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Nitrogen efficiency of strip-till combined with slurry band injection below the maize seeds

Nadine Tauchnitz[a,*], Joachim Bischoff[a], Matthias Schrödter[a], Stefan Ebert[a], Ralph Meissner[b]

[a] *State Institute for Agriculture and Horticulture Saxony-Anhalt, Centre for Agronomy and Crop Production, Strenzfelder Allee 22, 06406 Bernburg, Germany*
[b] *Helmholtz Centre for Environmental Research-UFZ, Dept. of Soil System Science, Lysimeter Station, Falkenberg 55, D-39615 Altmärkische Wische, Germany*

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ABSTRACT

The slurry strip-till technique (STR) allows the combination of reduced tillage (strip tillage) with placed injection of slurry below the plant seed position. This technique should improve nitrogen (N) use efficiency of organic fertilizers. The present study aimed at evaluating the N use efficiency of the strip-till technique compared to conventional broadcast slurry application (CONV) to maize (*Zea mays* L.). Field trials with five treatments (unfertilized control, slurry strip-till with and without nitrification inhibitor (NI), conventional surface broadcast slurry incorporation with and without NI) were conducted on loamy sandy soils in northern and central Germany for three study years (2014–2016). Soil samples were taken from three soil layers (0–30 cm, 30–60 cm, 60–90 cm) in rows and interrows and analysed for soil mineral N (SMN) contents to ascertain N displacement out of the top soil. Furthermore, maize dry matter (DM) yields and N uptakes were determined to calculate N recovery efficiency (NRE) of the studied application systems.

SMN analyses showed an increased proportion (+60%) of ammonium nitrogen (NH_4-N) in SMN by addition of NI until 34–40 days after fertilization. Nevertheless, DM yields and N uptakes of STR treatments were not significantly different from CONV treated plots. The largest differences between treatments were observed at the earlier harvest dates compared to main harvest presumably due to the observed high NH_4-N concentrations in the slurry band, which are known to positively affect early growth of maize plants and better preservation of soil moisture in the STR system. The addition of NI did not lead to significantly increased DM yields and N uptakes. This was most probably due to negligible nitrate leaching in the early growth stages, i.e. NH_4-N stabilization took place but could not display its full potential. The STR treatments (STR and STR + NI) showed the highest N recovery efficiencies (up to 78%) among all treatments indicating the lowest potential N losses of this application system. Significant differences between STR and CONV treatments were found, however, only in 2014 and partially in 2015. Thus it can be assumed that the STR system is beneficial to enhance N efficiency of slurry application but further research is required to prove this.

1. Introduction

Today, one of the main challenges in agriculture is to mitigate nitrogen (N) losses related to fertilization and thus prevent harmful environmental effects due to nitrate leaching and greenhouse gas emissions. In the last decades several fertilization technologies have been developed to enhance N use efficiency. One of these is the slurry strip-till system which combines reduced tillage in the form of strip-tillage with placed injection of slurry below the plant seed position (Herrmann et al., 2012). Strip-tillage is a tillage system for row crops which originally became widespread in the USA for cotton, corn, peanuts, soya beans and others (Mitchell et al., 2009). In the strip-tillage method only the prospective seed row is loosened whereas the interrow space remains un-tilled and covered by crop residues (Röseler et al., 2010). Recently developed techniques with auto-guidance systems allow injection of liquid organic fertilizers (slurry) below the subsequent seed row simultaneously with the tillage operation. Usually organic fertilizers are applied to the surface before being incorporated into the soil within four hours using a disc harrow or field cultivator as required by the current EU Nitrates Directive (91/676/EEC) and German Fertiliser Ordinance (FO, 2017). In contrast to broadcast surface application, injection of liquid manure is an effective method to mitigate ammonia (NH_3) emissions (Sommer and Hutchings, 2001; Hansen et al., 2003). However, it was shown recently that deep placement of organic fertilizers might enhance nitrous oxide (N_2O) emissions due to improved denitrification conditions (Chadwick et al., 1999; Leick, 2003).

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[*] Corresponding author.
E-mail address: nadine.tauchnitz@llg.mule.sachsen-anhalt.de (N. Tauchnitz).

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Nitrification inhibitors (NI) can contribute to reduce these N_2O emissions (e.g. Ruser and Schulz, 2015). Furthermore, NI are able to reduce nitrate (NO_3-N) leaching and increase the N use efficiency (Ruser and Schulz, 2015). The yield response of maize to NI added to fertilizers injected in spring strongly depends on the soil and site properties (e.g. temperature, pH, organic matter) (Schmitt et al., 1995).

Several studies reported an improvement of early growth and development of maize (*Zea mays* L.) and high N use efficiency following slurry injection (Schmitt et al., 1995; Petersen et al., 2010; Schröder et al., 2015). Field trials in northwestern Germany have shown that liquid manure injection with added NI led to increased N uptake and equal early growth and yields compared to broadcast application combined with starter mineral fertilization (N and phosphorus) (Federolf et al., 2016). Stabilization of slurry N in the ammonium form (49–69%) by adding NI could be ascertained up to 61 days after fertilization (Olfs et al., 2015) decreasing the risk of NO_3-N leaching.

Studies determining NO_3-N leaching in slurry strip-till systems are scarce up to now (Al-Kaisi and Licht, 2004). In studying dynamics of soil mineral N, Westerschulte et al. (2017) found significantly smaller N displacement out of the top soil after slurry injection compared to broadcast application. It was suggested that the reduced soil disturbance of the strip-till system might result in a decrease of soil organic N mineralization and thus contribute to smaller NO_3-N contents of soil. However, previous studies which compared different soil tillage systems reported contradictory results. On the one hand lower mineral N contents in soil and NO_3-N leaching were found in no-till and reduced soil tillage systems (e.g. Addiscott, 2000; Halvorson et al., 2001). However, no effect of tillage on NO_3-N leaching was reported elsewhere (e.g. Shipitalo et al., 2000). Indeed, some studies showed higher NO_3-N leaching with no-till compared to plough treatment due to the presence of macropores (e.g. earthworm tunnels) (Weed and Kanwar, 1996).

The main objective of this study was to evaluate whether slurry strip-till might contribute to an enhanced N use efficiency. Field trials in maize crops in Germany were conducted for three study years comparing surface broadcast slurry application versus injection (slurry strip-till) with and without NI to:

i quantify yields, N uptakes and N balances
ii evaluate stability of ammonium (NH_4-N) depots
iii determine NO_3-N displacement into deeper soil layers and
iv calculate N recovery efficiency to evaluate potential N losses.

Gaseous N losses through N_2O and NH_3 emissions associated with slurry strip-till and broadcast application were recently reported for one of the study sites (Pietzner et al., 2017).

2. Material and methods

2.1. Field sites

Field trials were conducted at two sites in Saxony-Anhalt (northern and central Germany), 2014 in Lückstedt, 2015 and 2016 in Quellendorf (Table 1). Soil class of the study sites was loamy sand. Climate is continentally influenced with a long-term precipitation level of 564 mm (Lückstedt) and 532 mm (Quellendorf) and a long-term mean temperature of 9.2 °C (Lückstedt) and 9.7 °C (Quellendorf), respectively (long-term mean from 1981 to 2010).

Yearly precipitation during the study period amounted to 636 mm (2014), 493 mm (2015) and 391 mm (2016) and average temperature was 10.7 °C (2014), 10.3 °C (2015) and 11.4 °C (2016). Usable field capacities (UFC) of the soils were in the range of 26% (2016)–88% (2014) during the vegetation period (Fig. 1).

2.2. Experimental design and treatments

The trials were conducted using a randomized complete block design with four replicates and five treatments: (1) control treatment without any fertilization (CONTROL), (2) slurry strip-till without NI (STR), (3) slurry strip-till with NI (STR + NI), (4) conventional broadcast surface slurry incorporation without NI (CONV) and (5) conventional broadcast surface slurry incorporation with NI (CONV + NI). Blocks were arranged adjacent to each other. Each plot had a size of 12 m × 50 m. Before field trials started, crop rotation was sugar beets – maize – winter wheat. Soil tillage for these crops was plough based. A frost-sensitive non-leguminous catch crop mixture of phacelia (*Phacelia tanacetifolia* Benth.), sunflower (*Helianthus annuus* L.), flax (*Linum usitatissimum* L.) and buckwheat (*Fagopyrum esculentum Moench*) was sown and frozen off completely over the winter before treatments started. NI with the active ingredients 1H-1,2,4-Triazol and 3-Methylpyrazol (PIADIN®, SKW Piesteritz, Wittenberg, Germany) was applied in Lückstedt and 3,4-Dimetyl-Pyrazol Phosphate (VIZURA®, BASF, Ludwigshafen, Germany) in Quellendorf at a rate of 3 l ha^{-1}. In the STR treatments slurry was injected as a slurry band placed about 15 cm below the soil surface using an X-Till S machine (Vogelsang, Essen/Oldenburg, Germany) equipped with eight injection shares placed 75 cm apart. Soil was loosened by ploughshares which are placed in front of the injector at a depth of about 25 cm. Maize (*Zea mays* L., cv. ES Bombastic) was planted on 17 April 2014, on 30 April 2015 and on 18 April 2016 directly above the slurry band with a planting density of eight plants per m^2 and a row spacing of 75 cm in all treatments. In the conventional broadcast and control treatments shallow (6–8 cm deep) non-turning soil tillage was performed using a compact disc harrow. Slurry was applied simultaneously with soil tillage and incorporated close to the soil surface (depth of 6–8 cm) with the same compact disc harrow (AMAZONE Catros pro package system, Hasbergen, Germany) which had a special equipment to connect with a liquid manure barrel (21 m^3, Holmer, Zunhammer, Traunreut, Germany) for slurry application. On 12 March 2014 an amount of 30 m^3 ha^{-1} cattle slurry (2.7% total N-N_t, Table 2) and on 9 May 2014 additional 70 kg N ha^{-1} of mineral fertilizer (calcium ammonium nitrate) were applied to the fertilized treatments (CONV and STR) in Lückstedt. Organic fertilizer application in Quellendorf was conducted on 18 April 2015 with 19 m^3 ha^{-1} digestate (6.0% N_t) and on 9 April 2016 with 17 m^3 ha^{-1} digestate (7.4% N_t). Mineral N was not applied in 2015 and 2016. Total nitrogen fertilization rates were 151 kg N ha^{-1} (2014), 112 kg N ha^{-1} (2015) and 126 kg N ha^{-1} (2016).

Table 1
Location and soil properties of the field trial sites.

Site	Lückstedt	Quellendorf
Latitude	52°50'N	51°75'N
Longitude	11°35'E	12°13'E
Soil Class	sandy loam	sandy loam
Soil type[a]	Stagnig Gleysol Luvisols	Gleysol
pH ($CaCl_2$)	6.5	5.7
C_{org} (%)	0.9	1.1
N_t (%)	0.08	0.1
CEC ($cmol_c\ kg^{-1}$)	7.6	
P CAL (mg 100 g^{-1})	2.3	3.8
K CAL (mg 100 g^{-1})	4.0	14.9
Mg $CaCl_2$ (mg 100 g^{-1})	6.0	6.0

[a] IUSS Working Group WRB (2014), CEC: cation exchange capacity.

2.3. Field measurements, sampling and calculations

Soil samples were taken at depths of 0–30 cm, 30–60 cm and 60–90 cm before fertilization and at different times until harvest of maize plants and then analysed for their soil mineral N (SMN) (NO_3-N + NH_4-N) contents (VDLUFA, 2012). In the STR treatments soil was sampled both in the maize row and in the interrow. In the CONV and CONTROL treatments soil was sampled from the whole plot area. Therefore, 10 soil samples were taken per plot and depth and pooled to

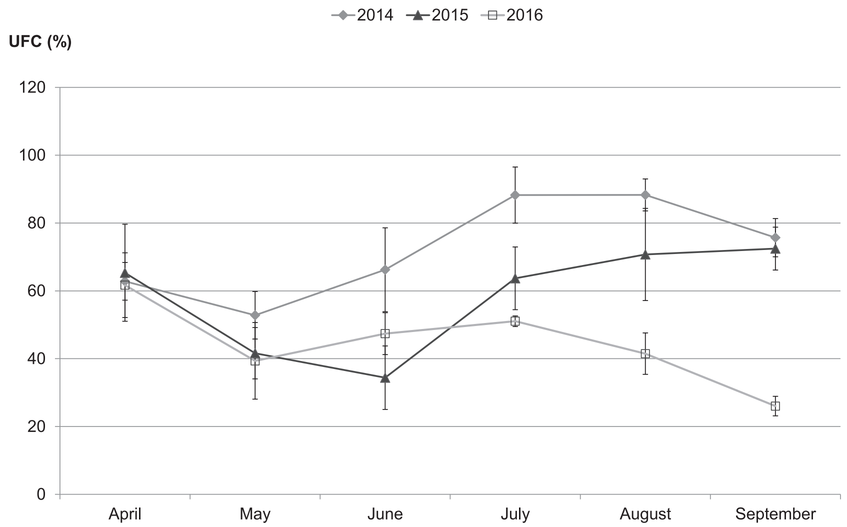


Fig. 1. Usable field capacities (UFC) for the three field trial years (data of the German Weather Services.

Table 2
Organic fertilizer properties.

Study year	Manure type	DM (%)	N (g kg^{-1})	NH_4-N (g kg^{-1})	P (g kg^{-1})
2014	Cattle Slurry	5.3	2.7	1.4	0.6
2015	Digestate	5.7	6.0	2.8	0.5
2016	Digestate	6.8	7.4	4.4	1.0

one mixed sample. In the STR treatments 10 samples were taken from the maize row and 10 samples from the interrow, and pooled to two samples. Aboveground biomass was collected at three different times (mid – July, August and September) in a row length of 2.67 m corresponding to an area of 2 m^2. Fresh weight was measured and a representative sample was taken to determine dry matter content and total N contents (DIN-EN-ISO-16634-1, 2008) to calculate N uptake of plants. N balance was calculated by the subtraction of applied fertilizer-N from plant N uptake for each treatment. Nitrogen recovery efficiency (NRE) was calculated to evaluate potential N losses of the different systems as described by Ciampitti and Vyn (2011) and Federolf et al. (2016) after Eq. (1):

$$\text{NRE} = \text{Nuptake}_{\text{fert.}} - \text{Nuptake}_{\text{unfert.}}/\text{N applied} \quad (1)$$

with Nuptake$_{\text{fert.}}$ as the N uptake of fertilized treatments and Nuptake$_{\text{unfert.}}$ as the N uptake of CONTROL treatment divided by N applied as the amount of applied N by fertilization.

2.4. Statistical analyses

Statistical analyses were performed using SPSS (version 22). Collected data were tested for normal distribution using the Shapiro-Wilk test. Differences in SMN contents, DM yields, N uptakes and NRE between all treatments in a study year were tested by univariate analysis of variance (ANOVA) with the Tukey Honest Significant Differences (Tukey HSD, $p < 0.05$) post hoc test. Furthermore, differences between study years per treatment were tested with the Tukey test to identify possible impacts of weather conditions in the three different trial years.

3. Results

3.1. Soil mineral N contents

Before fertilization SMN contents (0–90 cm) were 26 (± 9) kg N ha^{-1} (2014), 70 (± 16) kg N ha^{-1} (2015) and 30 (± 1) kg N ha^{-1} (2016) (data not shown). After slurry application, SMN contents (0–90 cm) in the fertilized rows of the STR treatments ranged between 35 and 428 kg N ha^{-1} with highest content in 2016 40 days after fertilization (Fig. 2, Table 3). At maize harvest in September SMN contents of fertilized rows were not different from those of the interrows during all three study years.

SMN contents in the top soil layer (0–30 cm) ranged from 11 to 365 kg ha^{-1} (Table 3) with significantly higher values in the STR treated plots compared to the CONV treatments shortly after slurry application (maximal 38 days after fertilization in 2015 in the STR + NI treatment). At later stages differences between treatments were not significant except in 2016. In the deeper soil layers SMN contents were in a range of 4–163 kg ha^{-1} (30–60 cm) and 5–30 kg ha^{-1} (60–90 cm) with highest values in 2016. Vertical distribution of SMN revealed significant highest share in the topsoil of the STR + NI treatment reaching 75% on average for the 2014 season. In contrast no significant differences between treatments were found in 2015 and 2016 (Table 4).

In the STR + NI treated plots NO_3-N comprised a low proportion (32% and 31% in 2014 and 2015, respectively) of the soil SMN pool 34 and 38 days after fertilization (Fig. 3). Afterwards, the proportion of NO_3-N increased markedly to about 90%. In 2016 more than half of SMN was present as NO_3-N 32 days after fertilization. Thus, the NH_4-N contents were increased by a maximum of 55% in 2014 (34 days after fertilization), 60% in 2015 (38 days after fertilization) and 43% in 2016 (32 days after fertilization) by the addition of NI in the STR treated plots. In 2016 NH_4-N contents were increased by 12% even 59 days after fertilization. By contrast, in the CONV + NI treatments 92% (2014) and 87% (2015, 2016) of SMN was present as NO_3-N 32–38 days after fertilization (Fig. 3).

3.2. Dry matter, N uptake and N balance

Aboveground dry matter (DM) yields of maize differed markedly between the three study years. Significantly lower yields occurred in the 2016 season while the highest maize yields were observed in 2014 (Table 5). Maize DM yield at the main harvest in September ranged between 6 Mg ha^{-1} (2016) and 21 Mg ha^{-1} (2014). Mean maize yields for all three years (2014–2016) were highest in the STR treatment with 15 Mg ha^{-1}. Nevertheless, average yield of the STR treatment only differed significantly from the CONTROL treatment (10 Mg ha^{-1}, Table 5). In 2014 maize DM yield of the STR treatment was also higher than the CONV + NI treatment. The addition of NI did not increase DM yield significantly neither in the STR nor in the CONV treatment. Significant differences of maize yields between the slurry injection

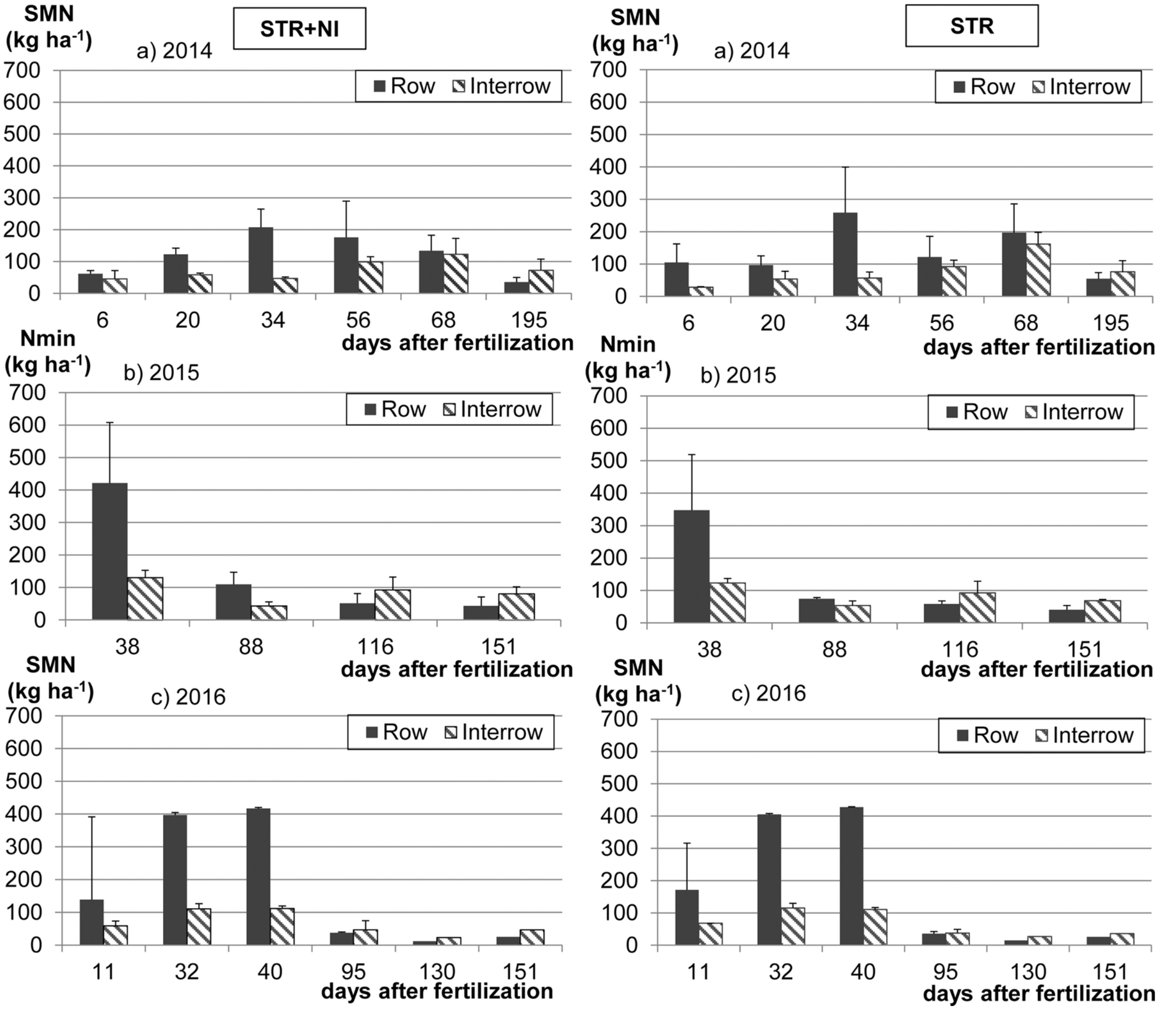


Fig. 2. Soil mineral nitrogen (SMN) content in 0–90 cm depth in rows and interrows of strip-till (STR) treatments with and without nitrification inhibitor (NI) in the three trial seasons (means ± standard deviation, n = 4).

treatment without NI (STR) and the slurry broadcast surface application (CONV, CONV + NI) occured only at the first sampling (July) in 2014 (Table 5). Significantly higher maize yields of STR and STR + NI treatments compared to the CONTROL were harvested in September 2016.

Mean N uptakes of all three years ranged between 112 kg ha^{-1} (CONTROL) and 180 kg ha^{-1} (STR, Table 5). N uptakes of maize in both STR treated plots (STR, STR + NI) were significantly higher compared to the CONTROL treatment. Similar to DM yields, N uptakes differed considerably between the three study years. The highest N uptakes of up to 233 kg ha^{-1} (STR) were obtained for 2014 (Table 5). Significant differences in N uptakes only occurred in 2014 between STR and CONV + NI treatments. As for DM yields, the addition of NI did not lead to increased N uptake for both the STR and the CONV treatment.

While in 2014 and 2015 N balances were negative for all treatments, positive N balances resulted for the fertilized treatments in 2016, ranging from +38 kg ha^{-1} (STR) to +56 kg ha^{-1} (CONV + NI) (Fig. 4). The STR treatment showed the lowest N balances of all fertilized treatments. Nevertheless, differences were only significant between STR and CONV + NI treated plots in 2014. Calculated NRE were in a range of 5–78% throughout the whole study period (Fig. 4), with highest NRE in 2015 and lowest for 2016. In all three years STR treatments showed higher NRE compared to the other fertilized treatments, but differences were only significant between STR and STR + NI as well as CONV and CONV + NI treatments (2014) and between STR and STR + NI as compared to CONV + NI treatment (2015).

4. Discussion

4.1. Stability of ammonium depots and N displacement in soil

SMN analyses showed that the addition of NI resulted in higher NH_4-N contents in the STR treatments up to 59 days after fertilization. Westerschulte et al. (2017) found 46% more NH_4-N in the injection + NI treatment compared to slurry injection without NI even 61 days after slurry application. Long lasting effects of NI applied at slurry injection were also reported elsewhere (e.g. Olfs et al., 2015). In contrast to STR the addition of NI did not significantly enhance NH_4-N contents in the CONV treatments. The reason for the weaker effect of NI at slurry broadcast application might be the higher contact surface for microorganisms (Laurenz, 2014).

A higher proportion of SMN in the top soil of the STR + NI treated plots compared to CONV treatments was only observed during the 2014 season. In other studies distinctly smaller N displacement for the slurry injection compared to broadcast application was reported (Chen et al., 2010; Westerschulte et al., 2017). Thus, SMN is more plant available compared to broadcast application of slurry (Federolf et al., 2017). Accordingly, only a small SMN displacement into the middle and bottom soil layer (30–90 cm) due to addition of NI took place (e.g. Yu et al., 2007). Westerschulte et al. (2017) also noted that dislocation of slurry N into the 30–90 cm soil layer was reduced in the injection + NI treatment but differences to broadcast application were not significant.

Distinct differences in SMN dynamics and contents were observed

Table 3
Soil mineral nitrogen (SMN) contents in different soil layers (means). Means with the same letter are not significantly different between treatments in each layer per sampling date (within one column per depth) (Tukey $p < 0.05$, n = 4).

SMN (kg ha−1)	Depth (cm)	2014										2015								2016							
		6	d.a.f.	20	d.a.f.	34	d.a.f.	56	d.a.f.	195	d.a.f.	38	d.a.f.	88	d.a.f.	116	d.a.f.	151	d.a.f.	11	d.a.f.	32	d.a.f.	40	d.a.f.	95	d.a.f.
CONTROL	0–30	20	a	32	a	40	a	53	a	28	a	81	a	38	a	15	a	26	a	27	a	54	a	46	a	11	a
CONV	0–30	24	a	50	a	63	ab	67	a	28	a	93	a	35	a	34	a	31	a	52	ab	126	ab	135	a	23	b
CONV + NI	0–30	20	a	35	a	47	a	79	a	27	a	112	a	64	a	25	a	34	a	63	ab	126	ab	129	a	18	ab
STR[1]	0–30	94	b	81	b	210	b	98	a	16	a	289	ab	46	a	36	a	19	a	133	c	212	ab	263	a	11	a
STR + NI[1]	0–30	46	ab	103	b	186	ab	157	a	15	a	365	b	76	a	29	a	26	a	97	bc	264	b	260	a	14	ab
CONTROL	30–60	6	a	10	a	12	a	16	a	20	a	33	a	19	a	10	a	15	a	18	a	38	a	31	a	4	a
CONV	30–60	4	a	9	a	9	a	10	a	23	a	30	a	14	a	13	a	18	a	21	a	43	a	47	a	13	b
CONV + NI	30–60	6	a	8	a	8	a	12	a	21	a	38	a	18	a	11	a	17	a	17	a	48	a	45	a	7	ab
STR[1]	30–60	6	a	9	a	19	a	15	a	19	a	42	a	17	a	12	a	11	a	22	a	163	a	141	a	7	ab
STR + NI[1]	30–60	10	a	12	a	15	a	11	a	11	a	40	a	22	a	12	a	9	a	23	a	103	a	131	a	10	ab
CONTROL	60–90	7	a	18	a	12	a	20	a	17	a	15	a	11	a	7	a	8	a	19	a	25	a	17	a	10	a
CONV	60–90	8	a	11	a	6	a	7	a	21	a	16	a	11	a	8	a	12	a	16	a	28	a	22	a	14	a
CONV + NI	60–90	10	a	9	a	8	a	7	a	15	a	18	a	11	a	8	a	10	a	13	a	22	a	19	a	10	a
STR[1]	60–90	5	a	7	a	30	a	9	a	19	a	16	a	12	a	11	a	10	a	16	a	30	a	23	a	19	a
STR + NI[1]	60–90	6	a	7	a	7	a	8	a	9	a	16	a	12	a	10	a	8	a	19	a	30	a	26	a	14	a

CONTROL: without fertilization, CONV: conventional treatment, NI: nitrification inhibitor, STR: strip-till treatment, d. a. f.: days after fertilization.

[1] SMN contents in fertilized rows.

between the three years. This could be explained by varying weather conditions and different biomass production. In 2014 and 2015 no precipitation events > 10 mm d^{-1} occurred in the first growth stages of maize suggesting that dislocation of slurry N could be largely excluded. On the contrary, in 2016 a heavy rain event of 35 mm d^{-1} at the end of May might have led to N displacement out of the top soil layer. This coincides with higher SMN contents in the bottom layer (60–90 cm) in 2016 (19% averaged for all treatments) compared to 2014 and 2015 (11%, respectively). It was suspected that SMN was less available for maize roots in this soil zone and thus the risk of N leaching below the rooting zone increased (e.g. Sticksel et al., 1999). Furthermore, no differences in SMN contents of subsoil between STR and CONV treatments occurred in 2016. SMN contents (0–90 cm depth) of CONV treatments are comparable to those reported by Westerschulte et al. (2017) while STR treatments showed higher values at early growth stages. In accordance with Westerschulte et al. (2017) we found significantly smaller SMN content (0–30 cm) in the CONV compared to the STR treatment shortly after slurry application. This was not surprising because a locally higher N concentrated slurry band was applied in the STR treatment. Furthermore, higher N losses by NH_3 volatilization (e.g. Webb et al., 2013) and N immobilization in soil (e.g. Cameron et al., 2013) after broadcast slurry application compared to slurry injection were discussed. Whereas SMN contents below the maize row in the STR treatments were higher than those of the interrows up to 88 days after fertilization, at harvest SMN contents were higher in the interrow space. This matches to findings of Westerschulte et al. (2017), and it might be due to more efficient plant N uptake in the STR system and slight lateral displacement of N into the interrow space (Westerschulte et al., 2017).

4.2. Dry matter yields and N uptakes

Highest DM yields and N uptakes in 2014 were associated with favorable weather conditions in that year. Furthermore soil properties in Lückstedt with more appropriate pH for maize plants, higher N fertilization rate and the application of mineral N (which is 100% plant available) might have contributed to higher growth rates in 2014. Limited water availability for maize plants throughout the vegetation period of 2016 probably resulted in the significantly lowest DM yields and N uptakes. Determined DM yields of STR and CONV treatments contradict the findings of other studies which reported higher yields with injection of liquid manure compared to broadcast application (e.g. Schröder et al., 2015; Federolf et al., 2017). Significant higher DM yields and N uptakes were only observed in 2014 in STR treated plots compared to CONV treatment (CONV + NI). Accordingly, Thiel et al. (2016) found a difference in N uptake of +17 kg ha^{-1} between shallow incorporation of slurry and strip-till which was also not significant. Higher differences between N uptake of the different treatments early in the growing season are in accordance with another study at seven sites in northwestern Germany (Federolf et al., 2016). They reported major differences between treatments in June while much of these differences faded out at the harvest. It is known that interaction of phosphate and NH_4-N applied in a band below the maize seeds might positively affect early growth of maize plants due to enhanced lateral root and fine root proliferation (Ohlrogge, 1962; Ma et al., 2013). Therefore, nutrient use efficiencies were enhanced (e.g. Sawyer et al., 1991; Petersen et al., 2010; Schröder et al., 2015). In addition the presence of plant material on the soil surface in the strip-till system better preserves soil moisture (e.g. Lascano et al., 1994) which might have resulted in better growth conditions in the dry spring months (2014–2016) compared to conventional soil tillage.

In contrast to previous studies (Laurenz, 2014; Federolf et al., 2016; Thiel et al., 2016) the addition of NI did not lead to increased DM yields and N uptakes neither in the STR nor in the CONV treatment. It has been stated that yield response of maize to NI added to slurry injected in spring depends on several soil and site specific parameters as well as management practices and thus might be very inconsistent (e.g.

Table 4
Proportion of soil mineral nitrogen (SMN) in topsoil (0–30 cm) and subsoil (30–90 cm) (means over the whole vegetation period) for the three trial years. Means with the same letter are not significantly different between treatments (within one column) (Tukey $p < 0.05$, $n = 4$).

SMN (%)	2014			2015			2016		
	topsoil 0–30 cm	subsoil 30–90 cm		topsoil 0–30 cm	subsoil 30–90 cm		topsoil 0–30 cm	subsoil 30–90 cm	
CONTROL	60	40	a	54	46	a	45	55	a
CONV	68	32	ab	56	44	a	59	41	b
CONV + NI	68	32	ab	61	39	a	62	38	b
STR[1]	75	25	bc	61	39	a	56	44	b
STR + NI[1]	75	25	c	65	35	a	58	42	b

CONTROL: without fertilization, CONV: conventional treatment, NI: nitrification inhibitor, STR: strip-till treatment.

[1] SMN in fertilized rows.

McCormick et al., 1984; Schmitt et al., 1995; Sawyer et al., 1991). Federolf et al. (2017) also found no significant increase of yields and N uptake at harvest by addition of NI. However, NI positively affected early growth of plants by improved P availability. It was shown recently that the application of an NH_4-N-based fertilizer with added NI lowered rhizosphere pH and increased P uptake of plants (Ma et al., 2013; Federolf et al., 2017). This might be the reason for larger differences of DM yields and N uptakes between STR and CONV treatments at the earlier sampling dates. Furthermore, it can be assumed that the placement of concentrated NH_4-N bands in the STR technique might delay turnover of the applied NH_4-N due to reduced soil-fertilizer interaction (Dosch and Gutser, 1995). However, the concentration of NH_4-N in the injected slurry band was higher when a NI was added (Westerschulte et al., 2017). For our study we assume that no relevant leaching occurred in the early growth stages of maize because of low precipitation. Consequentially, this will mask any beneficial effect of NI as also shown

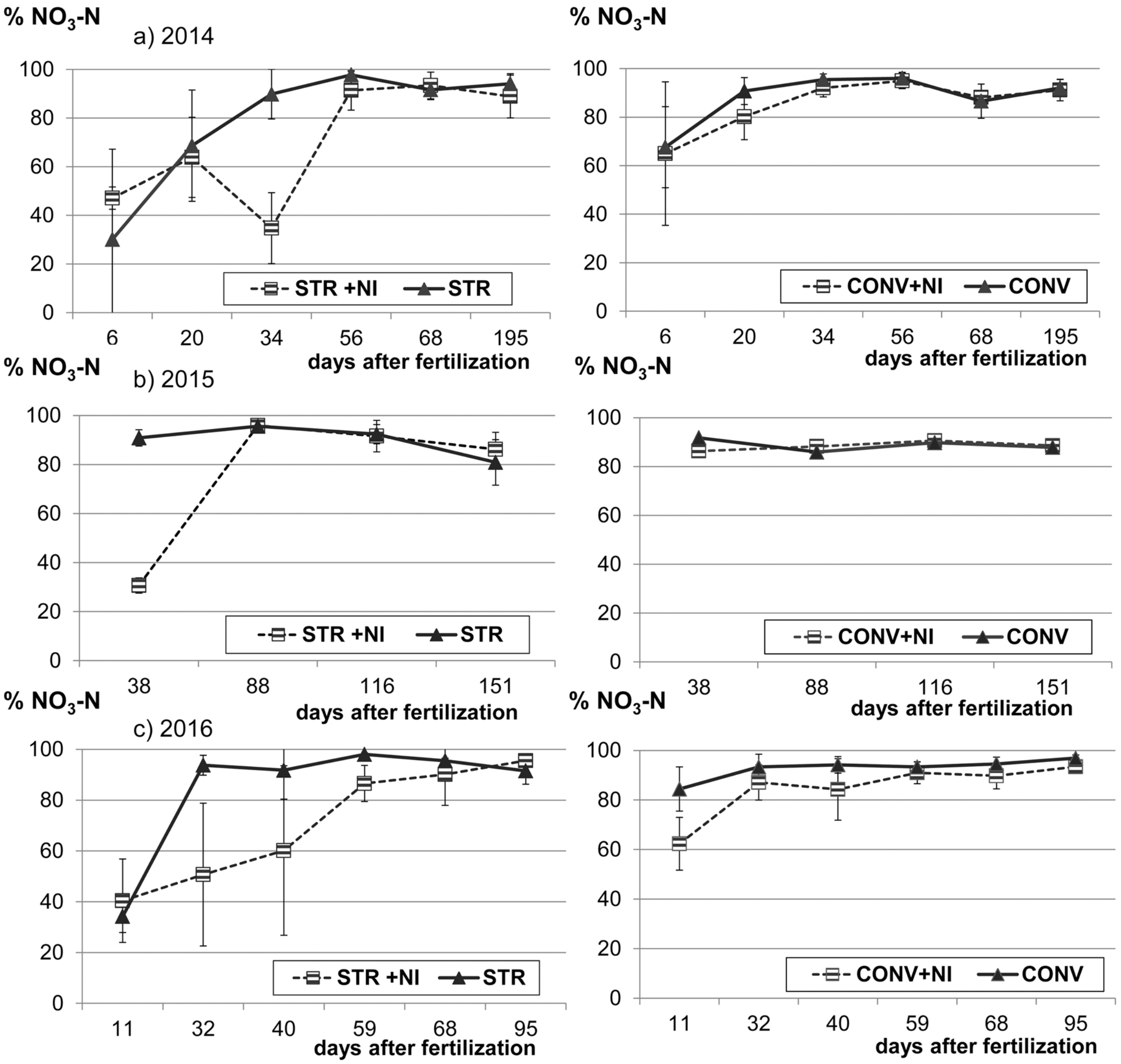


Fig. 3. Proportion of nitrate (NO_3-N) in soil mineral nitrogen (SMN) in the strip-till (STR) and conventional (CONV) treatments with and without nitrification inhibitor (NI) in the three trial seasons (means ± standard deviation, $n = 4$).

Table 5
Aboveground dry matter and N uptake of maize plants (means). Means with the same letter are not significantly different between treatments per sampling date (within one row) and between years per treatment (within one column) (Tukey $p < 0.05$, $n = 4$).

	Treatments				
	CONTROL	CONV	CONV + NI	STR	STR + NI
Dry matter (Mg ha^{-1})					
July 2014	3.9 ^{a}	4.8 ^{ac}	4.7 ^{ac}	7.6 ^{b}	7.2 ^{bc}
Aug. 2014	10.8 ^{a}	10.8 ^{a}	12.2 ^{ab}	15.3 ^{b}	14.9 ^{ab}
Sept. 2014	14.6 ^{a}	16.9 ^{ab}	15.1 ^{a}	20.7 ^{b}	17.3 ^{ab}
July 2015	3.9 ^{a}	3.2 ^{a}	3.6 ^{a}	5.1 ^{a}	5.0 ^{a}
Aug. 2015	6.9 ^{a}	7.6 ^{ac}	9.4 ^{ab}	10.4 ^{b}	10.1 ^{bc}
Sept. 2015	9.2 ^{a}	10.9 ^{ab}	11.6 ^{ab}	14.3 ^{b}	12.9 ^{ab}
July 2016	2.1 ^{ac}	3.4 ^{b}	3.1 ^{bc}	3.5 ^{b}	3.5 ^{b}
Aug. 2016	5.9 ^{a}	6.3 ^{a}	6.1 ^{a}	7.0 ^{a}	7.4 ^{a}
Sept. 2016	6.0 ^{a}	6.9 ^{ab}	7.1 ^{ab}	8.1 ^{b}	8.1 ^{b}
Mean 2014–2016	**10.2 ^{a}**	**12.1 ^{ab}**	**11.9 ^{ab}**	**15.1 ^{b}**	**13.4 ^{ab}**
Year differences[1]					
2014	a	a	a	a	a
2015	b	b	b	b	b
2016	b	b	c	c	c
N uptake (kg ha^{-1})					
July 2014	92.8 ^{a}	109.5 ^{ac}	102.2 ^{ac}	158.3 ^{b}	150.7 ^{bc}
Aug. 2014	141.6 ^{a}	141.7 ^{a}	143.5 ^{a}	177.7 ^{a}	185.8 ^{a}
Sept. 2014	163.1 ^{a}	194.3 ^{ab}	171.1 ^{ac}	233.4 ^{b}	184.8 ^{ab}
July 2015	84.4 ^{a}	91.3 ^{a}	98.6 ^{a}	129.9 ^{a}	135.1 ^{a}
Aug. 2015	90.7 ^{a}	119.8 ^{ab}	139.8 ^{ab}	154.3 ^{b}	152.7 ^{b}
Sept. 2015	104.7 ^{a}	150.3 ^{ab}	137.6 ^{ab}	191.6 ^{b}	176.7 ^{b}
July 2016	31.3 ^{a}	63.2 ^{b}	56.5 ^{b}	68.1 ^{b}	61.3 ^{b}
Aug. 2016	69.9 ^{ab}	59.6 ^{a}	66.7 ^{ab}	89.8 ^{b}	82.9 ^{ab}
Sept. 2016	53.6 ^{a}	72.5 ^{ab}	70.5 ^{ab}	87.7 ^{b}	87.0 ^{b}
Mean 2014–2016	**111.6 ^{a}**	**146.6 ^{ab}**	**134.8 ^{ab}**	**179.7 ^{b}**	**162.5 ^{b}**
Year differences[1]					
2014	a	a	a	a	a
2015	ab	ab	a	a	a
2016	b	b	b	b	b

CONTROL: without fertilization, CONV: conventional treatment, NI: nitrification inhibitor, STR: strip-till treatment.

[1] Main harvest (September).

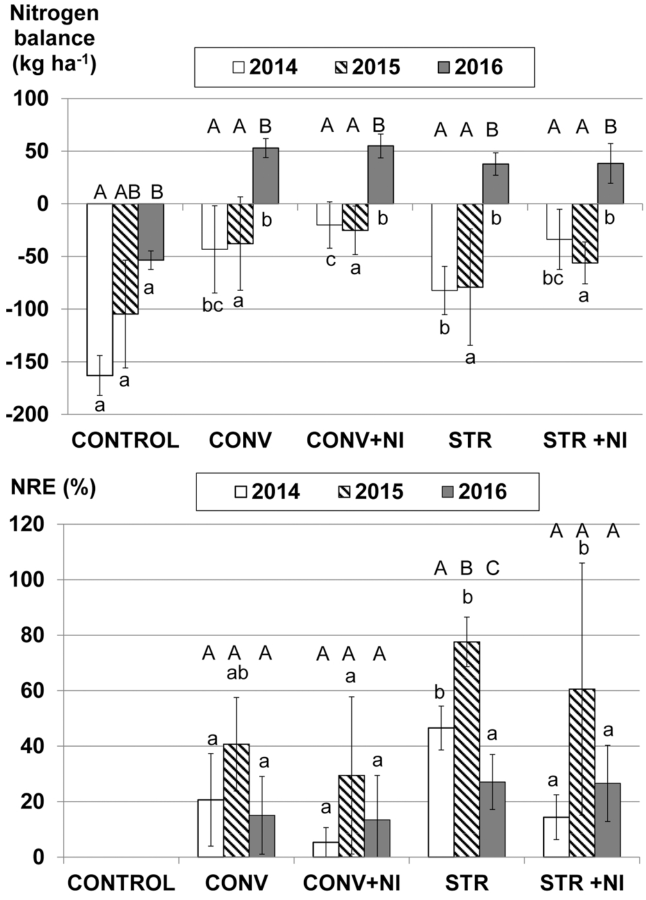
by Laurenz (2014). This is confirmed by SMN analyses which did not show NO_3-N displacement to deeper soil zones in the STR treatments in the early growth stages in 2014 and 2015.

4.3. Nitrogen balances and nitrogen recovery efficiency

Apart from 2016 N balances were mainly negative indicating reduced potential of NO_3-N leaching. This confirms findings of Federolf et al. (2016, 2017) and shows the potential of maize to use high amounts of fertilizer N. In contrast, N balances were positive for the 2016 season because of unfavorable growth conditions resulting in lowest biomass production and lowest N uptake among the three trial years. Thus, risk of N losses was highest in 2016 as evidenced by the highest proportion of SMN in the bottom soil layer (60–90 cm) at maize harvest.

The unfertilized CONTROL plots showed high N uptakes with a maximum of 163 kg N ha^{-1} (2014) and thus strongly negative N balances (see also Federolf et al., 2016, 2017). This suggests high mineralization rates of soil organic N and shows the importance of recovering the soil organic N pool in the long-term, e.g. by catch crops.

NRE (5–78%) values are markedly lower when compared to results of Federolf et al. (2017) who found a mean recovery rate of 49% for all fertilized treatments. These differences coincide with higher N uptakes of plants reported by Federolf et al. (2016, 2017) compared to our field trials.



CONTROL: without fertilization, CONV: conventional treatment, NI: nitrification inhibitor, STR: strip-till treatment

Fig. 4. Nitrogen balances and nitrogen recovery efficiency (NRE) for the three trial years (means ± standard deviation). Means with the same letter are not significantly different between treatments per year (lower case) and between years per treatment (upper case) (Tukey $p < 0.05$, $n = 4$).

Possible sinks for applied fertilizer N, other than plant uptake, are NH_3 and N_2O emissions, NO_3-N leaching and immobilization into the soil organic pool. Federolf et al. (2016) explained higher NRE in the STR treatments compared to broadcast application by enhanced N uptake, reduced N leaching and reduced NH_3 volatilization. Indeed Pietzner et al. (2017) reported significantly lower NH_3 emissions (43%) in 2014 for the STR treatments compared to broadcast slurry application for our study sites. It was reported that injection of slurry might reduce NH_3 losses by 2–75% (Rubaek et al., 1996; Hansen et al., 2003; Webb et al., 2010). Other studies indicate a higher risk of denitrification losses after slurry injection due to higher SMN contents and conditions favoring denitrification (Leick, 2003; Dell et al., 2012; Ruser and Schulz, 2015; Zurheide et al., 2016). This was not confirmed for our field trial in 2014 (Lückstedt), where Pietzner et al. (2017) did not detect significant differences in N_2O emissions between the STR and CONV treatments. In general N_2O emissions were on a low level at the study site with maximum 2.1 kg N ha^{-1} yr^{-1}, and emissions were more affected by the prevailing weather conditions than by the applied fertilization techniques (Pietzner et al., 2017).

5. Conclusions

Injection of slurry below the maize seeds by the STR technique led to in part higher N recovery efficiencies compared to broadcast slurry application which indicates that the STR system might potentially reduce N losses. Nevertheless no significant differences of DM yields and N uptakes between both application systems were found. In addition, the effect of added NI inhibitor was primarily detected in the early maize development by providing a stable high NH_4-N concentration in soil which might have stimulated plant root growth. Hence, the addition of NI in the STR system is generally recommended to avoid NO_3-N leaching at high precipitation rates, particularly in the early growth stages of maize plants. Although our study indicates that the STR system might be beneficial to reduce N losses in maize, further studies under different climatic and soil conditions are required for a final evaluation of the STR system and the effects of NI.

Future research should address the impact of the strip-till system with added NI on root growth, effects of reduced soil tillage on soil structure and soil moisture preservation, and furthermore the complex interactions between soil microorganisms at different fertilizer and soil properties such as soil organic matter, pH, and ammonium concentration.

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References

Addiscott, T.M., 2000. Tillage, mineralization and leaching. Soil Tillage Res. 53, 163–165.

Al-Kaisi, M., Licht, M.A., 2004. Effect of strip tillage on corn nitrogen uptake and residual soil nitrate accumulation compared with no-tillage and chisel plow. Agron. J. 96, 1164–1171.

Cameron, K.C., Di, H.J., Moir, J.L., 2013. Nitrogen losses from the soil/plant system: a review. Ann. Appl. Biol. 162, 145–173.

Chadwick, D., Misselbrook, T., Pai, N.B., 1999. Potential for reducing gaseous N emissions from high input agriculture. In: Abstract in: 10th Nitrogen Workshop. August 23–26, 1999, vol. 2, Theme IV.7, Copenhagen, Denmark.

Chen, Y., Assefa, B., Arkinrem, W., 2010. Soil nutrient levels and crop performance at various lateral positions following liquid manure injection. Agric. Eng. Int CIGR EJ, XII (Manuscript 1410).

Ciampitti, I.A., Vyn, T.J., 2011. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. Field Crops Res. 121 (1), 2–18.

Dell, C.J., Kleinman, P.J.A., Schmidt, J.P., Beegle, D.B., 2012. Low-disturbance manure incorporation effects on ammonia and nitrate loss. J. Environ. Qual. 41, 928–937.

DIN-EN-ISO-16634-1, 2008. Food Products - Determination of the Total Nitrogen Content by Combustion According to the Dumas Principle and Calculation of the Crude Protein Content – Part 1: Oilseeds and Animal Feeding Stuffs. Beuth, Berlin, Germany.

Dosch, P., Gutser, R., 1995. Reducing N losses (NH_3, N_2O, N_2) and immobilization from slurry through optimized application techniques. Fertil. Res. 43 (1), 165–171.

FO, 2017. German Fertiliser Ordinance, 26 May 2017.

Federolf, C., Westerschulte, M., Olfs, H.-W., Broll, G., Trautz, D., 2016. Enhanced nutrient use efficiencies from liquid manure by positioned injection in maize cropping in northwest Germany. Eur. J. Agron. 75, 130–138.

Federolf, C., Westerschulte, M., Olfs, H.-W., Broll, G., Trautz, D., 2017. Nitrogen dynamics following slurry injection in maize: crop development. Nutr. Cycl. Agroecosyst. 107, 19–31.

Halvorson, A.D., Wienhold, B.J., Black, A.L., 2001. Soil management. Tillage and nitrogen fertilization influence grain and soil nitrogen in an annual cropping system. Agron. J. 93, 836–841.

Hansen, M.N., Sommer, S.G., Madsen, N.P., 2003. Reduction of ammonia emission by shallow slurry injection: injection efficiency and additional energy demand. J. Environ. Qual. 32, 1099–1104.

Herrmann, W., Bauer, B., Bischoff, J., 2012. Strip-Till. Mit Streifen zum Erfolg, Agrar Praxis Kompakt, DLG-Verlag Frankfurt/Main. 120 pp.

IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. FAO, Rome 191 pp.

Lascano, R.J., Baumhardt, R.L., Hicks, S.K., Heilman, J.L., 1994. Soil and water evaporation from strip-tilled cotton: measurement and simulation. Agron. J. 86, 987–994.

Laurenz, L., 2014. Gülle-Strip till zu Mais auf Erfolgskurs. Top. Agrar. 3, 92–95.

Leick, B.C.E., 2003. Emission von Ammoniak (NH_3) und Lachgas (N_2O) von landwirtschaftlich genutzten Böden in Abhängigkeit von produktionstechnischen Maßnahmen. PhD. University of Hohenheim.

Ma, Q., Zhang, F., Rengel, Z., Shen, J., 2013. Localized application of NH_4^+–N plus P at the seedling and later growth stages enhances nutrient uptake and maize yield by inducing lateral root proliferation. Plant Soil 372, 65–80.

McCormick, R.A., Nelson, D.W., Sutton, A.L., Huber, D.M., 1984. Increased N efficiency from nitrapyrin added to liquid swine manure used as a fertilizer for corn. Agron. J. 76 (6), 1010–1014.

Mitchell, J., Shresta, A., Campbell-Mathews, M., Giacomazzi, D., Goyal, S., Bryant, D., Hererra, J., 2009. Strip Tillage in California's Central Valley. University of California, Division of Agricultural and Natural Resource, Publication 8361.

Ohlrogge, A.J., 1962. Some soil-root-plant relationships. Soil Sci. 93, 30–38.

Olfs, H.-W., Federolf, C.-F., Westerschulte, M., 2015. Nitratauswaschung stoppen. Dlz Agrarmagazin, Special Gülledüngung. pp. 16–18.

Petersen, J., Jensen, H.H., Rubæk, G.H., 2010. Phosphorus fertilization of maize seedlings by side-band injection of animal slurry. In: Proceedings 15th RAMIRAN Conference. 12 September 2010, Lisboa, Portugal.

Pietzner, B., Rücknagel, J., Koblenz, B., Bednorz, D., Tauchnitz, N., Bischoff, J., Köbke, S., Meurer, K.H.E., Meißner, R., Christen, O., 2017. Impact of slurry strip-till and surface slurry incorporation on NH_3 and N_2O emissions on different plot trials in Central Germany. Soil Tillage Res. 169, 54–64.

Rubaek, G.H., Henriksen, K., Petersen, J., Rasmussen, B., Sommer, S.G., 1996. Effects of application technique and anaerobic digestion on gaseous nitrogen loss from animal slurry applied to ryegrass (Lolium perenne). J. Agric. Sci. 126, 481–492.

Ruser, R., Schulz, R., 2015. The effect of nitrification inhibitors on the nitrous oxide (N_2O) release from agricultural soils—a review. J. Plant Nutr. Soil Sci. 178, 171–188.

Röseler, M., Graeff, S., Hermann, W., Claupein, W., 2010. Strip-Till-Verfahren in Zuckerrüben und Mais. Universität Hohenheim. Gesellschaft für Informatik in der Land- Forst- & Ernährungswirtschaft e.V, pp. 151–154.

Sawyer, J.E., Schmitt, M.A., Hoeft, R.G., Siemens, J.C., Vanderholm, D.H., 1991. Corn production associated with liquid beef manure application methods. J. Prod. Agric. 4, 335–344.

Schmitt, M.A., Evans, S.D., Randall, G.W., 1995. Effect of liquid manure application methods on soil nitrogen and corn grain yields. J. Prod. Agric. 8 (2), 186–189.

Schröder, J.J., Vermeulen, G.D., van der Schoot, J.R., van Dijk, W., Huijsmans, J., Meuffels, G., van der Schans, D.A., 2015. Maize yields benefit from injected manure positioned in bands. Eur. J. Agron. 64, 29–36.

Shipitalo, M.J., Dick, W.A., Edwards, W.M., 2000. Conservation tillage and macropore factors that affect water movement and the fate of chemicals. Soil Tillage Res. 53, 167–183.

Sommer, S.G., Hutchings, N.J., 2001. Ammonia emission from field applied manure and its reduction—invited paper. Eur. J. Agron. 15, 1–15.

Sticksel, E., Maidl, F.X., Valta, R., 1999. Untersuchungen zur verbesserten Gülleverwertung im Maisanbau. 2. Mitteilung: Einfluß des Düngungszeitpunktes auf die Ertragsbildung von Silo-und Körnermais. Pflbauwiss 3, 17–21.

Thiel, E., Spott, O., Fuchs, M., Schuster, C., 2016. Application of a nitrification inhibitor (PIADIN®) along with slurry using strip till approach for optimizing N fertilizer efficiency- laboratory and field results. In: Abstracts, 19th Nitrogen Workshop. Skara, Sweden. pp. 22–23. http://akkonferens.slu.se/nitrogenworkshop/wp-ontent/uploads/sites/18/2014/05/Nitrogen-Absracts-USB_ny.pdf.

VDLUFA, 2012. Bestimmung von mineralischem Stickstoff (Nitrat und Ammonium) in Bodenprofilen (Nmin-Labormethode). VDLUFA.

Webb, J., Pain, B., Bittman, S., Morgan, J., 2010. The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response—a review. Agric. Ecosyst. Environ. 137, 39–46.

Webb, J., Sørensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, P., Reid, J., 2013. An assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase manure-N efficiency. Adv. Agron. 119, 371–442.

Weed, J., Kanwar, R.S., 1996. Nitrate and water present in and flowing from root zone soil. J. Environ. Qual. 25, 709–719.

Westerschulte, M., Federolf, C.-P., Broll, G., Trautz, D., Olfs, H.-W., 2017. Nitrogen dynamics following slurry injection in maize: soil mineral nitrogen. Nutr. Cycl. Agroecosyst. 107, 1–17.

Yu, Q., Chen, Y., Ye, X., Tian, G., Zhang, Z., 2007. Influence of the DMPP (3,4-dimethylpyrazole phosphate) on nitrogen transformation and leaching in multi-layer soil columns. Chemosphere 69, 825–831.

Zurheide, T., Pralle, H., Westerschulte, M., Federolf, C.-P., Vergara, M.-E., Trautz, D., Olfs, H.-W., 2016. Untersuchung von Lachgasemissionen bei Gülledepot-Applikation mit Zugabe von Nitrifikationshemmstoffen am Standort Osnabrück. VDLUFA-Schriftenreihe 72, 88–96.