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Tine tip width and placement depth by row-injection of cattle slurry influence initial leaf N and P concentrations and final yield of silage maize

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ABSTRACT

There is an urgent need to replace mineral phosphorus (P) fertilizers placed near the maize seed at sowing with other management strategies to ensure a more environmentally friendly silage maize production and to avoid depletion of the phosphate rock reserve. The main objective of this study was to test and investigate effects of different tine geometry (operation depth and tine width) and use of the nitrification inhibitor (NI) 3,4-Dimethyl-pyrazole phosphate (DMPP) on early growth and final yields of maize under field conditions with the purpose of replacing mineral starter P fertilizers with row-injected liquid dairy manure (slurry). A two-year field experiment was carried out on a sandy loam and a loamy sand with moderate soil P status according to the Olsen P soil test. Cattle slurry with a NI was row-injected before sowing using newly developed goosefoot tine tips of three widths (8, 17 or 26 cm) with a roller to control injection depth. For the widest tine (26 cm) slurry was placed at 7 or 10 cm depth directly under the maize seed, and for the other tines slurry was placed at 10 cm depth. One of the placement methods was tested with and without a NI. The placement methods were compared to traditional slurry injection with random lateral positions relative to the maize row (non-placed slurry) and increasing rates of mineral P starter fertilizer with and without NI. The study showed that slurry placement using goosefoot tines of 17 or 26 cm width injected at 10 cm depth combined with a NI resulted in similar final yields (up to 17 Mg DM yield ha^{-1}) as when using mineral P as a starter fertilizer with non-placed slurry on the sandy loam. On the loamy sand, slurry placement increased early P concentration in maize, but final yield benefitted more from the mineral P fertilizer (+ 1.6 Mg DM yield ha^{-1} compared to the plots receiving non-placed slurry and no mineral P fertilizer). Addition of a NI to placed slurry increased early stage maize leaf P concentration on the sandy loam and early maize leaf N concentration on the loamy sand, but not with non-placed slurry. We conclude that maize yield benefitted from row-injection with medium or broad goosefoot tines placed at 10 cm depth combined with a NI, but only on the sandy loam soil in one of two trial years. The most optimal slurry distribution by placement varied with soil type and year.

1. Introduction

Silage maize (*Zea mayz* L.) harvested before grain maturity has become an important forage crop on many intensive dairy cattle farms in temperate regions with cold spring temperatures such as Northwestern Europe and Canada. An adequate phosphorus (P) supply is important for early growth and final yields of maize (Barry and Miller, 1989; Jokela, 1992). However, low mobility of P in soil and slow development of the maize root system under cold spring temperatures can restrict the young maize plants opportunities to take up sufficient amounts of soil P. To ensure that maize can access P during early growth, mineral P fertilizer produced from rock phosphate is routinely placed near the seed at sowing (starter fertilizer) at rates of 5–15 kg P ha^{-1} in these regions (Messiga et al., 2020; Schröder et al., 2015). In addition, liquid cattle manure (slurry) is typically injected into the soil in closed slots, where the soil is closed by rollers after filling the slots with slurry (Rodhe et al., 2006) with random lateral positions relative to the maize row before ploughing and sowing (non-placed slurry). When cattle slurry is applied to meet the N crop requirement, excess P contained in the cattle slurry is co-applied due to the lower N:P ratio in cattle slurry than in plant tissue (Eghball and Power, 1999; Sadeghpour et al., 2016). The resulting P surplus from P applied with cattle slurry and from mineral fertilizers has

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led to soil P accumulation on many intensive dairy cattle farms (Rubæk et al., 2013; Tóth et al., 2014), which poses an eutrophication risk in downstream waterbodies (Jarvie et al., 2013; Kronvang et al., 2009).

Injection of slurry near the maize row (placed slurry) has been shown to have the potential to replace the use of mineral starter P fertilizer (Hunt and Bittman, 2021; Pedersen et al., 2020; Schröder et al., 2015) leading to a more balanced P fertilizer use in maize cropping. However, the effect of placed slurry on final yields varies and depends on the placement depth and the design of the injection tine (Pedersen et al., 2020). In the present study, we examined the effects of four newly developed goosefoot tines with varying tip widths (8–26 cm) row-injected at different depths in order to identify the most promising placement method. By row-injecting slurry in wider bands, we expect that unfavorable root conditions that can arise in the concentrated slurry zone (Sawyer and Hoeft, 1990) could be reduced due to the greater contact zone between slurry and soil in broader bands. In addition, more roots would be exposed to broader slurry bands, which could improve the utilization of the slurry nutrients.

Nitrification inhibitors (NI) are used to inhibit the nitrification of NH_4^+ to NO_3^-. Inhibition of the nitrification could potentially decrease the formation of N_2O in the nitrification and denitrification process and a delayed formation of nitrate reduces the risk of nitrate leaching after application. 3.4-dimethylpyrazole phosphate (DMPP) is a widely used NI (Kösler et al., 2019) and delays the first step in the nitrification process by depressing the activity of *Nitrosomas* bacteria that oxidize NH_4^+ to NO_3^- (Zerulla et al., 2001). Increased plant uptake of NH_4^+ instead of NO_3^- after application of NI may also affect the P availability as the rhizosphere acidification by uptake of NH_4^+ improves the uptake of P in young maize plants (Jing et al., 2010; Pedersen et al., 2019).

The aim of this study was to test newly developed row-injection tines of different tip width and examine effects of tine tip widths and slurry placement depths on early plant P and N concentrations and final yield of silage maize. Furthermore, we studied effects of a nitrification inhibitor mixed with slurry on early P concentrations and yield of maize both with and without slurry placement.

2. Materials and methods

2.1. Experimental areas and design

Field experiments were conducted in 2019 and 2020 on two soil types (Table 1); a sandy loam at Foulum (56°49′ N, 9°56′ E) and a loamy sand at Skelhøje (56°35′ N, 9°31′ E) in Central Jutland, Denmark.

Each field experiment was organized as a randomized block design comprising 10 treatments with four replicates. The gross-plot size was 18 × 3 m (encompassing four rows), while the net-plot size for determination of final harvest yields was 10 × 1.5 m (two middle rows).

Table 1
Soil properties (0–25 cm) at the two experimental sites in 2019 and 2020.

Soil properties	Foulum		Skelhøje
	2019	2020	2020
Soil texture	Sandy loam	Sandy loam	Loamy sand
Clay (< 2 μm), g 100 g^{-1} soil	7.3	9.0	5.4
Silt (2–20 μm), g 100 g^{-1} soil	6.5	9.3	3.5
Fine sand (20–200 μm), g 100 g^{-1} soil	47.0	42.8	24.8
Coarse sand (200–2000 μm), g 100 g^{-1} soil	39.2	38.8	66.3
pH (0.01 M $CaCl_2$)	6.0	5.3	5.3
Bicarbonate-extractable P, mg kg^{-1} soil[a]	3.6	4.3	2.4
Total soil organic carbon, g 100 g^{-1} soil	1.0	1.5	2.1

[a]after Banderis et al. (1976), equivalent to Olsen P.

2.2. Slurry and mineral fertilizer application

Slurry was retrieved from a cattle house with dairy cows at Research Centre Foulum, Aarhus University in 2019 and from a local farmer nearby the field trials in 2020 (Table 3).

All plots received slurry at a rate of 110 kg NH_4^+ ha^{-1}. The nitrification inhibitor Vizura ® (BASF, Ludwigshafen, Germany) with the active compound 3.4-dimethylpyrazole phosphate (DMPP) was added to the slurry in the slurry tanker at a rate of 2 L ha^{-1}. One treatment with slurry placed with the 26 cm wide goosefoot tine with roller at 10 cm depth did not receive Vizura ("Broad GF tine-10 without NI", Table 2) to be able to assess the effect of NI for this placement method. In 2020, slurry with or without Vizura was applied to plots receiving non-placed slurry without mineral P fertilizers (Table 2).

Slurry was placed near the coming maize row after ploughing (0–25 cm) with an inter-tine distance of 75 cm using one of three different slurry placement tines mounted with goosefoot tips with different width (8, 17 and 26 cm) and with a discharged roller (Fig. 1a, b) or with a goosefoot tine without roller (Fig. 1c). The first three tines were rigid tines with spring protection giving a stable injection depth, whereas the last goosefoot was attached to a flexible S-shaped tine giving a less well-defined placement depth. The latter has been shown to be a promising injection tine in maize cropping in previous field trials (Pedersen et al., 2020). The broadest goosefoot tine (26 cm) with a roller was injected at two different depths (7 or 10 cm), whereas slurry was placed at 10 cm depths using the narrower goosefoot tines of 8 or 17 cm width (Table 2). The depth was measured from the upper side of the slurry layer to the soil surface. A roller installed behind the injection tines (Fig. 1b) functions to crush large soil aggregates and slightly compresses the soil to ensure a proper seedbed and is also used to steer the operation depth of tines in soils.

For reference treatments with more evenly distributed slurry (non-placed slurry), slurry was injected with a traditional closed slot soil injector in narrow bands with 25 cm distance prior to ploughing at 10 cm depth with random lateral positions relative to the maize row. This is common agricultural practice in Denmark. In the second

Table 2
Treatment overview indicating placement method and use of nitrification inhibitor (NI) in the two experimental years. GF: Goosefoot; NI: Nitrification inhibitor. Non-placed slurry was injected with a traditional closed-slot injector in narrow bands at 10 cm depths with 25 cm distance.

Abbreviation	Slurry application method	Placement depth cm	NI L ha^{-1}	Mineral starter P kg ha^{-1}
Non-placed+0P	Non-placed		2	0
Non-placed+0P without NI[a]	Non-placed		0	0
Non-placed+15P	Non-placed		2	15
Non-placed+30P	Non-placed		2	30
Broad GF tine-7	26 cm wide goosefoot tine with roller	7	2	–
Broad GF tine-10	26 cm wide goosefoot tine with roller	10	2	–
Broad GF tine-10 without NI	26 cm wide goosefoot tine with roller	10	0	–
Narrow GF tine-10	8 cm wide goosefoot tine with roller	10	2	–
Medium GF tine-10	17 cm wide goosefoot tine with roller	10	2	–
Broad GF tine-10 without roller	26 cm wide goosefoot tines without roller	10	2	–

[a] Only tested in 2020.

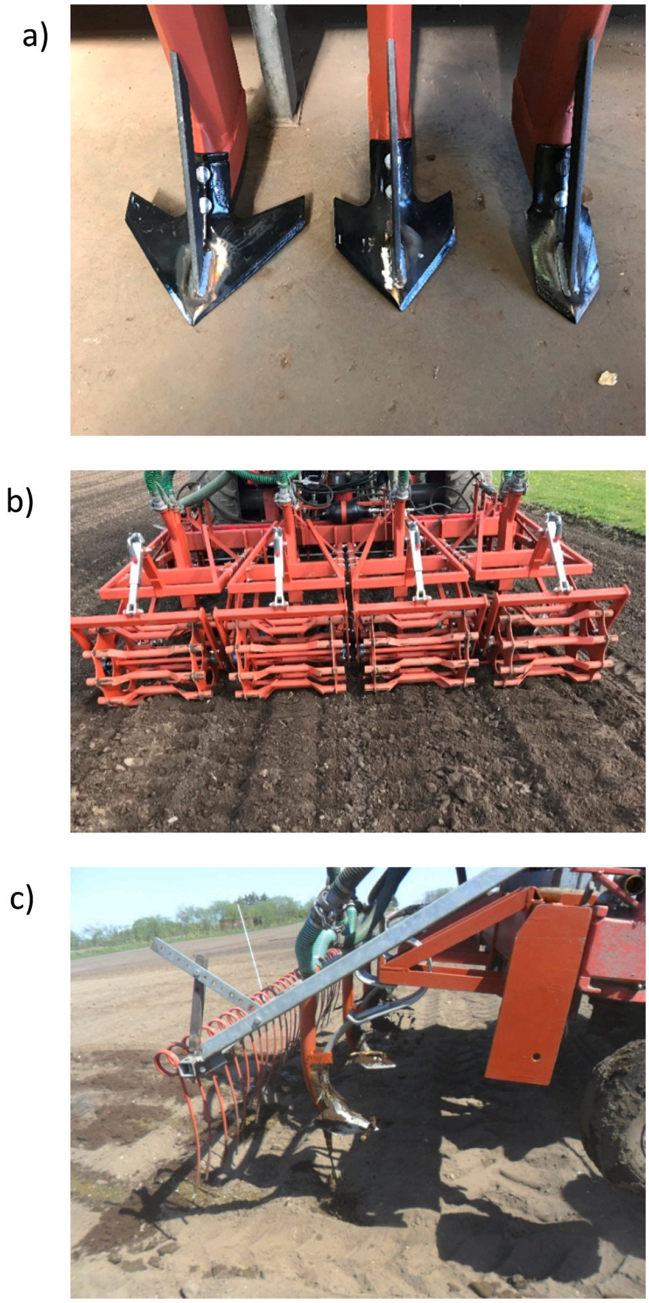

Fig. 1. a) Injection goosefoot tines used in the field trials to placement of slurry with a width of 26 cm (broad), 17 cm (medium) and 8 cm (narrow); b) Rollers installed behind the injection tines; c) Broad goosefoot tine without roller. Photos: Peter Storegård Nielsen and Peter Sørensen, Aarhus University.

experimental year, a treatment with non-placed slurry without NI was included.

After ploughing and slurry application, maize (cv. Ambition FAO 180) was sown at 5 cm depth using 75-cm row spacing and 13.3 cm between plants within rows, and directly over the middle of the placed slurry bands. This provides 100,000 plants ha^{-1}. At sowing, the reference treatments received 0, 15 or 30 kg mineral P ha^{-1} (diammonium hydrogenphosphate, DAP) placed 5 cm beside and 5 cm below the seeds, and all treatments received 27 kg mineral starter N ha^{-1} applied as ammonium sulphate accounting for ammonium in DAP (treatment with 30 kg P ha^{-1} in DAP received no ammonium sulphate). All treatments received patentkali equivalent to 100 kg K ha^{-1} and 72 kg S ha^{-1}. The total N application rate (Table 3) represents recommended N quotas to

Table 3
Cattle slurry properties and application rates.

Slurry properties and application rates	2019	2020
DM content, %	7.8	5.6
Total N, kg Mg^{-1}	3.6	3.4
NH_4^+-N, kg Mg^{-1}	1.6	1.9
Total P, kg Mg^{-1}	0.6	0.53
Total K, kg Mg^{-1}	2.7	2.1
Slurry application rate, Mg ha^{-1}	67	57
Slurry P application rate, kg ha^{-1}	38	30
Slurry NH_4^+-N application rate, kg ha^{-1}	110	110
Slurry N application rate, kg ha^{-1}	243	194
Total N application rate[a], kg ha^{-1}	270	221

[a] Including mineral starter N fertilization at a rate of 27 kg N ha^{-1} to all treatments.

maize in Denmark based on the NH_4^+-N content in slurry (van Grinsven et al. 2012).

2.3. Measurements and sampling

At the five-leaf stage (V5), 30 of the youngest fully developed leaves were sampled manually in each net- plot. The leaves were oven-dried at 60 °C to constant weight (min 48 h). The leaf samples were ground to pass a 1-mm screen.

Maize was whole-crop harvested with a special plot harvester for determination of final N, P and dry matter yields leaving 15 cm stubbles on October 1st in 2019 and October 9th in 2020. For each plot, a subsample of the chopped fresh material was dried at 60 °C for 48 h. The DM content ranged from 27% to 36% at harvest (a DM concentration of ca 32% is recommended for silage production).

2.4. Analytical methods

Leaf P concentration at V5 was determined by digesting dried plant material in concentrated hydrochloric acid after ashing at 500 °C. Phosphorus content in the digest was determined by Inductively Coupled Plasma- Optical Emission Spectroscopy (Yara, Analytical Services, Pocklington, UK). Leaf N concentration was determined by Kjeldahl digestion. Phosphorus concentration of the plant material from the whole-crop harvest was determined by pressurized microwave oven digestion following measurements by Inductively Coupled Plasma- Optical Emission Spectroscopy (EurofinsAgroTesting, Denmark). Nitrogen concentration at the final harvest was determined by combustion elemental analysis (EurofinsAgroTesting, Denmark).

2.5. Data calculation and statistics

Total N surplus was calculated as total N input from slurry and mineral fertilizers minus crop N uptake at harvest.

All statistical analyses were performed using R version 3.4.1 (R Development Core Team, 2017).

Data on early P and N concentrations and final DM yields from each year and site was analyzed using linear mixed-effects models from the R-package *lme4* with treatment as fixed effect and block as a random effect. The Dunnett's test implemented in the *multcomp* package was applied to compare the reference treatment with non-placed slurry and 0 kg mineral starter P (Non-placed+0 P) to the other treatments. In case of significant treatment effects by row-injecting slurry, multiple comparisons between treatments receiving placed slurry were performed using the Tukey's honestly significant differences test.

Significance was declared at the $p \leq 0.05$ level of error probability.

3. Results

3.1. Early phosphorus and nitrogen leaf concentrations

The P concentration in the youngest fully developed leaf increased with increasing rates of mineral starter P applied at both sites in 2019 and 2020 (Table 4). For the Foulum site in 2019, leaf P concentrations were above 0.3% of DM, whereas lower P concentrations were observed at the Skelhøje site in 2020 ranging from 0.16% to 0.29% of DM. In the first year at Foulum, early P concentrations were highest after placement at 7 cm depth (Broad GF tine-7) and with the goosefoot tine without a roller (Broad GF tine-10 without roller, Table 4). Omission of the nitrification inhibitor, when row-injecting slurry with the broad goosefoot tine at 10 cm depth, decreased the early P concentration at Foulum in 2020, whereas no effect of the inhibitor on early P concentration was observed at the Skelhøje site for this placement method. At Skelhøje, placement of slurry always increased the early P concentration compared to non-placed slurry and in most cases the increase was statistically significant. At Skelhøje, slurry placement with a nitrification inhibitor increased the early N concentration in maize leaves as compared to the reference treatment with non-placed slurry (Table 4). On both soils, early leaf N concentration in maize was lower when no nitrification inhibitor was added to placed slurry.

3.2. Final dry matter yields

Final DM yield benefitted from mineral starter P fertilizers, when a rate of 30 kg starter P ha^{-1} was applied in 2020 at both sites. In 2019 on the sandy loam, the final DM yield was higher, when 15 kg mineral P ha^{-1} was applied, but not 30 kg mineral P ha^{-1} (Table 5).

In 2020, the final DM yield was highest when slurry was placed at 10 cm depth with a broad or medium goosefoot tine combined with a nitrification inhibitor (Broad GF tine-10 and Medium GF tine-10) at the Foulum site. For the broad goosefoot tine at 10 cm depth, the DM yield was significantly higher when slurry was applied with a NI than without. In 2019 at Foulum and in 2020 at Skelhøje, the final yields in plots receiving placed slurry were similar to reference treatment with non-placed slurry and no additional mineral P fertilizer (Table 5).

Table 4
Concentrations of phosphorus (P) and nitrogen (N) in leaves at the five-leaf stage (V5) at Foulum and Skelhøje. Within each column, asterisks indicate significant differences in DM yield compared to the reference treatment with non-placed slurry and 0 kg P ha^{-1} (Non-placed+0P, Dunnett's test, $P < 0.05$). Different letters within columns denote statistically differences among treatments receiving placed slurry (Tukey, $P < 0.05$). For treatment codes, see Table 2.

	Leaf P concentration at V5, % of DM			Leaf N concentration at V5, % of DM		
	Foulum		Skelhøje	Foulum		Skelhøje
Treatment	2019	2020	2020	2019	2020	2020
Non-placed+0P (ref)	*0.30*	*0.24*	*0.16*	*4.97*	*4.91*	*4.03*
Non-placed +0P without NI	–	0.24	0.16	–	4.78	3.95
Non-placed+15P	**0.40****	**0.29****	**0.24****	5.08	5.11	4.66*
Non-placed+30P	**0.43****	**0.32****	**0.29****	5.16	5.20*	4.92*
Broad GF tine-7	0.38*a	0.26a	0.21*ab	5.22*	5.11a	4.73*ab
Broad GF tine-10	0.34ab	0.28a	0.20*ab	5.15	5.04a	4.68*ab
Broad GF tine-10 without NI	0.30b	0.20b	0.19b	5.02	4.63*b	4.28c
Narrow GF tine-10	0.31ab	**0.28*a**	0.22*ab	5.07	5.16a	4.74*ab
Medium GF tine-10	0.34ab	0.27a	0.24*a	5.01	5.06a	4.89*a
Broad GF tine-10 without roller	0.37*ab	0.25a	0.19b	5.27*	4.99a	4.53*bc

3.3. Phosphorus and nitrogen balances

The P uptakes at harvest were similar for each site within each year and averaged 38 kg P ha^{-1} (Foulum 2019), 27 kg P ha^{-1} (Foulum 2020) and 24 kg P ha^{-1} (Skelhøje 2020, Table 5). Consequently, the P surpluses at harvest (P input from slurry and mineral fertilizers minus crop P uptake at harvest) were significantly higher in plots receiving mineral P fertilizers. In 2019 at the Foulum site, the slurry P input matched the P uptake, whereas the P surplus ranged from 2 to 8 kg P ha^{-1} in 2020 at both sites (Table 6).

The N uptakes at harvest were slightly higher for some of the treatments receiving placed slurry and the reference treatment combined with 30 kg P ha^{-1} as compared to the treatment with non-placed slurry and no mineral P fertilizers at Foulum in 2020. At the Foulum site in 2019 and at the Skelhøje site in 2020, the N uptakes were similar among treatments (Table 5).

The total N surplus ranged from 30 to 79 kg N ha^{-1} across the two sites (Table 6). The NH_4^+-N input from slurry and mineral fertilizer totaled 137 kg N ha^{-1} in both years. Hence, the N uptake was on average 60 kg N ha^{-1} higher than the mineral N input in 2019 at the Foulum site, and 27 and 47 kg N ha^{-1} higher in 2020 at the Skelhøje and Foulum site, respectively.

4. Discussion

This study had a focus on effects of slurry placement geometry on early P leaf concentrations and final yields. Therefore, all treatments received the same amount of ammonium-N in a mineral starter fertilizer. Placement of slurry probably also has an effect on early N supply, but this effect we intended to be neutralized in the present setup with the starter N. At a realistic cattle slurry application rate there is room for extra mineral N application if the maize crop is not following a grass-clover crop with a high N release from soil (Eriksen et al., 2015).

4.1. Early nutrient concentrations and final yields

Determination of nutrient concentration in the youngest fully developed leaf has been used to evaluate the P and N status of crops (Frydenvang et al. 2015; Ziadi et al. 2009). The low leaf P concentrations in plants grown on plots receiving non-placed slurry without mineral P fertilizer at the Skelhøje site indicated P deficiency. Phosphorus tissue concentrations below 0.2% denoted severe P deficiency for maize (Haneklaus and Schnug, 2016). The soil at the Skelhøje site had the lowest Olsen P content and may therefore not be able to supply the plants with sufficient P from the labile soil pools, and plant P concentrations increased significantly by use of mineral starter P. All treatments with placed slurry also showed a higher P concentration in the young plants on this soil indicating that the plants accessed P from the placed manure in this soil. In some cases early P concentrations after placement was comparable with the treatment with 15 kg mineral P ha^{-1}, which is within the typical range of starter P application rates in Canada and Northwestern Europe (Messiga et al., 2020; Schröder et al., 2015; Withers et al., 2000). Slurry placement also increased the early N concentration in maize at Skelhøje (Table 4). However, early N concentrations in leaves were lower, when slurry was injected with a broad goosefoot tine at 10 cm depth without a nitrification inhibitor at both soils. Nitrification inhibitors are normally applied to reduce nitrate leaching (Di and Cameron, 2016), but it is unlikely that this effect on plant N concentration was due to leaching losses as precipitation was low in the period after application (Fig. 2). Thus, the results suggest that the retention of N on ammonium form lead to a higher early N uptake, which is in accordance with previous studies (Federolf et al., 2016; Westerschulte et al., 2018).

Table 5
Harvest DM yields of silage maize at Foulum and Skelhøje. Within each column, asterisks indicate significant differences in DM yield compared to the reference treatment with non-placed slurry and 0 kg mineral P ha^{-1} (Non-placed+0 P, Dunnett's test, P < 0.05). Different letters within columns denote statistically differences among treatments receiving placed slurry (Tukey, P < 0.05). For treatment codes, see Table 2.

	DM yield, Mg ha^{-1}			P uptake, kg ha^{-1}			N uptake, kg ha^{-1}		
	Foulum		Skelhøje	Foulum		Skelhøje	Foulum		Skelhøje
Treatment	2019	2020	2020	2019^{ns}	2020^{ns}	2020^{ns}	2019^{ns}	2020	2020^{ns}
Non-placed+0P (ref)	*17.6*	*15.3*	*14.2*	*40*	*26*	*21*	*195*	*174*	*164*
Non-placed +0P without NI	–	16.0	13.8	–	26	19	–	180	150
Non-placed+15P	**18.6***	16.1	15.2	44	27	22	206	179	168
Non-placed+30P	17.9	**17.0***	**15.8***	40	28	26	201	187*	176
Broad GF tine-7	17.4	16.3ab	14.2	39	27	19	199	188*	157
Broad GF tine-10	17.7	**17.0***a	14.3	40	28	20	202	191*	166
Broad GF tine-10 without NI	17.1	15.7b	14.0	36	27	20	196	182	151
Narrow GF tine-10	17.5	16.1ab	14.7	37	28	20	195	189*	164
Medium GF tine-10	16.8	**16.7*ab**	14.9	37	28	22	191	190*	181
Broad GF tine-10 without roller	17.0	15.9ab	14.8	37	24	20	198	182	165

Table 6
Phosphorus (P) and nitrogen (N) surplus at Foulum and Skelhøje calculated as total N and P applied minus N and P removal with the crop at the final harvest. Within each column, asterisks indicate significant differences in nutrient surplus compared to the reference treatment with non-placed slurry and no mineral P fertilizers applied (Dunnett's test, P < 0.05). For treatment codes, see Table 2.

	P surplus, kg ha^{-1}			N surplus, kg ha^{-1}		
	Foulum		Skelhøje	Foulum		Skelhøje
Treatment	2019	2020	2020	2019	2020	2020
Non-placed+0P (ref)	*- 2*	*4*	*6*	*75*	*47*	*57*
Non-placed +0P without NI		4	7	–	41	71
Non-placed+15P	**9***	**18***	**21***	64	42	53
Non-placed+30P	**28***	**32***	**33***	69	34	45
Broad GF tine-7	- 1	3	6	71	33	64
Broad GF tine-10	- 2	2	6	68	30	55
Broad GF tine-10 without NI	2	–	–	74	–	–
Narrow GF tine-10	1	2	6	75	32	57
Medium GF tine-10	1	2	5	79	31	40
Broad GF tine-10 without roller	1	6	8	72	39	56

The early leaf P concentrations were generally higher at the Foulum site. The Foulum soil had a high P status based on the Olsen P content according to Jordan-Meille et al. (2012), which could ensure a better P supply to the plants. For both sites however, the leaf P concentration increased, when mineral P fertilizers were applied, which accords to other studies with maize (Barry and Miller, 1989; Bates, 1971; Pedersen et al., 2020).

The final yields benefitted from 30 kg mineral P fertilizers in 2020 at both sites despite contrasting Olsen P contents. It is normally assumed that the probability of response to P supply is much lower on soils with high P status (Jokela, 1992). However, the present study indicates that P fertilizer supply may be beneficial to maize grown in regions with cold spring temperatures even on soils with high P-status, most likely due to limited access to soil P at critical growth stages.

4.2. Effect of placement depth and goosefoot tine width

The final DM yields were similar for plots receiving placed and non-placed slurry in 2019 at the Foulum site and in 2020 at the Skelhøje site, even though the final yields responded positively to mineral P starter fertilizers. This suggests that maize grown in plots with placed slurry had more difficulties in benefitting from slurry nutrients than from mineral P fertilizers these years. The results also show that placement of slurry did not guarantee improved final yields at harvest, even though the slurry placement equipment was applied, that provided a positive yield response at the Foulum site in 2020.

GPS technology combined with mechanical field markers mounted on the slurry injector can very accurately ensure that seeds are sown close to previously applied slurry bands. However, in the present study

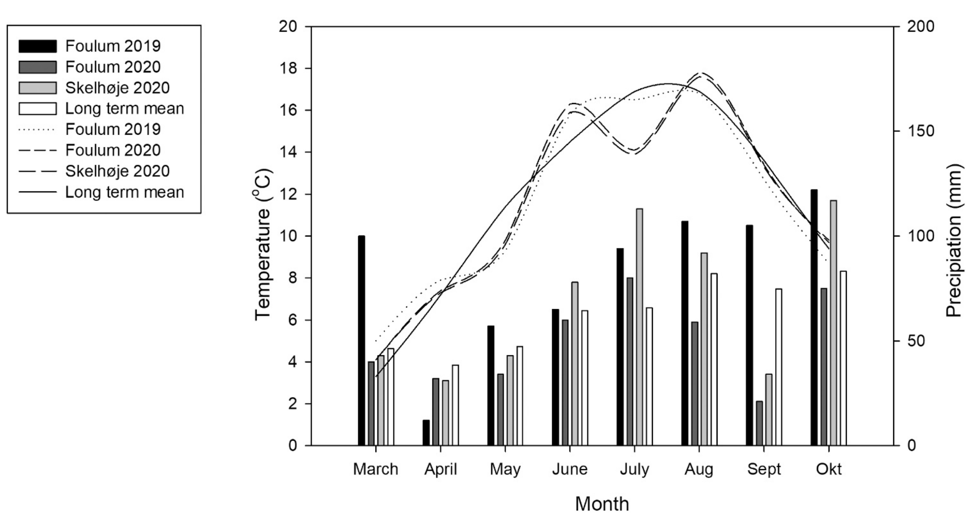

Fig. 2. Average air temperature in 2 m height (curves) and precipitation in 1.5 m height (bars) in the experimental period at Foulum and Skelhøje in 2019 and 2020. Long-term mean (1991–2020) is given. An additional irrigation of 30 mm at Foulum and Skelhøje was applied on August 13 2020.

the width of the injection tines was found to be of importance for the final yield. Tine widths of 26 cm (broad) or 17 cm (medium) were found to improve final yields on the Foulum site in 2020 as compared to the narrow goosefoot tine (8 cm), which was not an efficient row-injection tine. Therefore, it is necessary to design appropriate row-injection tines to improve the probability of a yield response following slurry placement. Another disadvantage by narrow bands is that they can form "drainage pipes" under the soil surface where slurry with low DM content can move to lower level points in the field (see illustration in Supplementary materials S1). By injecting slurry in wider bands this nuisance may better be avoided as the slurry-soil contact will be increased (Pedersen et al., 2017). However, increased contact zone between slurry and soil could potentially also increase the sorption of slurry P (Randall and Hoeft, 1988). Our study indicates that by placement of slurry centrally below maize seeds an optimal depth of the slurry is about 10 cm below the soil surface. An extra treatment with placement at 15 cm depth in the first year showed that this placement depth was less optimal (data not shown).

Surprisingly, the broad goosefoot tine without a roller installed did not provide improved final yields in this study in contrast to previous findings by Pedersen et al. (2020). A roller was not installed, when using this tine, and this could impair the quality of the seedbed as compared to tines with a roller installed. Furthermore, the broad GF tine-10 without roller was a flexible S-shaped tine that caused less constant depth making it more difficult to control the placement depth. Therefore, the slurry placement depth might be more varying for this goosefoot tine leading to lower opportunities to access and utilize slurry nutrients.

4.3. Effect of a nitrification inhibitor added to slurry

Addition of a nitrification inhibitor to slurry placed with a broad goosefoot tine at 10 cm depth with a roller installed increased final yields as compared to the same placement method without a nitrification inhibitor in the sandy loam in the second trial year. For non-placed slurry, the addition of a nitrification inhibitor had no effect. The beneficial effect of adding a nitrification inhibitor to placed slurry has also been found in other studies with maize (Pedersen et al., 2020; Regueiro et al., 2020). The results underline that initial leaf P concentrations and final yields only benefitted from slurry with a nitrification inhibitor, when slurry was placed near the maize row. This suggests that the beneficial effect of a nitrification inhibitor could be ascribed to high concentrations of NH_4^+ near the injection zone (Vogel et al., 2020; Westerschulte et al., 2016) that could stimulate early plant growth (Tauchnitz et al., 2021), but also improve P availability following NH_4^+ uptake due to the ammonium-induced proton release in the rhizosphere (Jing et al., 2010; Pedersen et al., 2019).

4.4. Phosphorus and nitrogen surpluses

The P surplus decreased significantly, when mineral starter P fertilizers were replaced by row-injected slurry. The P offtake matched the P input with slurry in 2019, whereas the P input with slurry exceeded the P crop offtake in 2020 revealing that P accumulation may continue even though the use of mineral P fertilizers is obviated. Soil P accumulation following slurry application even without input of mineral P fertilizers reflects the excess of P in slurry due to the lower N:P ratio in cattle slurry than in plant tissue (Eghball and Power, 1999). Alternatively, slurry treatments strategies such as separation that could ensure slurry fraction input with less P relative to N (Møller et al., 2002), or less slurry could be applied based on the crop's actual P demand.

The N uptake at harvest at the two sites was similar to previous field studies with high-yielding maize (Hansen and Eriksen, 2016; Kayser et al., 2011). The higher N uptake at harvest than the NH_4^+ fertilizer input indicates that the plants were able to benefit from mineralized organic slurry N or from the mineral N pool in soil. The maize plants' ability to benefit from N derived from organic fraction from the current or from previous applications accords with other field studies (Hunt and Bittman, 2021), and could be ascribed to the later harvest time for maize as compared to other annual crops enabling maize to acquire N mineralized from the organic fraction later in the growing season. However, total N input from slurry continuously exceeding N removal with the crop at harvest over several years will increase the risk of nitrate leaching, since large residual soil mineral N poses a leaching risk (Kayser et al., 2011).

5. Conclusion

Closed slot row-injection at 10 cm operation depth with a 17 or 26 cm wide goosefoot tine tip with a roller combined with a nitrification inhibitor improved final yields (+ 1.6 Mg ha^{-1}) in the sandy loam in the second trial year compared to traditional slurry injection without placement. The promising effect of the 26 cm goosefoot tine tip was not evident if a nitrification inhibitor was not applied to the slurry on this soil type. In the loamy sand, similar yields were obtained after injection of placed and non-placed cattle slurry.

By replacing traditional non-placed slurry injection and starter mineral P fertilizer with row-injected slurry, the P surpluses were significantly reduced. Hence, row-injection of slurry with medium or broad width goosefoot tines with a nitrification inhibitor could ensure a much more balanced P use in intensive maize cropping.

CRediT authorship contribution statement

Ingeborg F. Pedersen: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Tavs Nyord:** Conceptualization, Investigation, Methodology, Resources. **Peter Sørensen:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2021.126418.

References

Banderis, A., Barter, D.H., Henderson, K., 1976. The use of polyacrylamide to replace carbon in the determination of "olsen's" extractable phosphate in soil. J. Soil Sci. 27, 71–74.

Barry, D., Miller, M., 1989. Phosphorus nutritional requirement of maize seedlings for maximum yield. Agron. J. 81, 95–99.

Bates, T.E., 1971. Response of corn to small amounts of fertilizer placed with the seed: II. Summary of 22 field trials. Agron. J. 63, 369–371.

Di, H.J., Cameron, K.C., 2016. Inhibition of nitrification to mitigate nitrate leaching and nitrous oxide emissions in grazed grassland: a review. J. Soils Sediments 16, 1401–1420.

Eghball, B., Power, J.F., 1999. Phosphorus- and nitrogen-based manure and compost applications corn production and soil phosphorus. Soil Sci. Soc. Am. J. 63, 895–901.
Eriksen, J., Askegaard, M., Rasmussen, J., Søegaard, K., 2015. Nitrate leaching and residual effect in dairy crop rotations with grass–clover leys as influenced by sward age, grazing, cutting and fertilizer regimes. Agric. Ecosyst. Environ. 212, 75–84.
Federolf, C.-P., 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.
Frydenvang, J., van Maarschalkerweerd, M., Carstensen, A., Mundus, S., Schmidt, S.B., Pedas, P.R., Laursen, K.H., Schjoerring, J.K., Husted, S., 2015. Sensitive detection of phosphorus deficiency in plants using chlorophyll a fluorescence. Plant Physiol. 169, 353–361.
Haneklaus, S.H., Schnug, E., 2016. Assessing the plant phosphorus status. In: Schnug, E., De Kok, L.J. (Eds.), Phosphorus in Agriculture: 100% Zero. Springer Netherlands, Dordrecht, pp. 95–125.
Hansen, E.M., Eriksen, J., 2016. Nitrate leaching in maize after cultivation of differently managed grass-clover leys on coarse sand in Denmark. Agric. Ecosyst. Environ. 216, 309–313.
Hunt, D.E., Bittman, S., 2021. Precision injection of dairy sludge on crop yield and N and P uptake in juvenile and mature no-till silage corn. Agronomy 11, 370.
Jarvie, H.P., Sharpley, A.N., Withers, P.J.A., Scott, J.T., Haggard, B.E., Neal, C., 2013. Phosphorus mitigation to control river eutrophication: Murky waters, inconvenient truths, and "postnormal" science. J. Environ. Q. 42, 295–304.
Jing, J., Rui, Y., Zhang, F., Rengel, Z., Shen, J., 2010. Localized application of phosphorus and ammonium improves growth of maize seedlings by stimulating root proliferation and rhizosphere acidification. Field Crops Res. 119, 355–364.
Jokela, W.E., 1992. Effect of starter fertilizer on corn silage yields on medium and high fertility soils. J. Prod Agric. 5, 233–237.
Jordan-Meille, L., Rubæk, G.H., Ehlert, P., Genot, V., Hofman, G., Goulding, K., Recknagel, J., Provolo, G., Barraclough, P., 2012. An overview of fertilizer-P recommendations in Europe: soil testing, calibration and fertilizer recommendations. Soil Use Manag. 28, 419–435.
Kayser, M., Benke, M., Isselstein, J., 2011. Little fertilizer response but high N loss risk of maize on a productive organic-sandy soil. Agron. Sustain. Dev. 31, 709–718.
Kronvang, B., Rubæk, G.H., Heckrath, G., 2009. International phosphorus workshop: Diffuse phosphorus loss to surface water bodies—risk assessment, mitigation options, and ecological effects in river basins. J. Environm. Q. 38, 1924–1929.
Kösler, J.E., Calvo, O.C., Franzaring, J., Fangmeier, A., 2019. Evaluating the ecotoxicity of nitrification inhibitors using terrestrial and aquatic test organisms. Environ. Sci. Eur. 31, 91.
Messiga, A.J., Lam, C., Li, Y.K., Kidd, S., Yu, S.B., Bineng, C., 2020. Combined starter phosphorus and manure applications on silage corn yield and phosphorus uptake in southern BC. Front. Earth Sci. 8, 13.
Møller, H.B., Sommer, S.G., Ahring, B.K., 2002. Separation efficiency and particle size distribution in relation to manure type and storage conditions. Bioresour. Technol. 85, 189–196.
Pedersen, I.F., Rubæk, G.H., Nyord, T., Sørensen, P., 2020. Row-injected cattle slurry can replace mineral P starter fertiliser and reduce P surpluses without compromising final yields of silage maize. Eur. J. Agron. 116, 126057.
Pedersen, I.F., Rubæk, G.H., Sørensen, P., 2017. Cattle slurry acidification and application method can improve initial phosphorus availability for maize. Plant Soil 414, 143–158.
Pedersen, I.F., Sørensen, P., Rasmussen, J., Withers, P.J.A., Rubæk, G.H., 2019. Fertilizer ammonium: nitrate ratios determine phosphorus uptake by young maize plants. J. Plant Nutr. Soil Sci. 182, 541–551.
R Development Core Team, 2017. R: A language and environment for statistical computing.
Randall, G., Hoeft, R., 1988. Placement methods for improved efficiency of P and K fertilizers: a review. J. Prod. Agric. 1, 70–79.
Regueiro, I., Siebert, P., Liu, J., Müller-Stöver, D., Jensen, L.S., 2020. Acidified animal manure products combined with a nitrification inhibitor can serve as a starter fertilizer for maize. Agronomy 10, 1941.
Rodhe, L., Pell, M., Yamulki, S., 2006. Nitrous oxide, methane and ammonia emissions following slurry spreading on grassland. Soil Use Manag. 22, 229–237.
Rubæk, G.H., Kristensen, K., Olesen, S.E., Østergaard, H.S., Heckrath, G., 2013. Phosphorus accumulation and spatial distribution in agricultural soils in Denmark. Geoderma 209–210, 241–250.
Sadeghpour, A., Ketterings, Q.M., Godwin, G.S., Czymmek, K.J., 2016. Nitrogen- vs. Phosphorus-based manure and compost management of corn. Agron. J. 108, 185–195.
Sawyer, J.E., Hoeft, R.G., 1990. Effect of injected liquid beef manure on soil chemical properties and corn root distribution. J. Prod. Agric. 3, 50–55.
Schröder, J.J., Vermeulen, G.D., van der Schoot, J.R., van Dijk, W., Huijsmans, J.F.M., Meuffels, G.J.H.M., van der Schans, D.A., 2015. Maize yields benefit from injected manure positioned in bands. Eur. J. Agron. 64, 29–36.
Tauchnitz N., Bischoff J., Schrödter M., Ebert S., Meissner R. , 2021. Strip-till combined with slurry band injection below maize seeds—a new approach to enhance the nitrogen efficiency of organic fertilizers. In: L. Mueller, V.G. Sychev, N.M. Dronin, F. Eulenstein (eds) Exploring and Optimizing Agricultural Landscapes, Springer International Publishing, Cham. pp. 625–637.
Tóth, G., Guicharnaud, R.-A., Tóth, B., Hermann, T., 2014. Phosphorus levels in croplands of the European Union with implications for P fertilizer use. Eur. J. Agron. 55, 42–52.
van Grinsven, H.J.M., ten Berge, H.F.M., Dalgaard, T., Fraters, B., Durand, P., Hart, A., Hofman, G., Jacobsen, B.H., Lalor, S.T.J., Lesschen, J.P., Osterburg, B., Richards, K. G., Techen, A.K., Vertès, F., Webb, J., Willems, W.J., 2012. Management, regulation and environmental impacts of nitrogen fertilization in northwestern Europe under the Nitrates Directive; a benchmark study. Biogeosciences 9, 5143–5160.
Vogel, C., Sekine, R., Huang, J., Steckenmesser, D., Steffens, D., Huthwelker, T., Borca, C. N., Pradas del Real, A.E., Castillo-Michel, H., Adam, C., 2020. Effects of a nitrification inhibitor on nitrogen species in the soil and the yield and phosphorus uptake of maize. Sci. Total Environ. 715, 136895.
Westerschulte, M., Federolf, C.-P., Trautz, D., Broll, G., Olfs, H.-W., 2016. Nitrogen dynamics following slurry injection in maize: soil mineral nitrogen. Nutr. Cycl. Agroecosyst. 107, 1–17.
Westerschulte, M., Federolf, C.-P., Trautz, D., Broll, G., Olfs, H.-W., 2018. Slurry injection with nitrification inhibitor in maize: plant phosphorus, zinc, and manganese status. J. Plant Nutr. 41, 1381–1396.
Withers, P.J.A., Peel, S., Chalmers, A.G., Lane, S.J., Kane, R., 2000. The response of manured forage maize to starter phosphorus fertilizer on chalkland soils in southern England. Grass Forage Sci. 55, 105–113.
Zerulla, W., Barth, T., Dressel, J., Erhardt, K., Horchler von Locquenghien, K., Pasda, G., Rädle, M., Wissemeier, A., 2001. 3,4-Dimethylpyrazole phosphate (DMPP) – a new nitrification inhibitor for agriculture and horticulture. Biol. Fert. Soils 34, 79–84.
Ziadi, N., Bélanger, G., Gastal, F., Claessens, A., Lemaire, G., Tremblay, N., 2009. Leaf nitrogen concentration as an indicator of corn nitrogen. Agron. J. 101, 947–957.