The effect of mineral N fertiliser and sewage sludge on yield and nitrogen efficiency of silage maize

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ABSTRACT

A field experiment was conducted on a chernozem soil to estimate fertiliser N efficiency of silage maize (*Zea mays* L.) by the difference method as influenced by the type of N fertiliser (mineral-MF vs. sewage sludge-SS), and N rate. Eight N treatments were included (0, 60, 120, 180, and 240 kg N/ha prior to maize sowing, 60 kg N/ha at planting in MF; 120, and 240 kg N/ha in SS. The average dry mater (DM) yields were 11.2–14.8 t/ha. Average nitrogen uptakes were 88–185 kg N/ha, when the average N contents in DM were 0.8–1.25%. Nitrogen utilization efficiency (NUE) was a relatively stable value for treatments with MF. The best use of nitrogen from MF was reached by 60 and 120 kg/ha N doses. The average values of recovery efficiency of applied N (RE_N) were calculated as 41–57%. The use of SS increased the yield of silage maize by 19–25% compared to control, above all first and second year after their application. Mineral-fertilizer-N equivalents (MFE) for SS were calculated as 55 and 64%.

Keywords: long-term field experiment; maize yield; nitrogen; N agronomic efficiency; N recovery efficiency; N uptake; N utilization efficiency

Maize is one of the most important silage plants in the world because of its high yield, high energy forage produced with lower labour and machinery requirements than other forage crops. Maize production for whole crop silage has gained much popularity in Europe over the last decades. The area of maize has increased substantially and for silage around 13 million hectares are harvested in Europe. Silage maize is a key component of ruminant diets in intensive dairy farming due to its high yield and metabolic energy content (Givens and Rulquin 2004). Maize is also the most dominating crop for biogas production, but the acreage of silage maize greatly increased and there were significant negative effects on the (Möller et al. 2011). Silage maize is crop, which is very responsive to N fertilisation (Cox and Cherney 2001) and large amounts of N are generally applied to maize cultivations. Nitrogen fertilization of maize influences plant growth and yield by influencing leaf area index, leaf area duration and also nitrogen assimilation by plant (Bleken et al. 2009, Pavlík et al. 2010a,b). The positive effects of nitrogen supply from mineral fertilizer or organic fertilizers on the yield of dry matter (DM) from maize are well documented (Schröder et al. 1998). At low levels of N supply, yield responses were much higher for maize in monoculture than for maize in crop rotation, whereas at higher levels, differences disappeared and response curves levelled off, compared to the other crops (Berzsenyi et al. 2000, Nevens and Reheul 2001). Although maize has high N use efficiency field balances still show considerable N surpluses due to excessive input of organic and mineral fertilisers, which are applied alone or in combination (Schröder et al. 2005). Adjusting N application rates to crop needs can improve N use efficiency and reduce N loses. However, nitrogen application tailored to crop demand requires accurate knowledge of fertiliser N recovery, which is especially challenging with respect to short-term and residual N effects that have to be considered (Schröder et al. 2005, Šrek et al. 2010). But most agricultural companies in

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the Czech Republic limit fertilization to usage of mineral nitrogen fertilizers and the amount of nutrients uptake by main and secondary products is often higher than the input of nutrients to soil in fertilizers. Usage of organic fertilizers is also restricted. An alternative to the application of organic fertilizers and nutrients may be fertilization with stabilized sewage sludges from waste water treatment plants. Numerous publications describe advantages of sewage sludge application to agricultural soils, mainly for its influence on yield of fertilized crops (Ailincăi et al. 2007, Singh and Agrawal 2008, Černý et al. 2010).

The objective of this study is to evaluate effects of different dose of mineral nitrogen fertilizers and sewage sludge on yield of silage maize (*Zea mays* L.) and N uptake efficiency in long-term field experiment.

MATERIAL AND METHODS

Experimental site. The experiment was carried out on the experimental field of the Faculty of Agrobiology, Food and Natural Resources at the Czech University of Life Sciences Prague in Czech Republic. The climate is dry temperate, drought periods may occur, mainly in late spring and summer. The soil is chernozem, with its basic characteristics listed in Table 1.

Field experiment. The experiment was established in 1992. The silage maize is continuously cultivated since the beginning of the experiment. The treatments were compared in a split-plot design. The size of experimental plots was 46 m^2 (five rows with a length of 13 m). The trial comprised 8 treatments: no fertilization (control), four mineral N rates: 60; 120; 180; 240 kg N/ha prior to crop sowing; 60 kg N/ha at planting, two sewage sludge (SS) rates at 120, and 240 kg N/ha/year.

The maize was sown with 8 plants per m^2 at the end of April/start of May with 70 cm between the plant rows. Sewage sludge (SS) was applied every three years in autumn (October) and was immediately incorporated into soil by ploughing. Mineral nitrogen fertilizers (as calcium ammonium nitrate – CAN) were applied in spring prior to crop sowing except for treatment 3 with CAN application at planting at 7 leaves stage. At the mineral nitrogen treatments no other nutrients and liming were used since the beginning of the experiment. At the SS treatments, the dosage of other nutrients depended on the content of nutrients in sewage sludge (Table 2). The presented results were obtained during the last 12 years period of the experiment (four SS application periods every three years), i.e. from 1996/1997 to 2008.

Plant sampling. Fresh mass (FM) of maize was determined by cutting the plants of three rows in the centre of each plot at a stubble height of 10 cm. The average size of harvested plots was 27 m^2. Plant harvesting was done by hand (1997–2002) and with an experimental harvester (2003–2008).

Dry matter (DM) content was determined from 500 to 600 g chopped FM by drying in a forced-air oven to constant weight. The yield data sets were recalculated to DM yield per one hectare area.

Chemical analyses. 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. The N content of the aboveground biomass was estimated using the Kjeldahl procedure on the KjeltecAuto 1030 Analyzer (Tecator, Hoganas, Sweden) (1997–2005) and Vapodest (Gerhardt, Königswinter, Germany) (2006–2008).

Nitrogen efficiency of applied fertilizer. There is no common standard for the calculation of N efficiency at the field scale. Efficiency of fertilizer N and sewage sludge N were calculated according to the difference method (Cassman et al. 2002, Dobermann 2007, Nannen et al. 2011) considering the DM yield and N uptake by the maize:

(1) Nitrogen utilization efficiency (NUE, kg/kg) as the ratio between yield and total N uptake. NUE = Y/U (kg yield per kg N uptake);

(2) Agronomic efficiency of applied N (AE_N, kg/kg) as the ratio of (yield at N_x – yield at N_0)

Table 1. Experimental site characteristics and topsoil properties at the beginning of the experiment

Location	50°7'40''N, 14°22'33''E
Altitude (m a.s.l.)	286
Mean annual temperature (°C)	9.1
Mean annual precipitation (mm)	495
Soil type	Chernozem
Soil texture	loam
pH ($CaCl_2$)	7.5
CEC ($mmol_+$/kg)	230
P* (mg/kg)	91
K* (mg/kg)	230
Mg* (mg/kg)	240
Ca* (mg/kg)	9000

*Mehlich 3 extractable solution; 1:10 w/v

Table 2. Average characteristics of sewage sludge and their dry matter (DM) application rates

	Dose (t/ha/year)	DM content (%)	Nutrients content (% DM)				
			N	P	K	Ca	Mg
SS120	9.82	30.6	3.66	2.23	0.61	3.00	0.78
SS240	19.64						

SS – sewage sludge (nitrogen dose)

and applied N at N_x. $AE_N = (Y_{Nx} - Y_0)/N_x$ (kg yield increase per kg N applied);

(3) Recovery efficiency of applied N (RE_N, %) as the ratio of (uptake at N_x – uptake at N_0) and applied N at N_x. $RE_N = (U_{Nx} - U_0)/N_x \times 100$ (kg increase in N uptake per kg applied);

(4) Physiological efficiency of applied N (PE_N, kg/kg) as the ratio of (yield at N_x – yield at N_{N0}) and (uptake at N_x – uptake at N_0). $PE_N = (Y_{Nx} - Y_0)/(U_{Nx} - U_0)$ (kg yield increase per kg increase in N uptake from fertilizer).

Where: Y – crop yield (kg/ha); U – total plant N uptake in the aboveground biomass at maturity (kg/ha); N_x – amount of N applied at plot that received N (kg/ha); N_{0},$_0$ – control treatment with no N. The terminology of N efficiency parameters is in accordance with Dobermann (2007).

The N availability from sewage sludge was related to the availability of mineral-fertilizer N by calculating the apparent mineral-fertilizer-N equivalents (MFE, %) in accordance with Gutser et al. (2005): $MFE = (U_{SSx} - U_0)/(U_{Nx} - U_0) \times 100$, with U_{SSx} being the crop N uptake in the treatment with organic-fertilizer application and U_{Nx} N uptake in the treatment with mineral-N application, both corrected for the N uptake from a control treatment.

These methods are based on the assumption that the N supply by fertilizer and sewage sludge does not affect the mineralization of soil organic matter and the growth and N uptake by plant.

Statistical analysis. The results were assessed using the ANOVA statistical analysis. The differences in yields and nitrogen contents caused by the type of fertilization for the experimental period (1997–2008) were compared. To evaluate the obtained results, the STATICTICA (StatSoft, Tulsa, USA) programme was used.

RESULTS AND DISCUSSION

The average yields of the above-ground DM, nitrogen contents in DM, nitrogen uptakes and nitrogen balances are presented in Tables 3–4.

The yield of silage maize. The lowest yield was determined in the control treatment, the highest yield in the N240 one. The application of 60 kg N/ha increased the average yield by 9% compared with the control, in case of the application of the fertilizer during the maize growing season, by 14% when applied prior to the sowing. The amount of 120 kg N/ha, when compared with the control, increased the yield by 28%, 180 kg N/ha by 32% and 240 kg N/ha by 35% (Figure 1a). In some years, however, the amount of 240 kg N/ha did not increase the yield compared to the amount of 180 kg N/ha. Some authors mention higher differences in the yield of the dry matter of the silage maize between the fertilized and with N unfertilized treatments. Carpici et al. (2010) state higher yield of 51% by the amount of 200 kg N/ha, Nannen et al. (2011) of 101% by the amount of 150 kg N/ha compared with the control. The decisive effect can have the soil conditions, first of all potentiality of mineralization of the soil. In our experiment based on the chernozem, the control treatment of the continuous growing of maize remained unfertilized 16 years long; despite of this the average yield of the dry matter was 11.18 t/ha, and during the time of this experiment, no evidential drop of the yield was documented. The

Table 3. The effect of the N amount and of the N application forms on the DM yield, N content and the N uptake by the silage maize

Treatment	DM yield (t/ha)	N content (%)	N uptake (kg/ha)
Control	11.18	0.80	87.55
0 + 60	12.14	0.84	99.96
N60	12.57	0.93	116.91
N120	14.02	1.11	156.54
N180	14.21	1.22	177.29
N240	14.76	1.25	184.78
SS120	13.10	0.96	122.86
SS240	13.75	1.03	139.29

SS – sewage sludge (nitrogen dose)

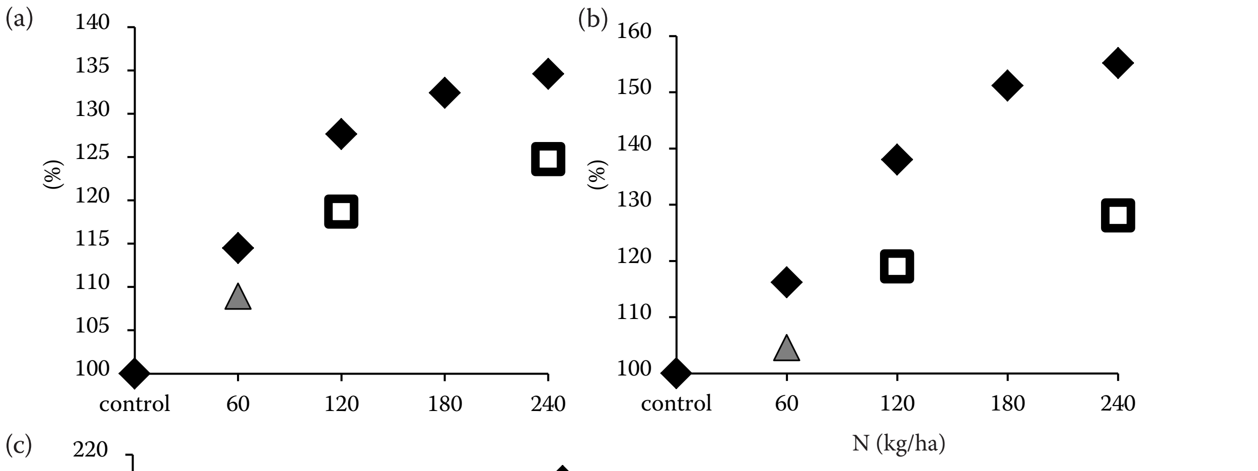
Table 4. The N balance on individual treatments during the experimental period

Treatment	N dose (kg/ha/year)	Total N dose[4] (kg/ha)	Total N uptake[4] (kg/ha)	N balance[4] (kg/ha)
Control	0	0	1051	–1051
0 + 60	60[1]	720	1200	–480
N60	60[2]	720	1403	–683
N120	120[2]	1440	1878	–438
N180	180[2]	2160	2128	32
N240	240[2]	2880	2217	663
SS120	120[3]	1440	1474	–34
SS240	240[3]	2880	1672	1208

[1]at planting; [2]before sowing; [3]in sewage sludge (SS; total nitrogen by the Kjeldahl method); [4]1997–2008

effect of soil type on crop yields is consistent with the results of other studies (Herrmann and Taube 2005, Hejcman and Kunzová 2010). The using of sewage sludge increased the yield of the silage maize by 19% in the SS120 and by 25% in the SS240 treatment. Sewage sludge had greater influence in the first and second year after their application. This findings confirm the results from other experiments with the sewage sludge (Ailincăi et al. 2007, Nedvěd et al. 2008, Černý et al. 2010).

The nitrogen content in the above-ground biomass. The nitrogen content in the dry matter of the silage maize was more influenced by fertilizing than the yield of the dry matter (Figure 1b). The lowest content of N 0.80% was estimated by the control treatment. During the whole evaluated period no fluctuating of the content of N was observed in the control treatment and the content of N varied between 0.76–0.84% of N, with the exception of the year 2006, when the content of N was estimated to 0.95%. The same results are describes in Balík et al. (1999), but with tendency to lower N content of plants at unfertilized treatment with duration of their experiment.



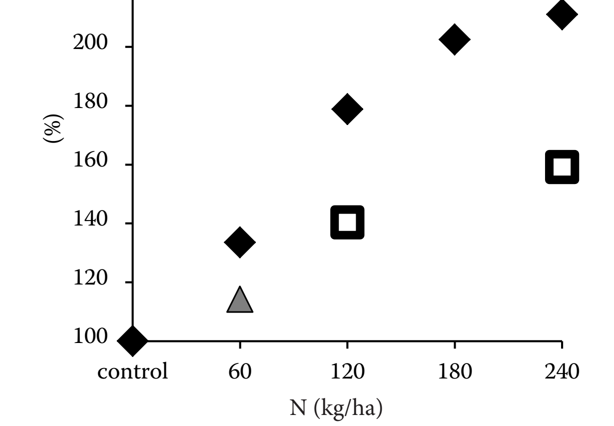


Figure 1. The relative effect of the N amount and of the N application forms (♦ before sowing; ▲ at planting, □ sewage sludge) on the DM yield (a), nitrogen content (b) and nitrogen uptake (c) by the silage maize related to the control (100%)

At the amount of 60 kg N/ha the average content of N in the dry matter of the silage maize was 0.93%, when the fertilizer was applied before the sowing. When applied during the growing season the content of N was only 0.84%. If plants have not enough of nitrogen in their first phase of growth the content of nitrogen shows lower values even in the later periods of growth till the plant maturity (Gastal and Lemaire 2001). By evaluating of the nitrogen in plants the literature gives the minimal amount of N needful for the maximal production to 1.05%. This minimal needful amount is stated to be the critical N concentration (CNC) (Plénet and Lemaire 1999, Herrmann and Taube 2005). Higher contents of N above the stated concentration CNC was estimated by amounts above 100 kg N/ha. In the N120 treatment the approximate content of N in the dry matter of the silage maize was estimated to 1.11%, in the N180 treatment to 1.22% and in the N240 treatment to 1.25%. From this result it is evident that the amount of 240 kg of N did not increase the content of nitrogen in the dry matter of silage maize more distinctly when compared with the N180 treatment. Comparable results were published by Ziadi et al. (2008), when stating that by amounts up to 100 kg N/ha the limiting nutrient was the N (CNC < 1.0), but by amounts above 200 kg N/ha the amount of nitrogen applied was too high. In treatments with the sewage sludge the average content of N 0.96% was estimated in the SS120 treatment and 1.03% in the SS240 treatment. In those treatments the influence of sewage sludge effect was evident, as the highest content of nitrogen in the dry matter of the silage maize was estimated always the first year after the application, and it decreased in the next years.

Nitrogen uptake. In view of the yield of the DM and the nitrogen content in plants the differences of nitrogen uptake among particular treatments were statistically significant. The average N uptake of the control treatment was 88 kg N/ha and varied between 62–111 kg N/ha, in particular with regard to the yield of the above-ground matter. The amount of nitrogen uptaken by the plants on the unfertilized treatment corresponds with the plant potential to use nitrogen from soil. Yan et al. (2006) estimated in the long-term not fertilized chernozem soil the uptake of N to 82 and 77 kg/ha described Campbell et al. (1992). But the mineralisation potential of soils of the chernozem type can be up to 300 kg N/ha in one year (Campbell et al. 1991).

In the treatment with application of 60 kg N at planting the uptake of N was estimated to 100 kg N, when the fertilizer was applied before sowing the uptake of N was 117 kg/ha. In spite of the fact that with the increasing amount of N its uptake was rising, in N180 and N240 treatments the uptake of nitrogen was estimated lower compared with the amount of N, which was at the beginning of the growing season applied in fertilizer. Similar values of N uptake were also estimated in other experiments with the silage maize (Wachendorf et al. 2006, Nannen et al. 2011). Total requirements of nitrogen fertilizer for the production of silage maize are approximately 150–200 kg N/ha. This recommendation is then adjusted based on previous crop and manure N credits. Cox et al. (1993) reported maximum economic yields at N rates of 140–160 kg N/ha. Nevens and Reheul (2001) quote higher uptake of N by the silage maize during their experiments, primarily in consideration of higher yields of dry matter in comparison with our findings. Especially in case of the long-term maize monoculture the uptake of nitrogen was lower, in comparison with the maize grown as rotation of crops, which was caused by lower yield, and also by the lower content of N in the dry matter (Berzsenyi et al. 2000, Nevens and Reheul 2001). In the sewage sludge treatments the N uptake was estimated to 123 kg N/ha (SS120) and 139 kg N/ha (SS240).

Nitrogen efficiency indices. Nitrogen utilization efficiency (NUE) describes the ability of plants to transform the nutrients from all available sources (soil, fertilizers) into the yield of the harvested product. Although this value depends on many factors as genotype, site conditions, management (Dobermann 2007), relatively stable values for the treatments of mineral fertilizers were found out during the whole period under consideration (Figure 2a). In spite of the fact that during the years of the continuation of the experiment the yield and/or content of nitrogen in the plant fluctuated, NUE indicates a stable utilization of N by the silage maize on the experimental station. Only in the sewage sludge treatments the three years cycle of application was apparent (Figure 2b). Higher values of NUE indicate the deficiency of the nutrient; low values suggest poor internal nutrient conversion (Dobermann 2007). From our results is evident that the experimental silage maize was not able to use better the amount of 240 kg N/ha, compared with the amount of 180 kg N/ha.

Agronomic efficiency of applied N (AE_N) amounts the yield of the dry matter per 1 kg N applied. The highest value of AE_N was calculated for the amount of 60 kg N before the sowing and 120 kg N,

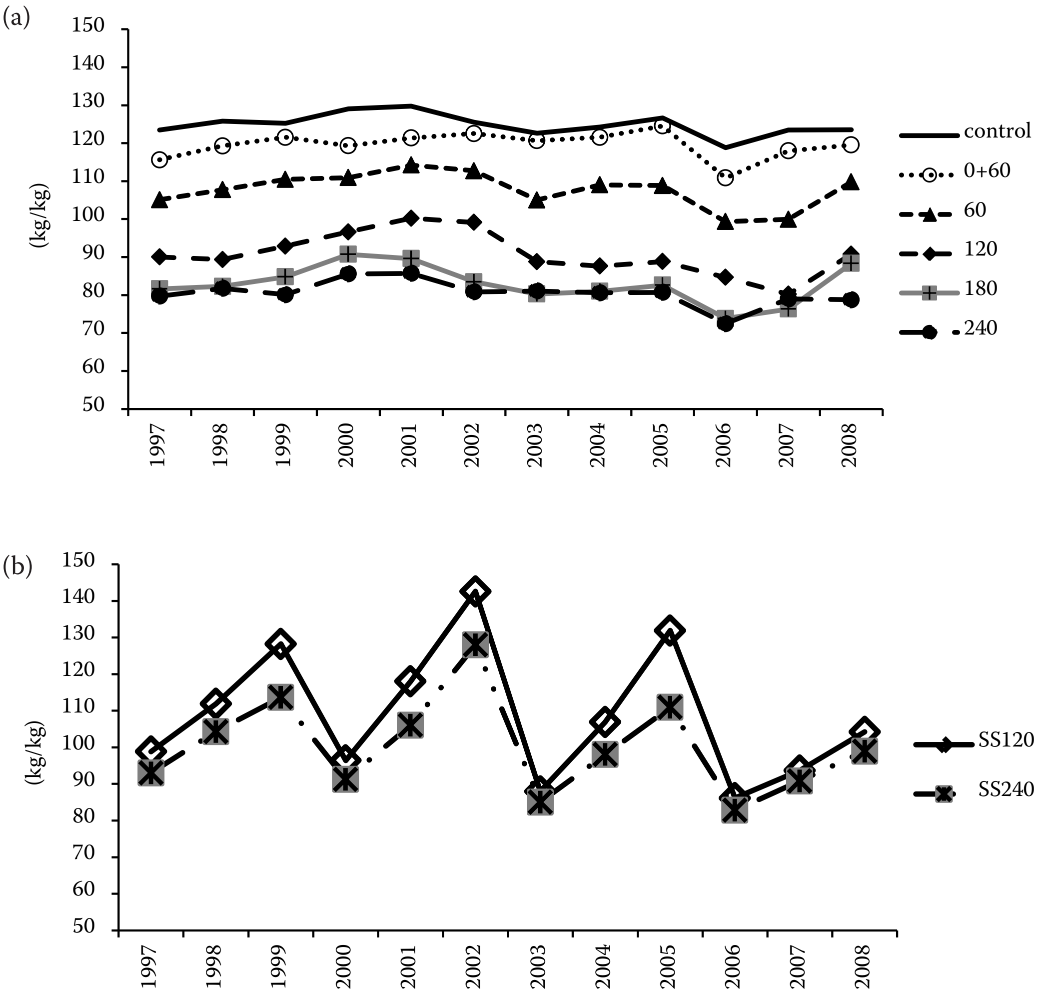
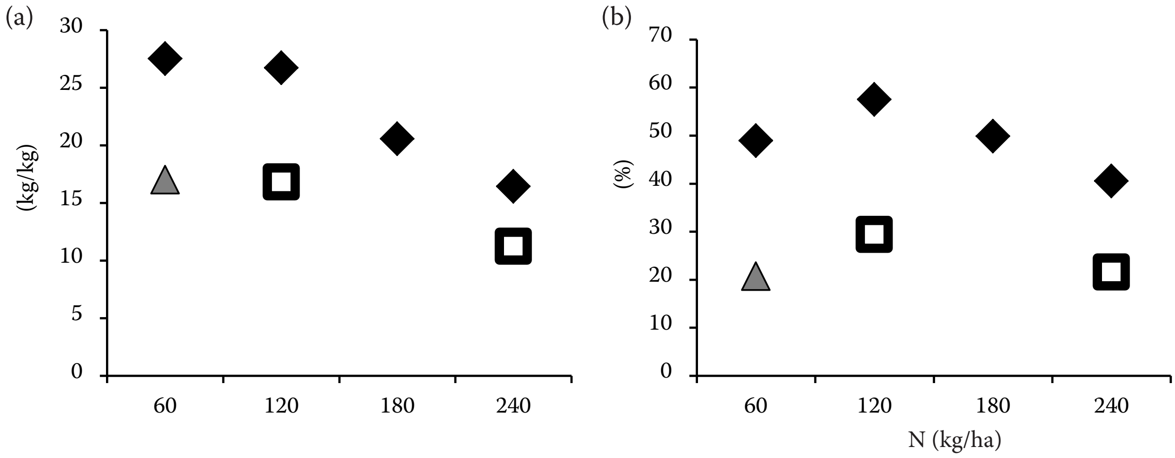


Figure 2. Nitrogen utilization efficiency (NUE) for particular amounts of N in the mineral fertilisers (a) and in the sewage sludge (b) during the continuation of the experiment

namely 27.5, or 26.7. For the amount of 180 kg N the increment of the yield was 20.6 kg of DM per 1 kg of N applied. The lowest amounts 17.0 and 16.4, were calculated for the application of 60 kg of N at the planting and the amount of 240 kg of N (Figure 3a). This results show that the best use of nitrogen from mineral fertilizers were reached by amounts of N ranging between 60 to 120 kg N/ha, however the calculated values varied year by year considerably. This confirms the conclusions of other research related to the more important influence of the year's crop development for use of N from applied fertilizers (Schröder et al. 1998, Wachendorf et al. 2006). But the NUE values imply that in the creation of the yield not only the nitrogen from applied fertilizers participates but also the nitrogen from the reserves in soil, namely on fertile lands (Vaněk et al. 1997).

Compared with the mineral fertiliser application, where the calculated values of AE_N in the SS120 treatment was 16.8 and in the SS240 treatment it was 11.3, for the sewage sludge lower values of AE_N were set. Those results correspond with the lower effectiveness of nitrogen from organic fertilizers on the yield of crop-plants compared with the N from mineral fertilizers. When evaluating the efficiency of N from the sewage sludge, there was calculated the value of mineral-fertilizer-N equivalents (MFE), which in the SS120 treatment was 55% and in the SS240 it was 64%. Similar results of MFE for the sewage sludge were stated by Gutser et al. (2005).

Recovery efficiency of applied N (RE_N) depends on the congruence between plant demand and nutrient release from fertilizers. In treatments fertilized by the mineral nitrogen fertilizer the lowest value of RE_N was calculated in 0 + 60, namely 21%. Those findings correspond with other studies, which document a lower use of N applied during the growing season instead before the sowing (Seo et al. 2006). In other fertilized treatments, with regard to year variability, the results were not



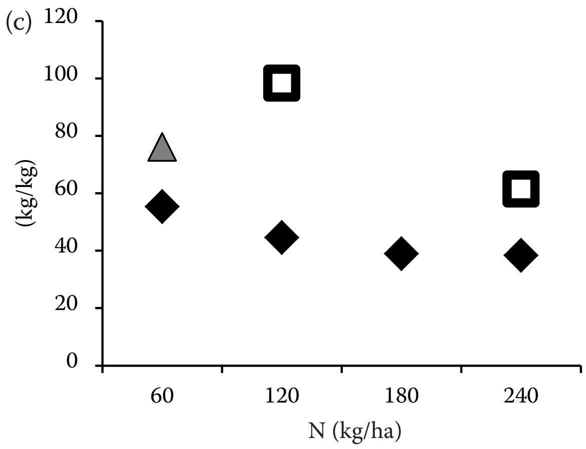


Figure 3. The effect of the N amount and of the N application forms (♦ before sowing; ▲ at planting; □ sewage sludge) on the silage maize N efficiency indices: AE_N (a), RE_N (b) and PE_N (c)

significant. The calculated value of RE_N during particular years ranged between 20% to 77%. The highest values of RE_N were calculated in the N120 treatment and they were decreasing with higher amount of N applied, which corresponds with the lower use of the applied N. The average values of RE_N in those treatments were calculated from 41 to 57% (Figure 3b). The calculated values correspond with the results of Nannen et al. (2011), who stated the range from 51 to 61%.

The values of physiological efficiency of applied N (PE_N) correspond with the mentioned results. The highest value of PE_N 76 was found out for the amount of 60 kg N/ha applied at planting. When applying the fertilizer before the sowing the value was estimated to 55 and the PE_N value decreased with an increasing amount of N. No difference was estimated between N180 and N240 treatments, where the value of PE_N was 39 and 38, respectively (Figure 3c). Compared with the mineral fertilisers, the higher value of PE was calculated in treatments with sewage sludge. It was 98 in the SS120 treatments and in the SS240 treatment the calculated value was 61. Those results correspond with the published results in maize (Nevens and Reheul 2001, Dobermann 2007, Carpici et al. 2010) but also in other crops (Delogu et al. 1998).

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