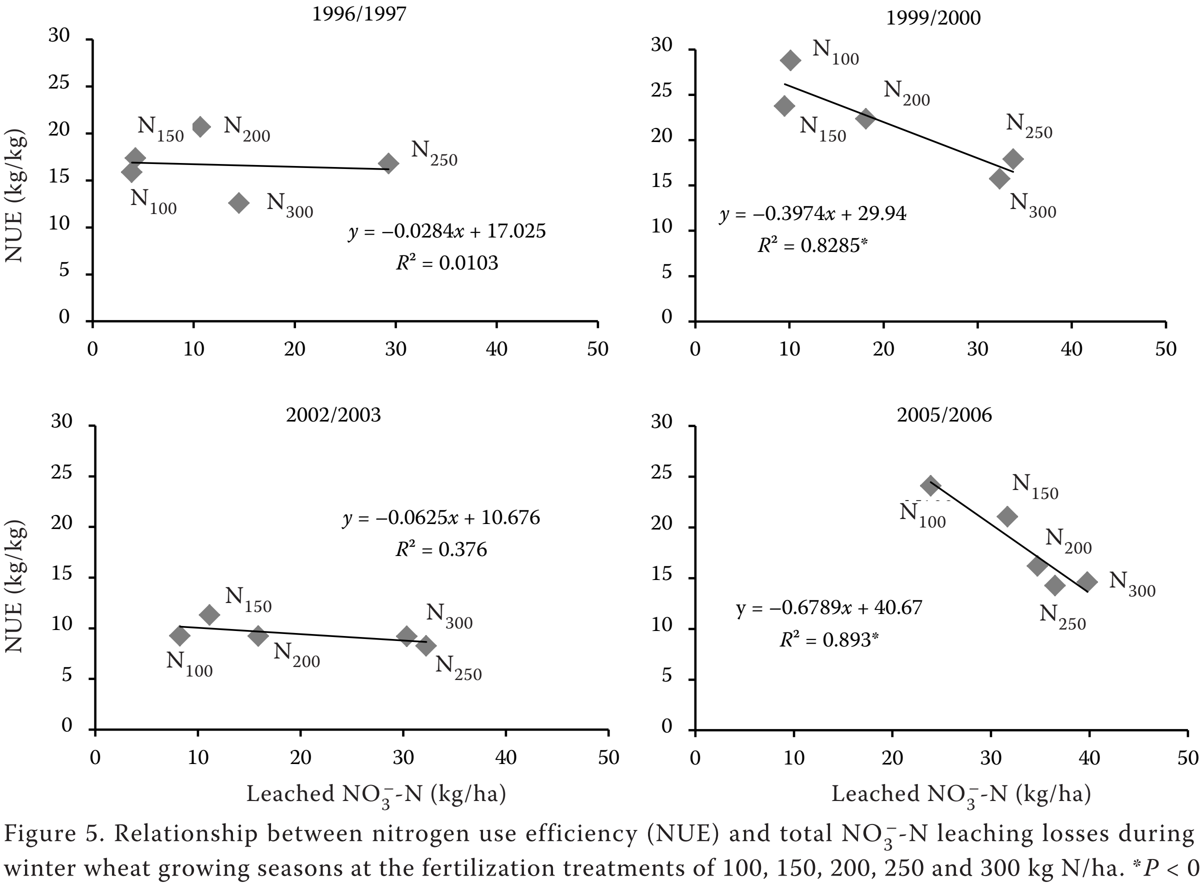

Figure 5. Relationship between nitrogen use efficiency (NUE) and total NO_3^--N leaching losses during four winter wheat growing seasons at the fertilization treatments of 100, 150, 200, 250 and 300 kg N/ha. $^*P < 0.05$

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