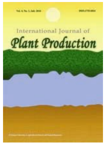

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Influence of mineral and organic fertilizers on yield and nitrogen efficiency of winter wheat

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Abstract

The aim of this study was to evaluate the long-term (16-years) nitrogen efficiency after the application of organic and mineral fertilizers at two sites Lukavec (S_1) and Suchdol (S_2) with different soil and climatic conditions in the Czech Republic (Central Europe) and to determine grain yield and nitrogen content with regard to the requirements of protein content for baking quality of wheat. After the application of NPK treatment the highest average values from both sites of grain yield (6.22 t ha^{-1}), nitrogen content (2.01%) and nitrogen uptake (123.6 kg ha^{-1}) were determined, which means 78%, 26% and 121% increases compared to the unfertilized treatment. At the less fertile S_1, located on Cambisol, the significant effect of nitrogen fertilization on yield was observed. The yield of the NPK treatment was by 144% higher compared to the unfertilized Control treatment. The limit of 11.5% of protein content for bakery wheat was not achieved for any of treatments at S_1, at S_2 for unfertilized treatment and treatments with organic fertilizers. Lower values of recovery efficiency of nitrogen and N input-output balance were found at S_2 situated on Chernozem.

Keywords: Nitrogen; Nitrogen balance; Wheat; Fertilization; Yield.

Introduction

Wheat is grown across a wide range of environments around the world (Blumenthal et al., 2001) and it is the most cultivated plant in the Czech Republic. In 2012 winter wheat was cultivated on 30.1% from the total sown area (Czech Statistical Office, 2012). Nitrogen is the key element in achieving consistently high yields in cereals (Delogu et al., 1998; Shi et al., 2012) and to improve the grain quality of wheat (Hussain et al., 1996; McKenzie et al., 2005; Pan et al., 2005). Increasing N supply generally improves kernel integrity and strength, resulting in better milling properties of the grain (Blumenthal et al., 2001). Crop response to applied N and use efficiency are important criteria for evaluating crop N requirements for maximum economic yield, because nitrogen is one of the most expensive nutrients to supply and commercial fertilizers represent the major cost in plant production. Worldwide, crops do not directly utilize about half of the applied N (Fageria et al., 2005; Dobermann, 2007; Maselaux-Daubresse et al., 2010). Values of NUE (nitrogen use efficiency) differed between world regions. Averages of cereal NUE between years 1999-2003 published Dobermann and Cassman (2005) differed from the lowest in East Asia (32 kg kg^{-1}) to middle in North America (45 kg kg^{-1}), Oceania (46 kg kg^{-1}) and Latin America (55 kg kg^{-1}) to the highest in East Europe, Central Asia (90 kg kg^{-1}) and Africa (123 kg kg^{-1}). Low recovery of N is not only responsible for higher cost of crop production, but also for environmental pollution (Fageria et al., 2005). Hence, nitrogen fertilization plays a central role in improving yield in wheat and high N use efficiency is desirable to protect ground and surface waters (Salvagiotti et al., 2009).

The objectives of this paper were to answer the following questions: (1) Which of the treatments supported the highest dry matter (DM) yield and nitrogen content in grain? (2) Which site achieved the greatest effect of nitrogen fertilization on yield? (3) Which of the treatments and sites comply with the requirements of the protein content for baking wheat? (4) Which location indicated the highest risk of nitrogen losses?

Material and Methods

Experimental site

The long-term field experiments were established in 1996 at two sites with different soil and climatic conditions (Table 1) in the Czech Republic: Lukavec (S_1) and Suchdol (S_2). A simple crop rotation contained: potatoes (*Solanum tuberosum* L.), winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.). Each year all of the crops were grown. Fertilization treatments were repeated in three blocks. The size of experimental plots was 60 m^2 at S_1 and 60.5 m^2 at S_2.

Table 1. Characteristic of experimental sites.

Site	Lukavec (S_1)	Suchdol (S_2)
Location	49° 33′ 23″ N, 14° 58′ 39″ E	50° 7′ 40″ N, 14° 22′ 33″ E
Altitude (m a.s.l.)	610	286
Average annual temperature (°C)	7.7	9.1
Average annual precipitation (mm)	666	495
pH	4.3	7.5
Soil type	Cambisol	Chernozem
Soil texture	sandy loam	silt loam

Field experiment

For the purpose of this research 6 fertilizing treatments were evaluated: 1. no fertilization (Control), 2. sewage sludge (SS), 3. farmyard manure (FYM), 4. N as mineral fertilizer (N), 5. NPK as mineral fertilizer (NPK) and 6. N as mineral fertilizer + spring barley straw (N+ST). Calcium ammonium nitrate was used for mineral nitrogen fertilization. The whole experiment was based on the same nitrogen rate of 330 kg N ha^{-1} to the crop rotation (of which 140 kg N ha^{-1} was applied to winter wheat) except the Control treatment, which was not fertilized. Organic fertilizers were applied in autumn only to potatoes in crop rotation. In the second year after the application of manure the availability of total applied N is assumed to be 11% (Eghball et al., 2002) and in case of anaerobically digested sludge 10% (Mininni et al., 1987). Nitrogen mineral fertilizers were applied before the vegetation to the potatoes and spring barley. For winter wheat the nitrogen rate was divided into two doses, the first rate (70 kg N ha^{-1}) was applied as regeneration fertilization and the second rate (70 kg N ha^{-1}) was applied as productive fertilization. Cereal straw was moved from experimental plots after harvest. Fertilization is shown in more details in Table 2. Between the years 1997-2000 the Samanta variety of winter wheat was grown and between 2001-2012 the Alana variety.

Table 2. Rates of nutrients N-P-K (kg ha^{-1}) during crop rotation cycle.

Treatment	Fertilization	Potatoes	Winter wheat	Spring barley
1	Control	-	-	-
2	SS[1]	330-207-44	-	-
3	FYM[1]	330-117-421	-	-
4	N[2]	120-0-0	140-0-0	70-0-0
5	NPK[2]	120-30-100	140-30-100	70-30-100
6	N[2]+ST[1,3]	138-6-47	140-0-0	70-0-0

[1] P and K in organic fertilizers - average dose taking into account nutrient content in organic fertilizers; [2]mineral fertilizers: N - calcium ammonium nitrate (27% N), P - triple super phosphate (21% P), K - potassium chloride (50% K); [3]5 t/ha spring barley straw.

Plant sampling and analysis

Plant samples were taken after the harvest of the mature plants (at maturity). Afterwards the samples were homogenized in a laboratory knife mill (Cutting mill, SM 100, Retch, Haan, Germany) equipped with normalised mesh with circle holes to sieve the particles <1 mm. Determination of total nitrogen was carried out by the Kjeldahl method (Kjeltec Auto 1030 Analyzer (Tecator, Hoganas, Sweden) (1997-2005) and Vapodest 50s (Gerhardt Gmbh & Co. KG, Germany) (2006-2012)). Statistical evaluation of the results was performed between treatments and between years with data over 16 years in the STATISTICA 12.0 program (StatSoft, Tulsa, USA) with the Main effects ANOVA followed by the Tukey´s test at the level of significance $P<0.05$. Results of the experiment were obtained from the years 1997-2012, which covered five crop rotations. To obtain the protein content in grain, the measured values of nitrogen were multiplied by a coefficient 5.7 (ČSN 46 1011-18). In the Czech Republic it is necessary to reach a minimum value of protein content in grain 11.5% to be classified as baking wheat. For the purpose of experiment ten characteristic features for winter wheat were observed: 1. DM yield of grain (t ha^{-1}), 2. nitrogen content in grain (%), 3. nitrogen uptake by grain (kg ha^{-1}), 4. nitrogen use efficiency (NUE, kg kg^{-1}) (Moll et al., 1982), 5. nitrogen utilization efficiency (NUtE, kg kg^{-1}), 6. recovery efficiency of applied N (RE_N, %) 7. agronomic efficiency of nitrogen (AE_N, kg kg^{-1}), 8. harvest index (HI, %) (Donald, 1962), 9. nitrogen harvest index (NHI, %) and 10. N input-output balance (ΔN, kg N ha^{-1}) (Liu et al., 2010).

$NUE = Y/F$
$NUtE = Y/U$
$RE_N = (U_x - U_0)/F$
$AE_N = (Y_x - Y_0)/F$
$HI = Y/Yt$
$NHI = U/Ut$
$\Delta N = F - U_t$

Y - grain yield (t ha^{-1})
Yt - yield of grain + straw (t ha^{-1})
U - uptake of nitrogen (kg ha^{-1})
Ut - total uptake (grain + straw) of nitrogen (kg ha^{-1})
F - amount of applied nitrogen (kg ha^{-1})
$_0$ - control treatment with no N fertilizing
$_x$ - treatments with N fertilizing

Results

At S_1 the lowest average yields of the Control treatment was only 2.59 t ha^{-1}, but the NPK treatment increased the average of the DM yield by 144% to 6.31 t ha^{-1}. The effect of treatment on DM yield was highly significant at S_1 (DF=5; F=36.870; P<0.05), differences in the post-hoc test are in Table 3. About 23% higher harvest index than Control was recorded for SS treatment (Table 4). Average values of nitrogen uptake were about 189% higher for NPK treatment than for Control. The highest nitrogen content was achieved in the grain of winter wheat at S_1 after the application of nitrogen in mineral form compared to the unfertilized treatment (NPK about 21% higher than Control). The lowest average nitrogen content was observed in the Control treatment. Values of protein content ranged between 8.93% and 10.82%, which means, that any of the treatments had sufficient protein content. At S_1 we determined a significantly higher N harvest index for mineral fertilized treatments compared to the Control. Average values of nitrogen harvest index for treatments with mineral fertilization were about 14% higher than for Control. Treatments with organic fertilizing achieved increases of about 8%. Significantly higher AE_N compare to other treatments was found for SS treatment at S_1 (Table 4), it was approximately about 65% higher than for treatments with fertilization in mineral form. The highest values of NUE occurred after the application of sewage sludge. The average values of NUE for treatments with mineral nitrogen were about 44 kg kg^{-1}.

At S_1 the highest average values of nitrogen utilization efficiency for SS treatment were observed (Table 5). In the NPK treatment average values of NUtE were about 17% lower than for the Control. The highest average RE_N was observed at S_1 for FYM (not significant).

Table 3. Average DM yield (t ha^{-1}), Nitrogen uptake (kg ha^{-1}) and Nitrogen content (%) of winter wheat grain at S_1 and S_2 site (average from years 1997-2012).

Treatment	DM yield (t ha^{-1})		Nitrogen uptake (kg ha^{-1})		Nitrogen content (%)	
	S_1	S_2	S_1	S_2	S_1	S_2
Control	2.59^{a}	4.42^{a}	40.7^{a}	71.2^{a}	1.56^{ac}	1.63^{a}
SS	4.94^{b}	5.38^{ab}	61.8^{b}	99.2^{b}	1.62^{abcd}	1.86^{ab}
FYM	3.87^{c}	4.80^{ab}	61.1^{b}	81.4^{ab}	1.59^{ace}	1.72^{a}
N	6.28^{de}	5.81^{ab}	113.2^{c}	120.8^{bc}	1.83^{abcd}	2.11^{b}
NPK	6.31^{de}	6.13^{b}	117.6^{c}	129.6^{c}	1.88^{bd}	2.14^{c}
N+ST	5.98^{bde}	5.80^{ab}	108.7^{c}	121.5^{bc}	1.84^{be}	2.12^{c}

Values in the column with the same letter were not significantly different at P<0.05.

Table 4. Harvest index (%), Nitrogen harvest index (%) and Agronomic efficiency of nitrogen (%) by winter wheat grain at S_1 and S_2 site (average from years 1997-2012).

Treatment	HI (%)		NHI (%)		AE_N (%)	
	S_1	S_2	S_1	S_2	S_1	S_2
Control	47.04^{a}	59.30^{a}	73.93^{a}	87.17^{a}	-	-
SS	57.87^{b}	56.81^{a}	79.54^{ab}	86.52^{a}	76.44^{a}	31.75^{a}
FYM	51.35^{ab}	56.84^{a}	80.82^{ab}	85.35^{a}	37.79^{b}	13.14^{b}
N	53.82^{ab}	56.44^{a}	83.94^{b}	85.42^{a}	27.96^{b}	10.58^{b}
NPK	55.77^{ab}	56.92^{a}	84.50^{b}	86.98^{a}	28.07^{b}	12.50^{b}
N+ST	56.31^{ab}	54.30^{a}	85.29^{b}	84.11^{a}	25.55^{b}	10.21^{b}

Values in the column with the same letter were not significantly different at P<0.05.

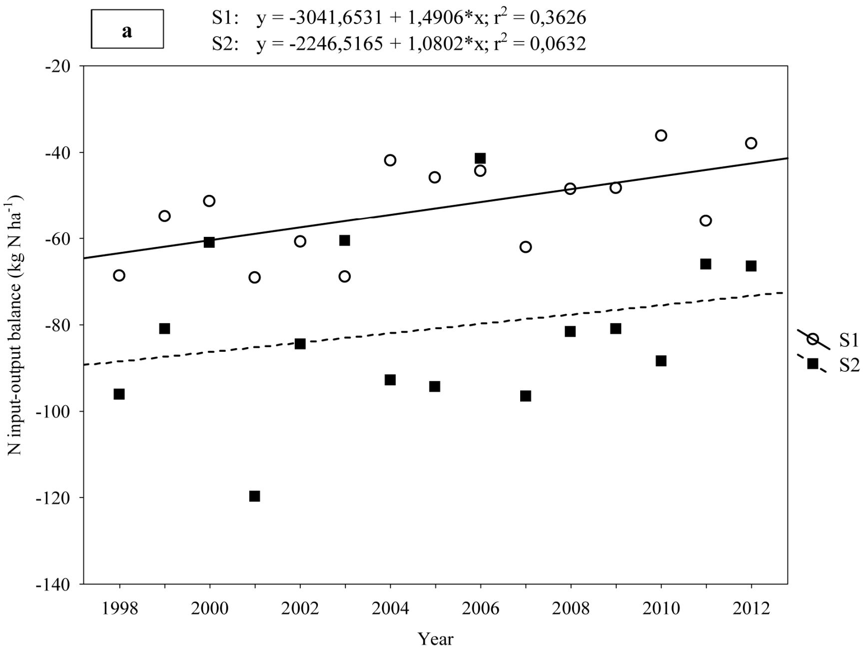
Table 5. Average Nitrogen use efficiency (kg kg^{-1}), Nitrogen utilization (kg kg^{-1}) and Recovery efficiency of nitrogen (%) of winter wheat grain at S_1 and S_2 site.

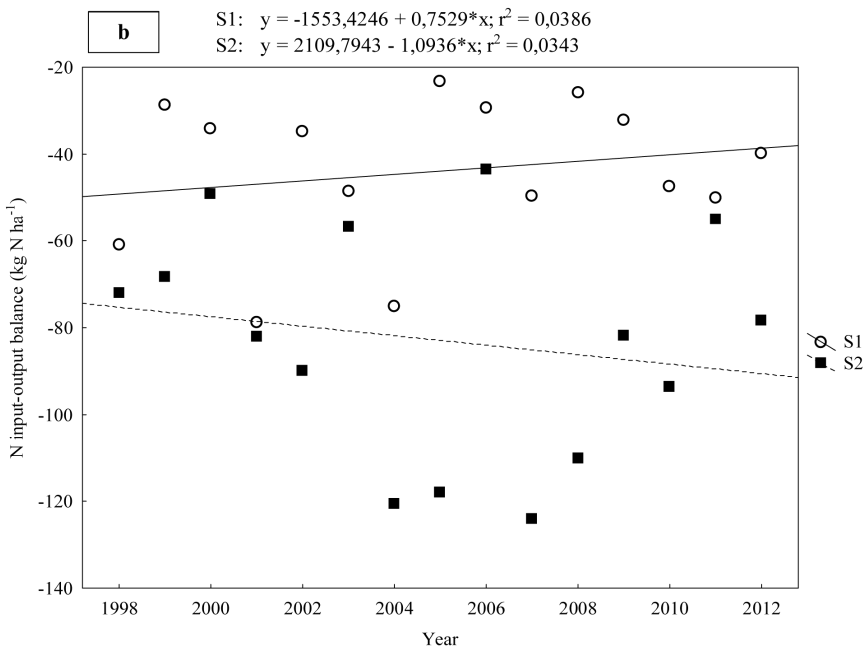
Treatment	NUE (kg kg^{-1})		NUtE (kg kg^{-1})		RE_N (%)	
	S_1	S_2	S_1	S_2	S_1	S_2
Control	-	-	64.90^{a}	62.84^{a}	-	-
SS	149.80^{a}	133.83^{a}	80.98^{b}	54.08^{b}	60.67^{a}	90.93^{a}
FYM	106.54^{b}	148.24^{a}	63.80^{ac}	59.18^{a}	66.54^{a}	32.82^{b}
N	44.87^{c}	34.29^{b}	55.67^{ac}	47.73^{c}	41.36^{a}	36.00^{b}
NPK	45.08^{c}	41.48^{b}	54.09^{c}	47.07^{c}	61.69^{a}	40.85^{b}
N+ST	42.69^{c}	43.80^{b}	55.34^{ac}	47.50^{c}	55.48^{a}	36.50^{b}

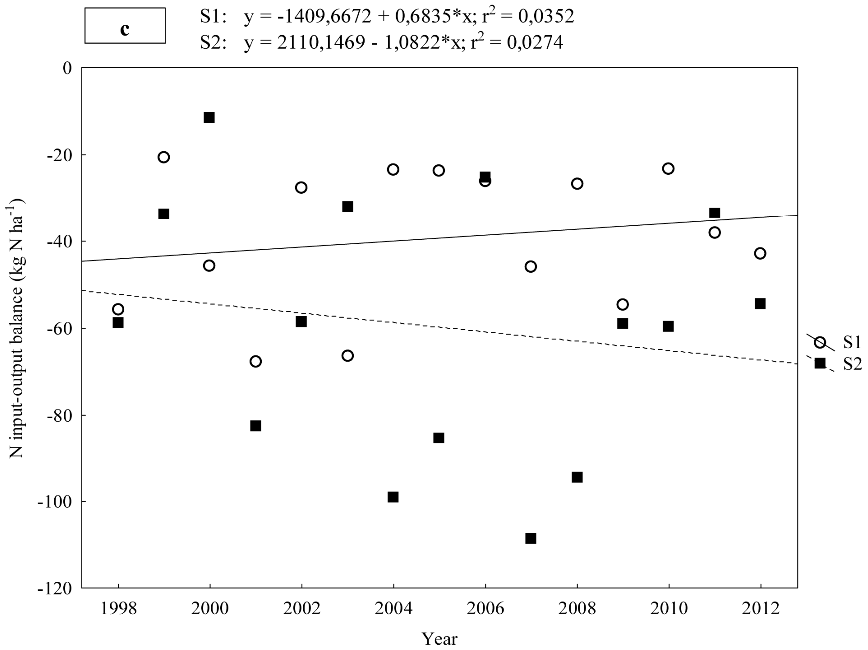
Values in the column with the same letter were not significantly different at P<0.05.

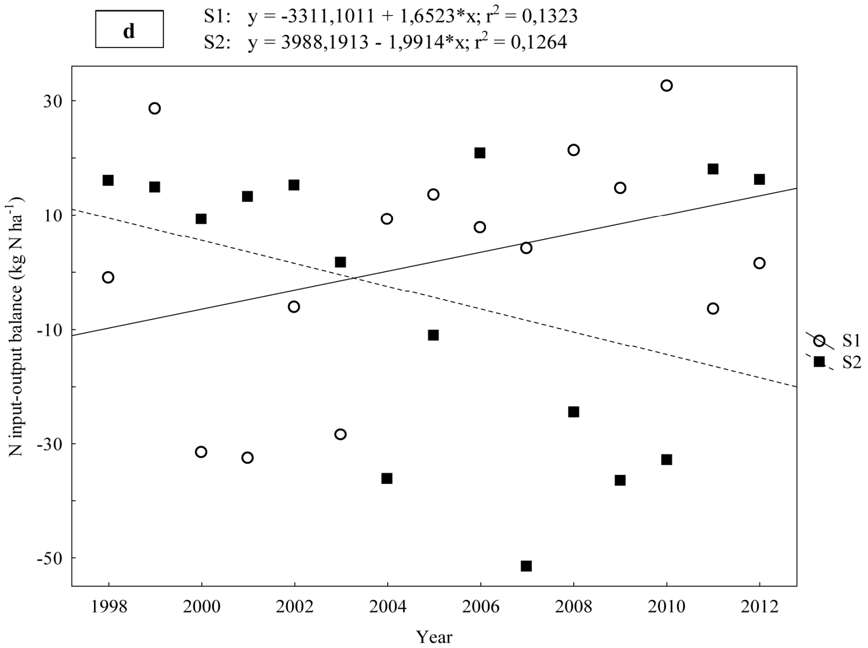
Positive average values from all experimental years were only found at S_1 for treatments with mineral nitrogen application and its combination with straw. At these two treatments (N and N+ST) were obtained the highest N input-output balances: N 1.82 kg N ha^{-1} (p=0.1827; r=0.3637); N+ST 9.32 kg N ha^{-1} (p=0.0666; r= -0.4855). All treatments showed a high variability between experimental years, but at S_1 rising tendency of ΔN for all treatments over time was observed, for the Control treatment at both sites (Figure 1). Average value of ΔN from all years was at S_1 for Control -52.97 (p=0.0175; r=0.6021); SS -43.89 (p=0.4831; r=0.1963); FYM -39.27 kg N ha^{-1} (p=0.5029; r=0.1877).

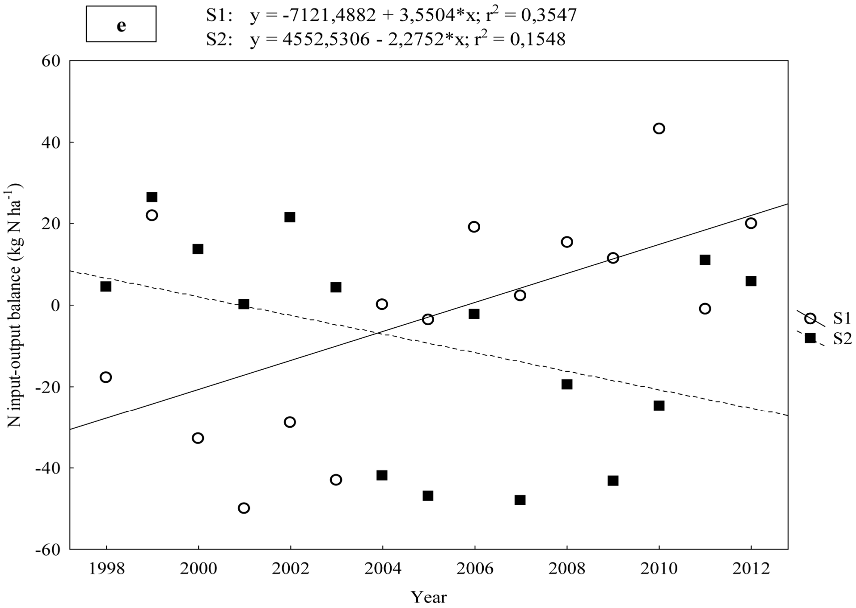
At S_2 the highest yield was achieved for NPK treatment (6.13 t ha^{-1}) (Table 3). Values of harvest index from all fertilized treatments were lower compared to the Control treatment (not significant). In the Control treatment significantly lower average nitrogen uptake of winter wheat grain was found as compared to treatments with mineral fertilizers. In the NPK treatment nitrogen uptake was about 82% higher than in the Control. At this location the highest content of N in grain (2.1%) was obtained in the treatments with mineral N fertilization. Sufficient protein content for baking wheat was achieved at S_2 only in treatments with mineral fertilizers (12%). Nitrogen harvest index was lower in mineral and organic fertilized treatments, than for unfertilized Control, but the differences were not significant. The lowest average values of AE_N were found after the application of N+ST at S_2 (11 kg kg^{-1}). Use of mineral fertilizers resulted in low NUE values. Values of treatments with mineral fertilizers decreased about 73% compared to the FYM treatment. At S_2 was the significantly highest RE_N at SS treatment, for the other treatments values were about 60% lower. The highest N input-output balances were obtained for N treatment with -4.49 kg N ha^{-1} (p=0.1934; r= -0.3555) and N+ST treatment with-4.65 kg N ha^{-1} (p=0.1594; r= -0.3825). Average value of ΔN from all years was at S_1 only -80.80 kg N ha^{-1} for Control (p=0.3660; r= 0.2514); -82.91 kg N ha^{-1} for SS (p=0.5088; r= -0.1852) and -59.75 kg N ha^{-1} for FYM (p=0.5558; r= -0.1654). The averages of ΔN were higher for all treatments at S_1 than at S_2.


a
S1: y = -3041,6531 + 1,4906*x; r2 = 0,3626
S2: y = -2246,5165 + 1,0802*x; r2 = 0,0632
N input-output balance (kg N ha-1)
Year
S1
S2


b
S1: y = -1553,4246 + 0,7529*x; r2 = 0,0386
S2: y = 2109,7943 - 1,0936*x; r2 = 0,0343
N input-output balance (kg N ha-1)
Year
S1
S2


c
S1: y = -1409,6672 + 0,6835*x; r2 = 0,0352
S2: y = 2110,1469 - 1,0822*x; r2 = 0,0274
N input-output balance (kg N ha-1)
0
-20
-40
-60
-80
-100
-120
1998
2000
2002
2004
2006
2008
2010
2012
Year
S1
S2


d
S1: y = -3311,1011 + 1,6523*x; r2 = 0,1323
S2: y = 3988,1913 - 1,9914*x; r2 = 0,1264
N input-output balance (kg N ha-1)
30
10
-10
-30
-50
1998
2000
2002
2004
2006
2008
2010
2012
Year
S1
S2



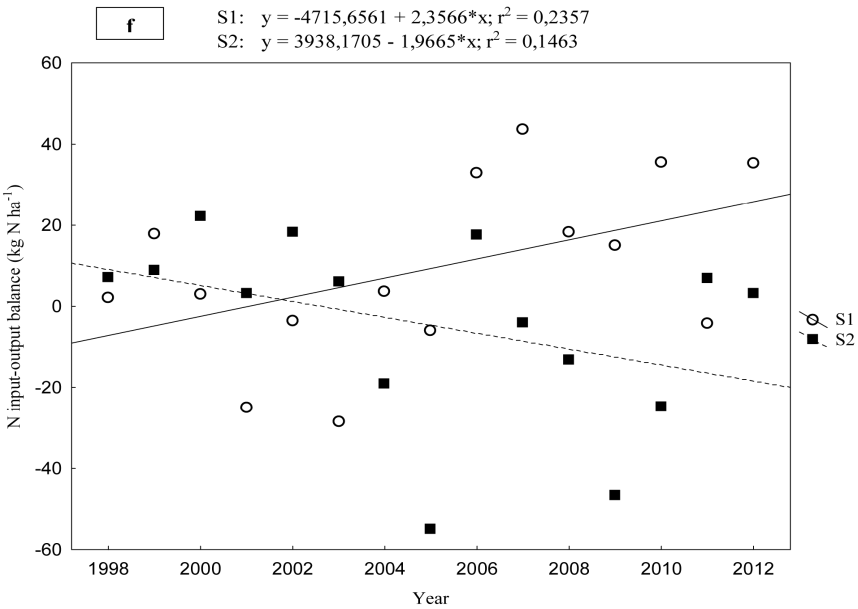


Figure 1. N input-output balances (ΔN, kg N ha^{-1}) in different experimental years at S_1 and S_2 at different treatments: a) Control (unfertilized), b) SS (sewage sludge), c) FYM (farm yard manure), d) N, e) NPK, f) N+ST.

Discussion

Many previous experiments documented that the use of nitrogen fertilization supported production of higher yields (Hussain et al., 1996; Delogu et al., 1998; Latiri-Souki et al., 1998; Balík et al., 2003; Modhej et al., 2008; Shah et al., 2009). The highest yields were observed in our experiment after using mineral nitrogen. The higher influence of fertilizer application on yield was achieved at S_1. Černý et al. (2010) presented results of winter wheat and spring barley, where the highest influence of nitrogen fertilizer application was observed on less fertile locations and relatively little direct influence of applied nitrogen fertilizer was on more fertile Hejcman et al. (2010) evaluated a long-term experiment with winter wheat at our S_1, where the lowest increases of yield were at unfertilized control treatment and after the application of lower doses of nitrogen (15 kg N ha^{-1}), which indicates the low naturally fertility of sandy loam Cambisol (predominant soil type in Central Europe) After the application of 140 kg N ha^{-1} an increase of nitrogen uptake of about 116 % compared to the Control treatment was found. Cossani et al. (2012) described, that at intermediate fertilized treatments (lower than 100 kg N ha^{-1}) N uptake was about 60% higher, as compared to the unfertilized treatment and for high fertilized treatments ($\geq$100 kg N ha^{-1}) N uptake was even about 80% higher compared to the unfertilized treatments. In our experiment the lowest N uptake we found in the Control treatment (40.7 kg N ha^{-1}) and the highest nitrogen uptake at NPK treatment (117.6 kg N ha^{-1}). Grain N concentration is one of the main quality parameters of winter wheat grain. At both experimental sites the lowest average N content we found in the Control treatment, which is in agreement with the results of Delogu et al. (1998). Kozlovský et al. (2009) achieved with the application of 150 kg N ha^{-1} to winter wheat similar values to our mineral fertilized treatments (about 2%). The limit for baking wheat as an average for all reporting years was not achieved for the Control treatment and after the application of organic fertilizers (FYM, SS) at S_2. The minimal value of the N content for baking wheat at S_1 was not achieved for any of the treatments, which is assumed to be caused by the low natural fertility of this location. From our results it is evident that the highest response to nitrogen fertilization was at the less fertile S_1, especially after use of nitrogen in mineral fertilizers.

The average values of AE_N at S_1 for treatments with mineral fertilizer application ranged about 27% and 11% at S_2, which is comparable with similar experiments with winter wheat (Delogu et al., 1998; Chuan et al., 2013; Duan et al., 2014). According to Dobermann and Cassman (2005) global NUE for cereal production is at the level of 37 kg kg^{-1}, which was mostly exceeded by our results. The only exception was treatment N at S_2, where the average was 34.3 kg kg^{-1}. At S_1 we found higher values of NUtE than at S_2, which could be due to insufficient precipitation at S_2. This assumption is supported by results of Hejcman et al. (2012). The average of NUtE from both sites for Control treatment was about 25% higher than for treatments with mineral nitrogen fertilizers. Similar decreases in NUtE as in our experiment were observed with the increasing N application in many experiments with nitrogen fertilizing of wheat (Hussain et al., 1996; Delogu et al., 1998; Limon-Ortega et al., 2000; López-Bellido et al., 2005; Dobermann, 2007; Cossani et al., 2012). According to Dobermann et al. (2004) RE_N depends on the congruence between plant N demand and the quantity of N released from applied N. After the application of 140 kg N ha^{-1} we obtained average values of RE_N for N treatment 46%, 55% NPK treatment and 53% N+ST, similar values observed Shi et al. (2012) in the experiment with the nitrogen application for winter wheat. At S_2 were low values for FYM (33%) and treatments with fertilization in mineral form (37%). According to Fageria et al. (2005) low recovery of N in annual crop is associated with its loss by volatilization, leaching, surface runoff and denitrification. The use of organic fertilizers or any application of nitrogen led at both sites to considerably negative balances of nitrogen compare to fertilization in mineral form. There was variability between the experimental years for ΔN. Lower N uptake by plants resulted in some years in higher values of ΔN after the use of N in mineral form (especially treatment N+ST). It can be caused by higher microbial immobilization after application of higher doses of nitrogen and straw (Bremer and Kuikman, 1997).

Conclusions

(1) In our study we proved, that the highest positive influence on DM yield and nitrogen content in grain was for NPK treatment. Average DM yield from both sites increased about 78% for NPK treatment compared to the unfertilized Control treatment.
(2) At less fertile S_1 location was observed the greatest effect of nitrogen fertilization on yield, especially for fertilizers in mineral form. The average yield for NPK treatment at this site was 6.31 t ha^{-1}, which means an increase of about 144% compared to the Control treatment.

(3) Three of our six experimental treatments comply with the proteincontent requirements for baking wheat. Only treatments with mineral nitrogen fertilizers exceeded the minimal limit of 11.5% at S_2. At S_1 the limit was not exceeded for any of the treatments.

(4) From lower values of RE_N for treatments with mineral nitrogen and farmyard manure and from lower values of ΔN for treatments with organic fertilizers and without fertilization at S_2, it can be concluded, that this location has greater risks of nitrogen losses compared to S_1. Higher efficiency of nitrogen from mineral fertilizers was found at the low productive S_1, situated on Cambisol, compare to the naturally more fertile S_2, situated on Chernozem. On fertile sites with less precipitation, it is necessary to select a dose of N fertilizers with regard to the higher rate of nitrogen losses to the environment.

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