STØTTET AF

Promilleafgiftsfonden for landbrug

Miljø- og Fødevareministeriet

gudp

European Journal of Agronomy 116 (2020) 126057

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Row-injected cattle slurry can replace mineral P starter fertiliser and reduce P surpluses without compromising final yields of silage maize

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ARTICLE INFO

Keywords:
Liquid animal manure
Corn
DMPP
Slurry acidification
Starter fertiliser

ABSTRACT

Accumulation of phosphorus (P) in soil can be a problem on intensive livestock farms with maize cropping, when mineral P starter fertilisers are applied in combination with evenly injected liquid manure before sowing.

We examined the possibilities of replacing mineral P starter fertiliser with placement of cattle slurry close to the maize row before sowing in a two-year field study. The study was carried out on a sandy loam (pH of 6.1 and Olsen-P content of 44 mg P kg^{-1}) and a coarse sandy soil (pH of 5.9 and Olsen-P content of 34 mg P kg^{-1}) in Denmark. Slurry was row-injected at 10 cm depth in a broad-band with a 26-cm wide goosefoot tine or in a narrow-band. These two row-injection methods were combined with a nitrification inhibitor and/or slurry acidification. Treatments with evenly injected slurry at random lateral positions relative to the maize row (non-placed slurry) with increasing amounts of mineral starter P (0, 10 and 30 kg P ha^{-1}, respectively) were included as reference treatments.

Slurry placement in narrow or broad bands combined with slurry acidification or a nitrification inhibitor resulted in leaf P concentrations at the five-leaf stage that were significantly higher than the reference treatment with non-placed slurry and no mineral starter P. However, increased leaf P concentrations at the early growth stage did not always turn into higher yields at harvest. The highest dry matter yields (up to +1.9 Mg dry matter yield ha^{-1} compared to the reference treatment with non-placed slurry and no mineral starter P) were obtained when slurry was applied in a broad band below the maize row, but on the sandy loam only in combination with a nitrification inhibitor or slurry acidification. The P uptake at harvest did not differ among treatments (averaged 37 and 28 kg P ha^{-1} on the sandy loam and coarse sandy soil, respectively), and consequently the P surplus could be markedly reduced by omitting the use of mineral starter P fertiliser. We conclude that placement of cattle slurry in broad bands below the row can substitute the use of mineral P starter fertiliser and thus reduce farm P surpluses in silage maize cropping.

1. Introduction

In Northwestern Europe, maize (*Zea mays* L.) is an important crop on intensive dairy cattle farms. In Denmark, silage maize has completely replaced fodder beets and the area with maize has increased from 47,000 ha in 1998 to 179,000 ha in 2018, corresponding to 7% of the cultivated land. Lack of phosphorus (P) during early growth can seriously compromise final maize yields (Grant et al., 2001), and Barry and Miller (1989) showed with maize grown in turface (baked crushed clay) that elimination of P deficiency between seeding and the six-leaf stage was necessary for obtaining maximum final grain yields. Therefore mineral P fertilisers are routinely placed near the maize seed at sowing in starter fertilisers (e.g. Withers et al., 2000), even on dairy farms, where the amounts of P in dairy manure often matches or exceeds crop P demand. Generous input of P from both dairy manure and mineral starter fertilisers can lead to soil P accumulation (e.g. Rubæk et al., 2013; van Dijk et al., 2016), which poses a long-term eutrophication risk in watercourses (George et al., 2016). Furthermore, it is important to minimise the use of mineral P fertiliser derived from phosphate rock to aid a transition towards a circular economy (EC, 2014).

Livestock manure is the largest resource of recyclable P in Europe (Ott and Rechberger, 2012), and all P in animal manure is considered to be plant-available in the long term (Haneklaus and Schnug, 2016; Jing et al., 2019). However, a shift from a mineral P-based starter fertiliser regime to a solely manure-based fertiliser regime in maize cropping requires that sufficient P in livestock manure becomes immediately available to the young maize plants to avoid a lack of P during early

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https://doi.org/10.1016/j.eja.2020.126057
Received 3 June 2019; Received in revised form 10 March 2020; Accepted 25 March 2020
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Table 1
Soil properties (0-25 cm) at the start of the experiments for each field at the two experimental sites in 2017 and 2018. Mineral nitrogen in soil was not determined in 2018.

Soil properties	Foulum 2017	2018	Havris 2017	2018
Soil texture	Sandy loam	Sandy loam	Coarse sand	Coarse sand
Clay (< 2 µm), g 100 g^{-1} soil	7.8	8.4	3.1	5.5
Silt (2–20 µm), g 100 g^{-1} soil	6.9	4.7	2.0	1.4
Fine sand (20–200 µm), g 100 g^{-1} soil	48.7	47.2	25.8	37.7
Coarse sand (200–2000 µm), g 100 g^{-1} soil	36.7	37.0	69.1	55.3
pH (0.01 M $CaCl_2$)	6.3	5.8	5.9	5.9
Bicarbonate-extractable P, mg kg^{-1} soil[a]	45	43	32	35
Soil organic carbon, g 100 g^{-1} soil	1.5	1.5	1.2	1.4
NH_4^+-N in 0 – 50 cm depth, kg ha^{-1}	8.9	n/a	24.6	n/a
NO_3^--N in 0 – 50 cm depth, kg ha^{-1}	11.9	n/a	43.9	n/a

[a] modified after Banderis et al. (1976).

growth.

Replacing mineral P starter fertiliser by slurry injection below the maize row seems as a promising management tool to reduce P surplus in maize cropping. In a field study with silage maize, Schröder et al. (2015) found that positioning of slurry 5 – 10 cm below the seed with a lateral distance of 0 – 10 cm from the seed in some cases resulted in dry matter (DM) yields that were similar to yields after conventional non-positioned injection of slurry combined with mineral P starter fertiliser. However, in some cases neither mineral P starter fertiliser nor placed slurry increased yields at harvest (Schröder et al., 2015). This could be ascribed to a higher soil P status in these experiments, which is also in line with Kuchenbuch and Buczko (2011), who found that soil P status followed by soil pH and clay content influenced the P fertiliser response the most.

There are several methods for placing slurry and the method can be crucial for the plant growth response. This was clearly demonstrated in a pot study with maize, where broad-banded cattle slurry placed below the seed improved DM yield in the early growth stages compared to narrow-banded slurry placed below and beside the seed (Pedersen et al., 2017). Whether the positive effect of broad-banded slurry is present under field conditions lacks documentation.

Slurry treatment strategies such as slurry acidification and addition of a nitrification inhibitor might also improve the availability of slurry nutrients in placed slurry bands. Slurry acidification is usually carried out to reduce ammonia emissions (Kai et al., 2008), but it has been shown that acidification can also increase the amount of dissolved P in slurry (Pedersen et al., 2017), which is mainly attributed to the dissolution of struvite and calcium phosphate minerals (Christensen et al., 2009; Fordham and Schwertmann, 1977; Li et al., 2019). A higher content of dissolved P in slurry may enhance plant P uptake. A positive response to placed acidified slurry has been observed for maize during the early growth stages on a coarse sandy soil with a low buffer capacity (Pedersen et al., 2017), but whether this also applies to maize grown to silage maturity is not documented.

The pH of the rhizosphere soil may affect P availability, since pH controls P speciation, precipitation and sorption processes (e.g. Barrow, 2017). Pedersen et al. (2018b) recently showed that P acquisition from dicalcium phosphate, which is one of the main inorganic forms of P in dairy manure (Güngör et al., 2007), can be improved by ensuring a high ammonium-N (NH_4^+-N) uptake in plants, which in turn causes pH to decrease in the rhizosphere. Addition of nitrification inhibitors like 3,4-dimethyl pyrazole phosphate (DMPP) to cattle slurry can effectively inhibit NH_4^+ oxidation and ensure that mineral nitrogen (N) remains in NH_4^+-N form for a longer period (Fangueiro et al., 2009). This suggests that placement of slurry combined with addition of a nitrification inhibitor could enhance P availability.

The aim of this study was to test under field conditions, whether placement of slurry in a broad or narrow band below the maize row would ensure final harvest yields that were similar to yields obtained after application of mineral P starter fertiliser combined with non-positioned slurry injection. Furthermore, we examined whether slurry acidification and/or addition of a nitrification inhibitor to the placed slurry could improve the availability of nutrients in placed slurry. We hypothesised that early plant tissue P concentrations and final yields of silage maize would benefit from i) placed slurry compared to evenly injected slurry (non-placed slurry) with broad-banded slurry being superior to narrow-banded slurry, ii) slurry acidification combined with placement and iii) addition of a nitrification inhibitor to placed cattle slurry. Finally, we assessed P and N balances at harvest in the contrasting fertiliser regimes.

2. Materials and methods

2.1. Experimental areas and design

Field experiments were established in 2017 and 2018 on two soil types; a sandy loam at Foulum (56°49′ N, 9°56′ E) and a coarse sand at Havris (56°53′ N, 9°41′ E) in Central Jutland, Denmark (Table 1). The climate is temperate and humid, and Fig. 1 shows the monthly mean temperature and cumulative precipitation derived from nearby local meteorological stations during the experimental period. The Foulum soil is classified as a Typic Hapludalf and the Havris soil as a Typic Haplorthod (USDA Soil Taxonomy System), and both soils are typical for maize cropping in Denmark.

The experiments were organised as a randomised complete block design with four replicates and 12 treatments (Table 2). The plot size was 18 × 3 m (four rows) with 75 cm row distance, and the harvest plot size was 12 × 1.5 m (the two middle rows). All measurements were performed on the harvest plots.

2.2. Slurry treatment and fertiliser application

The slurry used in 2017 had been stored in a slurry tank since spring 2016 until field application, and the long storage period in a relatively small storage tank resulted in high slurry pH (Table 3). In 2018, slurry was retrieved directly from a cattle house with dairy cows a few weeks before application to the field.

For treatments with slurry placed below the maize row, slurry was applied after ploughing (0 – 25 cm deep) and a few days before sowing at a rate of 100 kg NH_4^+-N ha^{-1} (Table 2). Broad-band (BB) slurry injection below the maize row was carried out with a 26-cm broad goosefoot tine constructed specifically for the experiment with a tine distance of 75 cm. The slurry was placed in a thin layer below the maize row at 10 cm depth from the soil surface to the bottom part of the slurry band (Fig. 2). Placed BB-injected slurry was compared to narrow-band (NB) injected slurry, which was carried out with an ordinary 6-cm S-spring tine with a discharge pipe for slurry placement (Samson CM, Samson Agro, Viborg, Denmark). Tines were mounted at a distance of

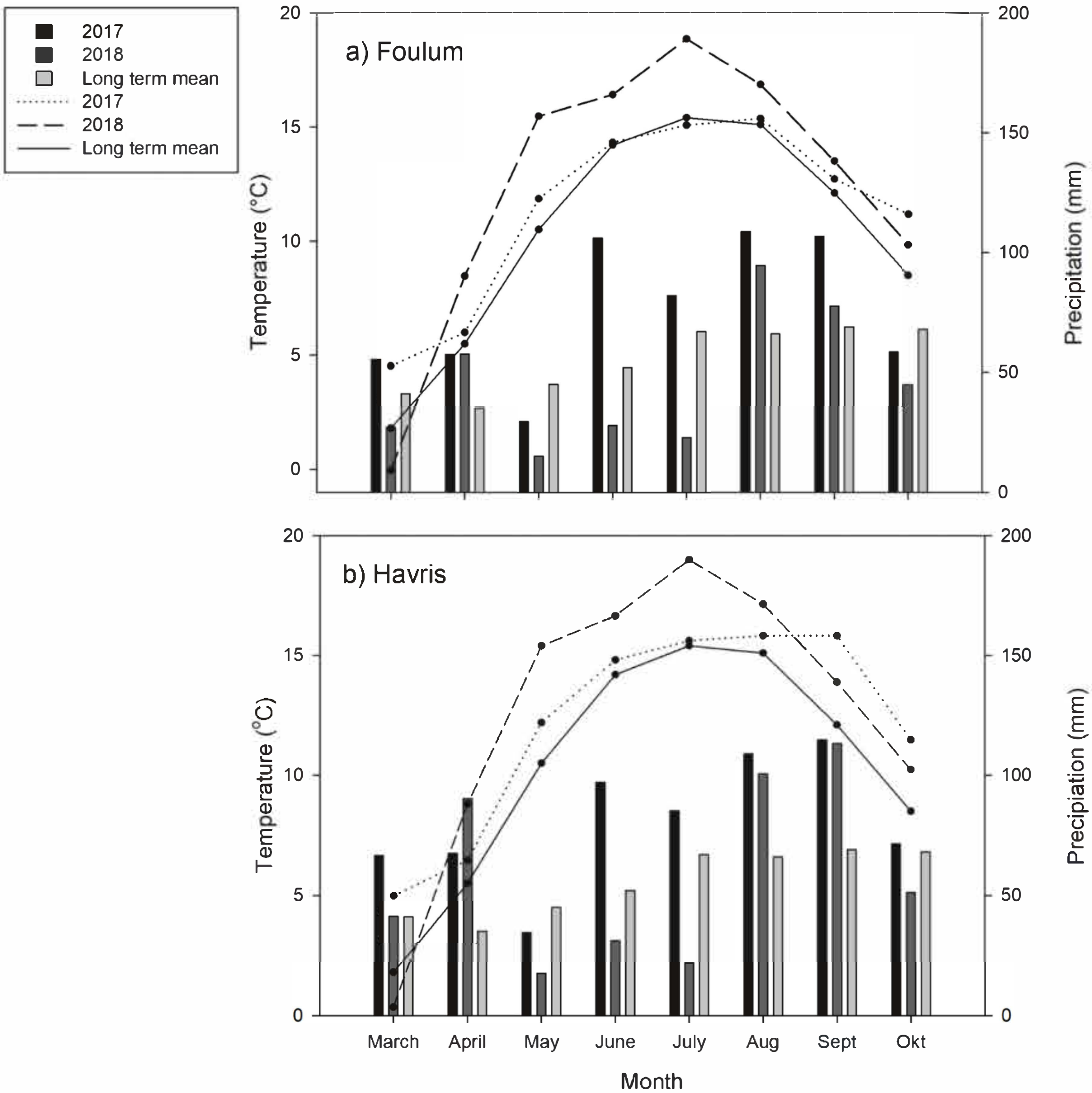

Fig. 1. Mean monthly air temperature at 2 m height (curves) and cumulative monthly precipitation at 1.5 m height (bars) in the experimental period in 2017 and 2018 including long-term mean (1961-1990) at a) Foulum and b) Havris. In 2018, an additional irrigation of 100 mm (in July) at Foulum and 189 mm (from mid-May to early August) at Havris was applied.

Table 2
Treatment overview showing experimental combinations of slurry application method, nitrification inhibitor (NI), slurry acidification (SA) and mineral starter N and P application. NB: Narrow band row-injection with a 6-cm wide S-spring tine at 10 cm depth with a tine distance of 37.5 cm. BB: Broad band row-injection with a 26-cm wide goosefoot tine at 10 cm depth with a tine distance of 75 cm. All treatments received slurry NH_4^+-N at a rate of 100 kg ha^{-1} except the reference treatment without mineral starter N and P (Non-placed + 0NP), which received slurry NH_4^+-N at a rate of 120 kg ha^{-1}.

Abbreviation	Slurry application method	NI	SA	Mineral starter fertiliser	
		L ha^{-1}		kg N ha^{-1}	kg P ha^{-1}
Non-placed + 0NP	Non-placed	0	No	0	0
Non-placed + 0P	Non-placed	0	No	20	0
Non-placed + 10P	Non-placed	0	No	20	10
Non-placed + 30P	Non-placed	0	No	20	30
NB untreated	Narrow band row-injection	0	No	20	0
NB + SA	Narrow band row-injection	0	Yes	20	0
NB + NI	Narrow band row-injection	2	No	20	0
NB + SA + NI	Narrow band row-injection	2	Yes	20	0
BB untreated	Broad band row-injection	0	No	20	0
BB + SA	Broad band row-injection	0	Yes	20	0
BB + NI	Broad band row-injection	2	No	20	0
BB + SA + NI	Broad band row-injection	2	Yes	20	0

Table 3
Cattle slurry properties and application rates in the two experimental years.

Slurry properties and application rates	2017	2018
DM content, %	7.0	8.6
Total N, kg Mg^{-1}	3.5	4.2
NH_4^+-N, kg Mg^{-1}	2.0	2.3
Total P, kg Mg^{-1}	0.67	0.65
Total K, kg Mg^{-1}	3.6	3.7
pH in untreated slurry	7.8	7.2
pH in acidified slurry	5.8	5.4
Amount of Acidline (50 % sulphuric acid), L Mg^{-1} slurry	34	11.5
Slurry application rate[a], Mg ha^{-1}	50	44
Slurry P application rate[a], kg ha^{-1}	35.0	30.4
Slurry N application rate[a], kg ha^{-1}	175	183
Total N application[b], kg ha^{-1}	265	203[c]

[a] Application rates in treatments that received slurry with an application rate of 100 kg NH_4^+-N ha^{-1} (all treatments except treatment "non-placed 0N + 0P", that received 120 kg NH_4^+-N ha^{-1} as slurry).
[b] Total N application rate = slurry N + starter mineral N + later surface N application.
[c] No late fertiliser application (70 kg mineral N ha^{-1}) in 2018.

37.5 cm. Half of the slurry in the NB treatments was placed 5 cm next to the maize row at 10 cm depth from the soil surface to the bottom part of the slurry band, the other half in bands between rows at the same depth. The two row-injection techniques were combined with 1) slurry acidification, 2) addition of a nitrification inhibitor, 3) slurry acidification and a nitrification inhibitor or 4) untreated slurry (Table 2). Acidification of slurry was carried out in the slurry tanker just before field application by adding 7.08 *M* sulfuric acid (AcidLine®, DanGødning, Fredericia, Denmark) while stirring. In total 34 and 11.5 L of 7.08 *M* sulfuric acid Mg^{-1} slurry was added in 2017 and 2018, respectively, which corresponded to 382 and 114 kg sulphur (S) ha^{-1}. For treatments receiving a nitrification inhibitor, 3.4-dimethylpyrazole phosphate (DMPP) was added to the slurry in the slurry tanker as Vizura® (BASF, Ludwigshafen, Germany) just before slurry application with an application rate of 2 L ha^{-1}. The stock solution consisted of 10 % (w/w) DMPP ($C_5H_{11}N_2O_4P$) in 40 % phosphoric acid (w/w) and had a density of 1.23 kg L^{-1}. Phosphorus from Vizura® was equal to 426 g P ha^{-1}, and corresponded to 1.3 % of total P applied with the slurry across the years.

Reference treatments were included with a conventional application method, where cattle slurry was injected a few days prior to ploughing with a 26 cm inter-tine distance at 10 cm depth with random lateral positions relative to the rows (Non-placed slurry, Table 2). At sowing 0, 10 or 30 kg mineral P ha^{-1} (triple superphosphate) was applied as P starter fertiliser at a distance of 5 cm beside and 5 cm below the seed sowing (Non-placed + 0 P, Non-placed + 10 P and Non-placed + 30 P, respectively). The rate of 10 kg P ha^{-1} represents typical starter mineral P rates in Denmark, and the rate of 30 kg P ha^{-1} was included to avoid potential P limitation to maize growth.

In all treatments, slurry was applied at a rate of 100 kg NH_4^+-N ha^{-1}, except for the reference treatment without placed mineral NP starter fertiliser (Non-placed + 0NP), which received slurry at a rate of 120 kg NH_4^+-N ha^{-1}. The same experimental applicator mounted with different injection tines according to the treatment was used. The wheel distance of the applicator was 3 m, which ensured that the plots were unaffected by the slurry tanker wheels.

In all treatments, except the Non-placed + 0NP treatment, 20 kg mineral N ha^{-1} (as ammonium sulphate nitrate) was also placed at the time of sowing. A supplementary broadcast mineral fertiliser dressing of 70 kg N ha^{-1} (as ammonium sulphate nitrate) was applied at the six-leaf stage (V6) in all treatments in 2017. The mineral N fertilisation was omitted in 2018 because of very high growth rates in that period and thus a high risk of harming the plants during the field operation. The total N application rate in 2017 (Table 3) corresponds to the recommended N application rate to maize in Denmark on these soil types, based on the amount of readily available NH_4^+-N in slurry (Landbrugsstyrelsen, 2018).

Maize (cv. Ambition FAO 180) was sown at 5 cm depth in May (Table 4) with a 75-cm row spacing and 13.3 cm between plants within rows using standard equipment for sowing mounted on a tractor.

Herbicides were applied on all plots (Table 4). In 2018, irrigation totaled 100 mm at Foulum in July and 189 mm at Havris from mid-May to early August by using an irrigation sprinkler system.

2.3. Measurements and sampling

At the five-leaf stage (V5), 40 of the youngest fully developed leaves were sampled manually in each harvest plot (Table 4). 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 prior to N and P analyses. Plant height was measured at the seven-leaf stage (V7, Table 4) by measuring the height of four plants per plot 5 m from each end of the harvest plot in two rows.

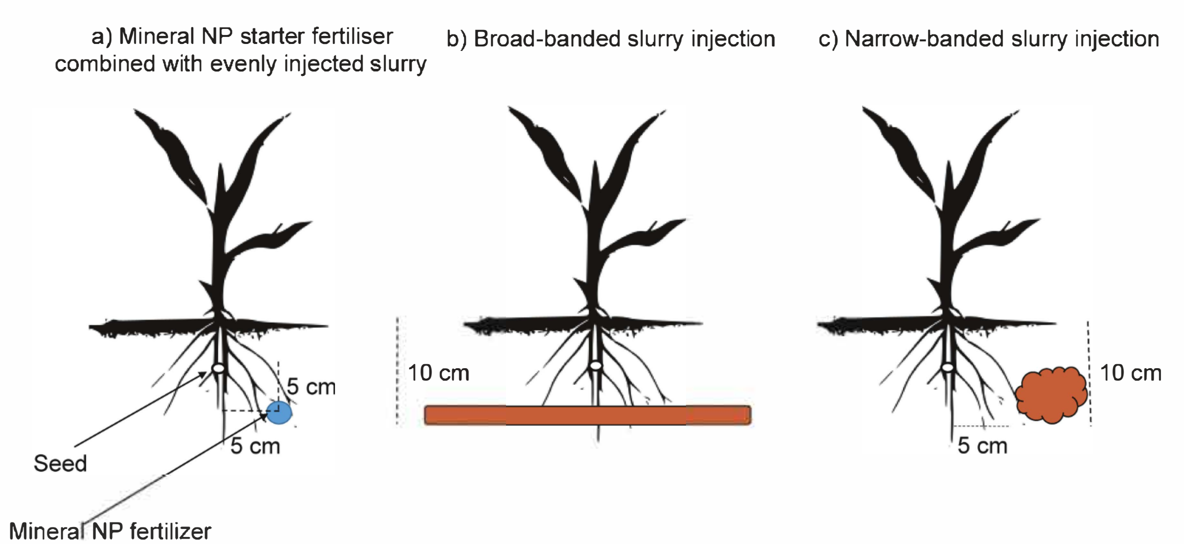

Fig. 2. Schematic view of the fertiliser application methods: a) Placement of mineral starter N and P at sowing (blue circle) in combination with non-placed slurry; b) Broad-band (BB) slurry injection using a 26-cm broad goosefoot tine with a tine distance of 75 cm (one slurry band per row) and c) Narrow-band (NB) slurry injection using a 6-cm narrow S-spring tine with a tine distance of 37.5 cm (two slurry bands per row).

Table 4
Dates of main field operations for each year.

Field operation	2017 Havris/Foulum	2018 Havris/Foulum
Previous crop	Maize/Maize	Rye/Maize
Slurry application, non-placed	08.05	30.04
Ploughing	08.05	03.05/04.05
Slurry application, placed	10.05	03.05/04.05
Sowing + mineral starter N and P	15.05	06.05
Chemical weed control	10.06	25.05/24.05
	Callisto (0.5 L ha^{-1})	Starship (0.5 L ha^{-1})
	MaisTer (50 g ha^{-1})	MaisTer (50 g ha^{-1})
	MaisOil (0.67 L ha^{-1})	MaisOil (0.67 L ha^{-1})
Leaf sampling at V5	16.06/19.06	01.06/04.06
N fertilisation (70 kg N ha^{-1})	26.06/26.06	Not applied
Chemical weed control	27.06	05.06
	Starship (0.5 L ha^{-1})	Callisto (0.5 L ha^{-1})
	MaisTer (50 g ha^{-1})	MaisTer (50 g ha^{-1})
	MaisOil (0.67 L ha^{-1})	MaisOil (0.67 L ha^{-1})
Height measurement at V7	03.07/03.07	12.06/12.06
Harvest	23.10/23.10	-/17.09

For determination of final yields, maize was whole-crop harvested at silage maturity (aiming at a DM content of approximately 32 percent) using a special plot harvester. The DM content was determined on a subsample of approximately 1 kg of the chopped fresh material by drying at 60 °C for 48 h. Half of the dried subsample was ground prior to determination of the total N and P content. In 2018, N and P concentrations at harvest were determined at treatment-level without replicates after unintended pooling of samples from all replicates of each treatment.

2.4. Analytical methods

Leaf P concentration was determined by digesting 1.5 g dried plant material in concentrated hydrochloric acid after ashing at 500 °C. The P concentration in the digest was determined by inductively coupled plasma-optical emission spectroscopy (ICP-OES, Yara, Analytical Services, Pocklington, UK). Leaf N concentration was determined by Kjeldahl digestion.

Total P concentration in harvested plant material of the whole crop was determined by pressurised microwave oven digestion following measurement by ICP-OES (EurofinsAgroTesting, Denmark). Total N was measured by combustion elemental analysis (EurofinsAgroTesting, Denmark). Results are expressed on an oven-dry basis.

2.5. Data calculation and statistics

Data from individual years and sites were analysed using the R-Project software package version 3.4.1 (R Development Core Team, 2015) in linear mixed-effects models from the R-package *lme4* with treatments as a fixed effect and replicate as a random effect. The assumption of homogeneity of variance and normality of residuals was verified using plot of residuals against fitted values and histogram of the residuals. The Dunnett´s test was applied using estimated marginal means from the R-package *emmeans* to compare means of the treatments against the reference treatment Non-placed + 0 P within each year for each location. A three-way analysis of variance (ANOVA) was applied to study the effect of placement method, slurry acidification, addition of a nitrification inhibitor and their interaction on leaf P concentration at V5 and final DM yield. In case of a three-way interaction, differences between treatments with placed slurry within each year for each location were analysed by the Tukey´s honestly significant difference (HSD) using estimated marginal means from the R-package *emmeans*. We examined the relationship between leaf P and N concentrations and height at V7 and DM yield, respectively, by simple linear regression.

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

3. Results

3.1. Nutrient concentrations and height at early growth

3.1.1. Foulum

In 2017, mineral P starter fertiliser increased leaf P concentration at V5 compared to the Non-placed + 0 P treatment (Table 5). Treatments with placed narrow-banded slurry combined with a nitrification inhibitor (NB + NI and NB + SA + NI) and treatments with placed broad-banded slurry combined with slurry acidification or a nitrification inhibitor (BB + SA and BB + NI) had leaf P concentrations that were significantly higher than the Non-placed + 0 P treatment (Table 5). The highest leaf N concentrations were found when the slurry was placed in narrow bands combined with slurry acidification and a nitrification inhibitor (NB + SA + NI) and when the slurry was placed in broad bands combined with slurry acidification (BB + SA, Table 5). Leaf N concentration was significantly related to height at V7 and to final DM yield at harvest (Fig. 3).

In 2018, mineral starter P increased initial leaf P concentrations, when 30 kg P ha^{-1} was applied compared to the Non-placed + 0 P treatment (Table 5). Treatments with placed slurry in narrow bands combined with slurry acidification and a nitrification inhibitor

Table 5
Leaf P and N concentration at the five-leaf stage (V5). Within each column, asterisks indicate significant different leaf P and N concentrations compared the reference treatment *Non-placed + 0 P* (Dunnett´s test, $P < 0.05$). For leaf P concentrations at Foulum, different letters within columns denote statistically significant differences (Tukey, $P < 0.05$). NB: Narrow band row-injection, BB: Broad band row-injection, SA: slurry acidification, NI: Nitrification inhibitor (Vizura ®). The two highest P and N concentrations for each year and location are indicated by bold numbers.

	Leaf P concentration at V5, % of DM				Leaf N concentration at V5, % of DM			
	Foulum		Havris		Foulum		Havris	
Treatment	2017	2018	2017	2018	2017	2018	2017	2018
Non-placed + 0NP	0.29	0.28	0.32	0.23	3.86*	4.98	4.34	4.58
Non-placed + 0 P (ref)	*0.31*	*0.27*	*0.34*	*0.22*	*4.22*	*5.03*	*4.61*	*4.65*
Non-placed + 10P	0.38*	0.30	0.47*	0.26	4.44	5.03	4.87	4.84
Non-placed + 30P	**0.46***	0.34*	**0.55***	**0.37***	4.57*	5.01	4.56	4.97*
NB untreated	0.32c	0.27cd	0.37	0.26	4.49	5.11	4.87	4.90*
NB + SA	0.35abc	0.30bc	0.46*	**0.34***	4.60*	5.26	4.88	5.16*
NB + NI	0.36*abc	0.31*b	0.42*	0.28*	4.72*	5.25	**5.09***	5.05*
NB + SA + NI	**0.40*a**	**0.36*a**	0.48*	0.32*	**4.97***	5.40*	4.84	5.23*
BB untreated	0.33c	0.26d	0.46*	0.30*	4.63*	5.04	**5.14***	5.05*
BB + SA	0.39*ab	0.32*b	0.47*	**0.34***	**5.07***	5.43*	4.97	**5.27***
BB + NI	0.39*ab	0.31*b	**0.49***	0.31*	4.85*	**5.44***	5.13*	5.07*
BB + SA + NI	0.34bc	0.33*b	0.43*	0.33*	4.87*	**5.46***	4.75	**5.36***

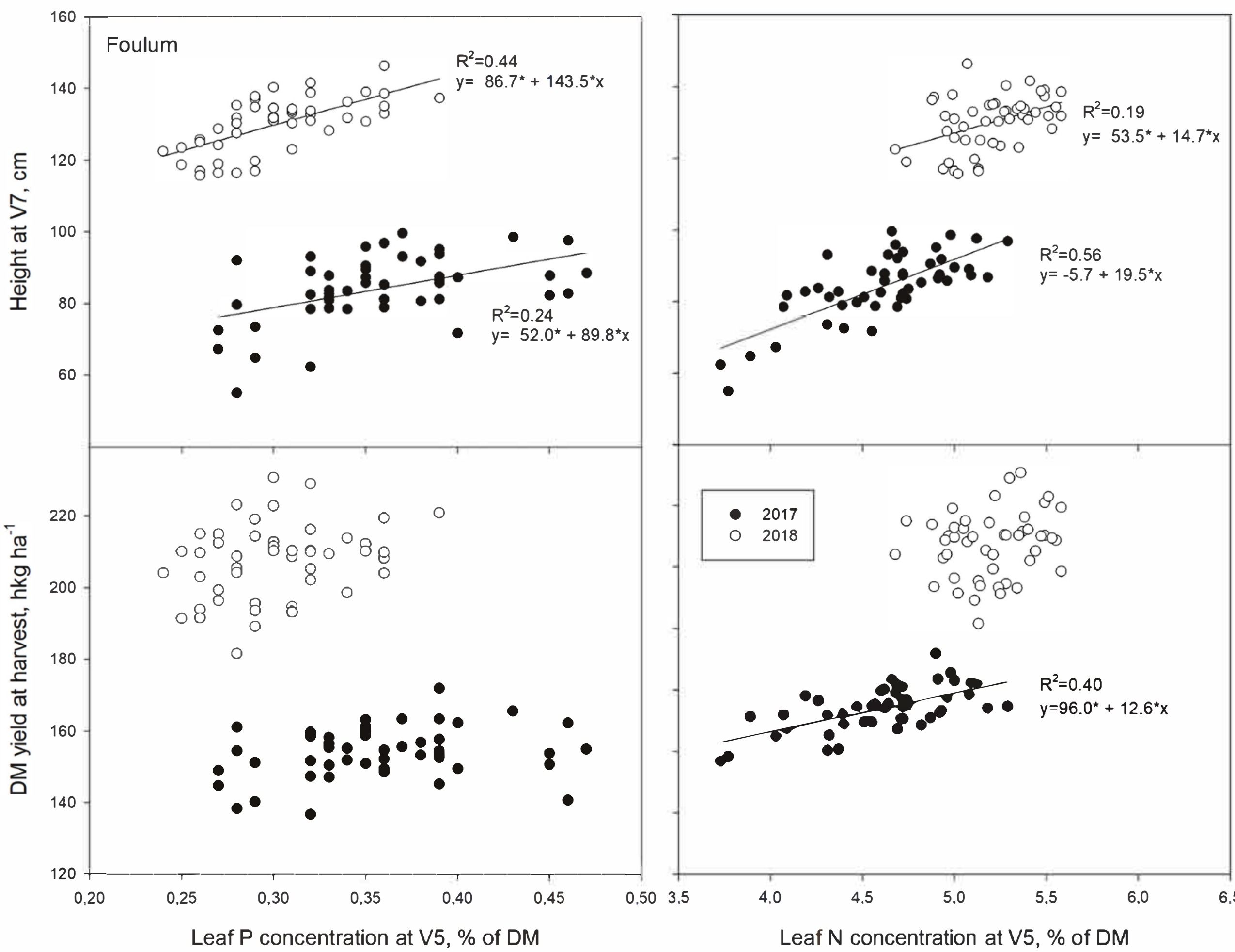

Fig. 3. Leaf P and N concentrations at five-leaf stage (V5) related to height at seven-leaf stage (V7) and DM yield at harvest at Foulum for each year (2017 and 2018). The solid line represents the linear regression for each year, and asterisks (*) indicate significant slopes and intercepts ($P < 0.05$).

(NB + SA + NI) had the highest leaf P concentration (Table 5). There was a strong relationship between leaf P concentration at V5 and height at V7, whereas the link between leaf N concentration at V5 and height at V7 was less pronounced (Fig. 3). In 2018, neither leaf P concentrations nor N concentrations at V5 were significantly related to the final DM yield.

3.1.2. Havris

In 2017, mineral P starter fertiliser increased leaf P concentrations, and treatments with placed slurry had higher leaf P concentrations than the Non-placed + 0 P treatment, except when untreated slurry was injected in a narrow band (Table 5). In non-acidified slurry treatments, BB slurry treatments had higher leaf P concentrations than NB slurry treatments regardless of nitrification inhibitor addition (Table 7). Plant height at V7 was more closely related to the leaf P concentration at V5 than to the leaf N concentrations (Fig. 4). Dry matter yield at harvest was also significantly related to the nutrient concentrations at V5, but less strongly than height (Fig. 4).

Also in 2018, applications of mineral P starter fertiliser increased leaf P concentration (Table 5). All treatments with placed slurry had a higher P concentration than the Non-placed + 0 P treatment except when untreated slurry was placed with narrow-band injection (NB untreated). Higher leaf P concentrations were obtained, when the slurry was placed in a broad band compared to a narrow band, when no nitrification inhibitor was added to the slurry, whereas there was no 'ifference in leaf P concentration between the two placement strategies, en a nitrification inhibitor was added (Table 7). Leaf N concentrations were significantly higher in all treatments with placed slurry than in the Non-placed + 0 P treatment (Table 5). Both leaf P and N concentrations were strongly correlated to the height at V7 (Fig. 4).

3.2. Dry matter yield at harvest

3.2.1. Foulum

In 2017, the effect of mineral P starter fertiliser on DM yields at harvest was insignificant. Contrastingly, the DM yield was significantly higher in some of the treatments with placed slurry than the Non-placed + 0 P treatment (Table 6). The three-way ANOVA revealed that only placement method was a significant factor among the slurry treatments with placed slurry with BB-slurry treatments having a higher DM yield (+0.33 Mg ha^{-1}) than the NB-slurry treatments (Table 7).

Higher DM yields were observed in 2018 than in 2017 (Table 6), coinciding with a mean temperature in 2018 that was much higher than the long-term mean and the temperatures in 2017 (Fig. 1). In 2018, an application of 30 kg P ha^{-1} as starter fertiliser increased DM yield (Table 6) compared to the Non-placed + 0 P treatment. The DM yield was significantly higher for the BB + SA and BB + NI treatments than for Non-placed + 0 P treatment. The multiple pairwise comparison among treatments with placed slurry showed that the BB + SA, BB + NI and the NB + SA + NI treatments had a significantly higher DM yield than the NB untreated treatment (Table 6).

3.2.2. Havris

In 2017, no effect of starter mineral P was observed among the

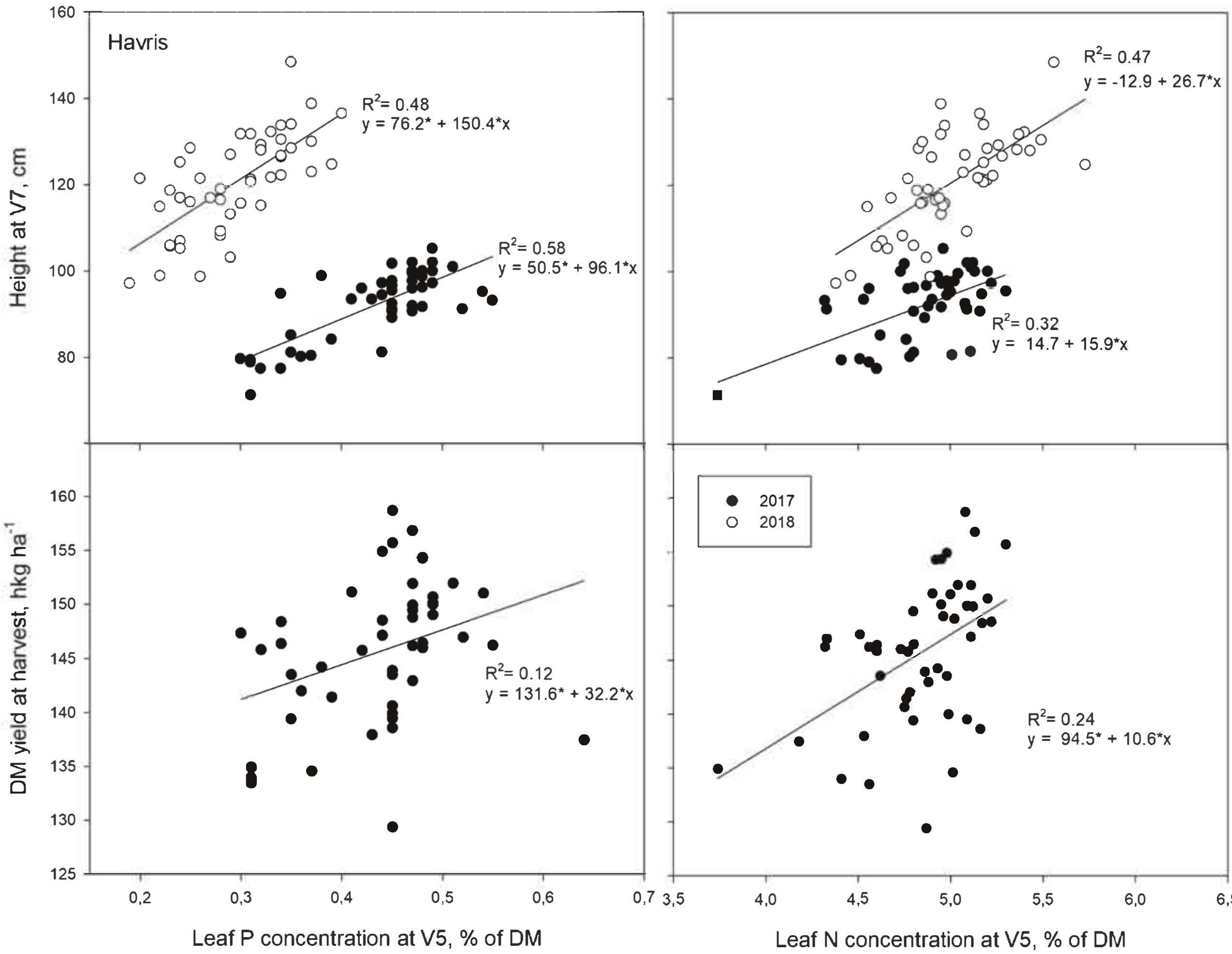

Fig. 4. Leaf P and N concentrations at five-leaf stage (V5) related to height at the seven-leaf stage (V7) and DM yield at harvest at Havris for each year (2017 and 2018). The solid line represents the linear regression for each year, and asterisks (*) indicate significant slopes and intercepts ($P < 0.05$). Alternative regression for the relationship between leaf N concentration and height at V7 in 2017, where the outlier (marked with filled square) is excluded: y = 21.3 + 14.6*x, $R^2 = 0.21$.

Table 6
Maize dry matter yield at harvest at Foulum and Havris. Within each column, asterisks indicate significant higher DM yields than the reference treatment *Non-placed + 0 P* (Dunnett´s test, $P < 0.05$). For 2018 at Havris different letters within columns denote statistically significant differences (Tukey, $P < 0.05$). NB: Narrow band row-injection, BB: Broad band row-injection, SA: slurry acidification, NI: Nitrification inhibitor (Vizura ®). The experiment was not harvested in 2018 at Havris due to corn smut. The two highest DM yields for each year and location are indicated by bold numbers.

	DM yield, Mg ha^{-1}			
	Foulum		Havris	
Treatment	2017	2018	2017	2018
Non-placed + 0NP	14.3	20.1	14.0	n/a
Non-placed + 0 P (ref)	*14.7*	*19.9*	*14.1*	*n/a*
Non-placed + 10P	14.9	20.2	14.4	n/a
Non-placed + 30P	15.0	21.3*	14.4	n/a
NB untreated	15.5	20.7abc	14.2	n/a
NB + SA	15.6	21.1abc	15.0	n/a
NB + NI	15.3	20.3bc	14.8	n/a
NB + SA + NI	15.8*	21.2ab	14.6	n/a
BB untreated	15.6	19.7c	**15.6***	n/a
BB + SA	**15.9***	**21.6*ab**	14.3	n/a
BB + NI	**16.2***	**21.8*a**	**15.1**	n/a
BB + SA + NI	**15.9***	20.8abc	14.3	n/a

reference treatments with non-placed slurry. The DM yield was significantly higher for BB untreated treatment than for the Non-placed + 0 P treatment. The effect of placement method was dependent on the slurry acidification, and for treatments applied with non-acidified slurry, BB row-injection increased DM yield (+0.84 Mg ha^{-1}, Table 7) compared to NB row-injection, whereas no effect of placement method was present for treatments applied with acidified slurry.

In 2018, the maize plants suffered attack of corn smut (*Ustilago maydis*) in late August. The infection rate varied from 10 to 90% among harvest plots, and therefore the final harvest was abandoned.

3.3. P and N uptake and nutrient balances at harvest

In 2017, P uptake at harvest did not differ significantly among treatments and averaged 34.7 and 27.9 kg P ha^{-1} at Foulum and Havris, respectively (Table 8). In 2018, the P uptake averaged 38.6 kg P ha^{-1} at Foulum. Treatment effects could not be tested statistically this year, because the plant material was pooled for each treatment prior to P and N analyses. At both locations, the greatest P surpluses were observed in the non-placed slurry treatments applied with 30 kg mineral starter P ha^{-1} (Table 9). In 2017, the P surplus ranged from -3.3 to 2.0 kg P ha^{-1} and from 5.3 to 10.6 kg P ha^{-1} at Foulum and Havris, respectively, among treatments applied with placed slurry. In 2018,

Table 7
Results of the three-way ANOVA for leaf P concentration and DM yield at harvest and conditional contrasts based on the results from the ANOVA. In case of a three-way interaction, a multiple comparison was performed among the eight treatments with placed slurry (displayed in Table 5 and 6). NB: Narrow band row-injection, BB: Broad band row-injection.

Source of variation	Leaf P concentration at V5, % of DM				DM yield at harvest, Mg ha^{-1}			
	Foulum		Havris		Foulum		Havris	
	2017	2018	2017	2018	2017	2018	2017	2018
Placement method (PM)	ns	ns	**	*	*	ns	ns	–
Slurry acidification (SA)	**	***	*	ns	ns	ns	ns	–
Nitrification inhibitor (NI)	*	***	ns	**	ns	ns	ns	–
PM x SA	*	ns	***	ns	ns	ns	**	–
PM x NI	ns	ns	ns	**	ns	ns	ns	–
SA x NI	*	ns	*	ns	ns	ns	ns	–
PM x SA x NI	***	**	ns	ns	ns	***	ns	–
Conditional contrasts								
Effect of placement method (PM)								
BB vs. NB across NI and SA	–	–	–	–	0.33*	–	–	–
BB vs. NB for SA = yes across NI	–	–	–	–	–	–	-0.47^{ns}	–
BB vs. NB for SA = no across NI	–	–	–	–	–	–	0.84*	–
BB vs NB for SA = yes, NI = yes	–	–	-0.05*	–	–	–	–	–
BB vs NB for SA = yes, NI = no	–	–	0.01^{ns}	–	–	–	–	–
BB vs NB for SA = no, NI = yes	–	–	0.07***	–	–	–	–	–
BB vs NB for SA = no, NI = no	–	–	0.09***	–	–	–	–	–
BB vs. NB for NI = yes across SA	–	–	–	0.02^{ns}	–	–	–	–
BB vs. NB for NI = no across SA	–	–	–	0.03*	–	–	–	–

*, ** and *** indicate significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively. ns, not significant.

more P was removed with the crop than applied with the placed slurry (up to 11.9 kg P ha^{-1} in the NB + SA + NI treatment) at Foulum.

The N surplus ranged from 73 to 104 kg N ha^{-1} and from 85 to 116 kg N ha^{-1} in 2017 at Foulum and Havris, respectively, whereas the N surplus ranged from -33 to +20 kg N ha^{-1} in 2018 at Foulum (Table 9).

4. Discussion

4.1. Effect of mineral P starter fertiliser

The positive response to mineral starter P fertilisation on leaf P concentration was evident at both sites, even though the soils had a moderate P status (Olsen-P contents of 44 and 34 mg P kg^{-1} soil at Foulum and Havris, respectively). Interestingly, leaf P concentrations continued to increase when the amount of mineral starter P increased from 10 to 30 kg P ha^{-1}. The positive effect of mineral starter P on early maize growth and plant tissue P concentration has been found in a number of studies (e.g. Barry and Miller, 1989; Bates, 1971). The typical explanation given for this is that low soil temperatures in humid temperature regions reduce P uptake due to lower diffusion rates and reduced root growth (Grant et al., 2001) and that this can be alleviated by placement of fertiliser P close to the roots. However, we also observed a positive response in leaf P concentration to mineral starter P in 2018, where it was uncommonly warm during early growth. This could be because it was also very dry, which may reduce P mobility in soil (Withers et al., 2014). Haneklaus and Schnug (2016) reported that shoot P concentrations of 0.34 % indicate sufficient P supply, whereas P concentrations of 0.2 % denote severe P deficiency among plants in the grass family (*Poaceae*) including maize. Plants in the Non-placed + 0 P reference treatment had in most cases leaf P concentrations below 0.34 % (Table 5), whereas the plants grown in the Non-placed + 30 P treatments had leaf P concentration above 0.34 %, which indicated sufficient P supply.

The positive initial response to mineral starter P in 2017 disappeared at the final harvest at both sites (Table 6), which shows that the use of mineral starter P was redundant from the farmers' perspective this specific year. Nonetheless, the results support the common

Table 8
N uptake and P uptake at harvest at Foulum and Havris. Within each column, asterisks indicate significant higher N and P uptakes than the reference treatment *Non-placed + 0P* (Dunnett´s test, $P < 0.05$). NB: Narrow band row-injection, BB: Broad band row-injection, SA: slurry acidification, NI: Nitrification inhibitor (Vizura ®).

Treatment	N uptake, kg ha^{-1}				P uptake, kg ha^{-1}			
	Foulum 2017	2018[a]	Havris 2017	2018	Foulum 2017	2018[a]	Havris 2017	2018
Non-placed + 0NP	176	199	164 ns	n/a	33.1 ns	36	29.1 ns	n/a
Non-placed + 0 P (ref)	*180*	*201*	*165 ns*	*n/a*	*34.6 ns*	*38*	*29.0 ns*	*n/a*
Non-placed + 10P	184	204	168 ns	n/a	34.6 ns	47	26.4 ns	n/a
Non-placed + 30P	182	213	163 ns	n/a	35.7 ns	38	25.2 ns	n/a
NB untreated	190	213	164 ns	n/a	36.3 ns	35	28.5 ns	n/a
NB + SA	191	217	169 ns	n/a	38.3 ns	38	28.1 ns	n/a
NB + NI	185	203	172 ns	n/a	33.8 ns	35	28.9 ns	n/a
NB + SA + NI	188	225	162 ns	n/a	34.4 ns	42	27.8 ns	n/a
BB untreated	186	204	180 ns	n/a	33.1 ns	37	28.8 ns	n/a
BB + SA	190	220	162 ns	n/a	33.0 ns	39	24.4 ns	n/a
BB + NI	192*	236	177 ns	n/a	36.5 ns	39	29.0 ns	n/a
BB + SA + NI	186	203	166 ns	n/a	33.0 ns	35	29.7 ns	n/a

o statistics available. ns, not significant.

Table 9
N and P surplus (input minus output in harvested crop) at Foulum and Havris. Within each column, asterisks indicate significant higher N and P surpluses than the reference treatment *Non-placed + 0P* (Dunnett´s test, $P < 0.05$). NB: Narrow band row-injection, BB: Broad band row-injection, SA: slurry acidification, NI: Nitrification inhibitor. The maize plants were not harvested in 2018 at Havris due to extended corn smut decease. The highest and lowest N and P balances for each year and location are indicated by bold numbers.

	N surplus, kg ha^{-1}				P surplus, kg ha^{-1}			
	Foulum		Havris		Foulum		Havris	
Treatment	2017	2018[a]	2017	2018	2017	2018[a]	2017	2018
Non-placed + 0NP	**103.7***	**20.4**	**115.7***	n/a	8.9*	0.4	12.9*	n/a
Non-placed + 0 P (ref)	*85.3*	*1.6*	*99.6*	*n/a*	*0.4*	*−7.5*	*6.0*	*n/a*
Non-placed + 10P	81.0	−1.5	97.1	n/a	10.4*	−6.1	18.6*	n/a
Non-placed + 30P	83.2	−9.7	102.4	n/a	**29.3***	**22.1**	**39.8***	n/a
NB untreated	75.3	−9.9	100.6	n/a	−1.3	−4.7	6.5	n/a
NB + SA	74.2	−13.9	95.5	n/a	**−3.3**	−7.5	6.9	n/a
NB + NI	79.8	−0.2	92.9	n/a	1.2	−4.1	6.1	n/a
NB + SA + NI	76.7	−21.5	102.8	n/a	0.6	**−11.9**	7.2	n/a
BB untreated	79.3	−1.4	**85.4**	n/a	1.9	−6.9	6.2	n/a
BB + SA	75.1	−17.3	103.1	n/a	2.0	−8.4	10.6	n/a
BB + NI	**72.7**	**−32.8**	88.0	n/a	−1.5	−8.9	6.0	n/a
BB + SA + NI	78.7	−0.4	98.8	n/a	2.0	−4.9	**5.3**	n/a

[a]No statistics available.

experience among farmers that mineral starter P most often improves growth of young maize plants, as also reported in other field studies (e.g. Withers et al., 2000). A lack of response in DM yield and P uptake at harvest in spite of significant responses in leaf P concentrations to mineral starter P might also occur when growth conditions later in the growing season favor compensatory growth for plants with reduced early growth, so that the final DM yield at harvest is not affected.

4.2. Effect of slurry placement and row-injection method

Injection of slurry in a broad band resulted in a thin slurry layer at 10 cm depth. Visual inspection of a vertical soil profile immediately after injection indicated that the visible slurry layer was thinner than 1 cm. With narrow-band injection the slurry layer was much thicker and extended upwards.

Placement of injected slurry close to the maize row compared to non-positioned injection of slurry showed beneficial effects on leaf N and P concentrations at V5 and DM yields at both experimental sites (Tables 5 and 6), which is in line with previous studies (e.g. Bittman et al., 2012; Schröder et al., 1997, 2015).

At Havris in 2017, placement of non-acidified slurry with BB injection was superior to NB injection (+0.84 Mg DM ha^{-1}, Table 7), and likewise BB slurry improved DM yield at harvest at Foulum the same year. The better effect of injecting slurry with a 26 cm broad tine below the maize row at 10 cm depth could be due to a larger exposure of nutrients to the young maize roots in the broad slurry band because of the band shape in addition to aeration and loosening of the soil following broad-banded slurry injection. However, a field trial conducted on the Foulum soil in 2016 showed that BB slurry placed at 17 cm depth resulted in low leaf P concentrations at V5 and reduced DM yield at harvest (Pedersen et al., 2020a). This may indicate that slurry was placed at 17 cm depth was too far away from the roots to allow them to benefit sufficiently from the broad-banded slurry.

The slurry dose near the roots was doubled in the broad-banded slurry treatment as a result of the tine distance of 75 cm compared to the narrow-banded treatments, where slurry was applied with a tine distance of 37.5 cm. Hereby, the roots in the NB treatments would reach half of the slurry dose between two rows much later, which may further amplify the superior effect of BB slurry. However, it was not possible to inject the full dose of slurry in the NB treatments with a tine distance of 75 cm, due to the high slurry application rate.

4.3. Effects of slurry acidification and addition of a nitrification inhibitor

The slurry used in 2017 had been stored for more than one year before application. During storage, slurry pH had increased and much more acid was needed to reach a pH of 5.8 than in 2018 (Table 3). This increase in pH during storage was most probably a result of microbial decomposition and CO_2 release. When released CO_2 is dissolved in the slurry as bicarbonate, it binds hydrogen ions and causes pH to increase (Sommer and Husted, 1995). The properties of this slurry were similar to those of anaerobically digested manures, which also have a high pH, high carbonate content and low content of decomposable organic matter. Despite different slurry compositions in the two years, the effect of the slurry acidification was evident in both years. Slurry acidification increased both P and N concentrations at V5, implying that slurry acidification affects both P and N availability in line with a previous study by Pedersen et al. (2017). A recent study by Li et al. (2019) showed that acidified cattle slurry (pH = 5.5) has a much higher content of finer inorganic P fractions (< 45 μm) than untreated slurry. The finer inorganic P fractions were found to be less prone to leaching compared to particulate fractions, which constituted the major part of total P in untreated slurry (Li et al., 2019). Despite reduced P leaching potential after slurry acidification, it is still important that the increased content of dissolved P in cattle slurry after acidification is placed close to the roots to ensure plant uptake of P, as the greater content of dissolved P will rapidly be sorbed onto non-calcareous soil particles at a low pH (Gustafsson et al., 2012). We cannot rule out that the high S input via the acidified slurry in 2017 might have given rise to an extra S fertilisation effect, but since cattle slurry normally contains some available S and all treatments this year also received S via the supplementary broadcast mineral fertiliser, we surmise the S fertilisation effect from the acidified slurry to be of minor importance.

Some studies report increased biomass production and N uptake during early growth after addition of a nitrification inhibitor (e.g. Federolf et al., 2016), while a number of studies could not detect any effects on harvest yields (e.g. Sawyer et al., 1991; Tauchnitz et al., 2018). A positive effect of the nitrification inhibitor on DM yields at Foulum in combination with BB injection was demonstrated in 2018. The benefits of nitrification inhibitors have been ascribed to a lower risk of nitrate leaching (Westerschulte et al., 2016) and lower N_2O emissions, which may improve the N use efficiency (Ruser and Schulz, 2015). Moreover, NH_4^+-N fertilisation with addition of a nitrification inhibitor in combination with a P source has been shown to increase the P uptake in young maize plants due to a pH decrease in the rhizosphere following NH_4^+-N uptake (Ma et al., 2013; Pedersen et al., 2018b). This mechanism may also explain the positive effect of adding a nitrification inhibitor to the slurry found in the present study. The present study also shows that a positive effect of a nitrification inhibitor was only achieved, when the full slurry dose was injected with a goosefoot tine below the row. This reaffirms that sufficient rates of NH_4^+-N and dissolved P have to be applied close to the root for the plant to benefit from the enhanced availability of these nutrients.

Both slurry acidification and addition of nitrification inhibitor could increase leaf P concentration at V5, and it is possible that similar mechanisms were involved. In fact, slurry acidification may also inhibit or delay nitrification (Fangueiro et al., 2010), which potentially could increase NH_4^+-N uptake.

4.4. Early growth related to final yields

It has been shown that leaf P concentrations represent the concentration in the whole shoot at V5 (Pedersen et al., 2018a). The leaf P concentration measured in these field trials could therefore be used as a proxy for the shoot P concentration in the early growth stages. Barry and Miller (1989) showed that maximum maize grain yields were associated with shoot P concentration at V6 of 0.5 % or higher. We observed P concentrations larger than 0.5 % in 2017 in treatments receiving non-positioned slurry in combination with 30 kg mineral starter P ha^{-1}. Interestingly, the highest DM yields at harvest were not obtained in these treatments, revealing that high initial P concentrations in the plant do not always turn into extra yields at harvest. Bates (1971) also reported that the main effect of placed inorganic N, P and potassium (K) in 22 field trials was a kick-start to early growth and development, but that this did not necessarily turn into increased grain yields. Late-season stress unrelated to P supply such as a drought during the reproductive growth stages can restrict harvest yield, so that the yield potential obtained by an optimal early season P supply is not fully realised (Grant et al., 2001). Phosphorus deficiencies on the other hand can set a limit to the maximum potential yield at harvest (Barry and Miller, 1989), which suggests that a sufficient P supply in the early growth stage is a prerequisite for obtaining maximum yields, but that there is no guarantee.

Surprisingly, the P uptake at harvest did not differ between the years within each site. The similar maize P uptakes irrespective of yield, treatment and year indicate that the synchronisation of P supply in relation to crop demand is more important to the final yield than the final P uptake itself. The P uptake in the present study was higher than P uptake rates reported in other field trials with maize (Bittman et al., 2012; Withers et al., 2000).

In some trials (e.g. Foulum in 2017, Fig. 3), the leaf N concentration at V5 was more closely correlated to the subsequent growth and DM yield than the leaf P concentrations. This is in line with results reported in Sawyer et al. (1991). In other studies, a close link between shoot P concentration and final maize yields has been found (e.g. Barry and Miller, 1989). These findings suggest that it may vary between years and sites as to whether the positive effects of placed slurry is a result of improved availability of slurry P or N or a synergy effect of the two nutrients.

4.5. Nutrient balances and practical implications

When non-positioned injected slurry was combined with mineral starter P fertilisation, the P surplus was as high as 40 kg P ha^{-1} confirming that accumulation of P can be a problem on intensive livestock farms with maize cropping. Farmers in Canada and in Northwestern Europe have been advised to apply mineral P fertiliser in addition to animal manure in maize cropping to reduce the risk of an insufficient P supply (e.g. Grant et al., 2005; Withers et a. 2000). However, this insurance-based philosophy for P fertilisation is questionable due to the environmental impacts (Withers et al., 2015). The slurry P input fully matched the crop P uptake at Havris, and at the Foulum site high silage maize yields could be obtained even with a negative P balance. Addition of mineral starter P increased substantially the P surplus, and with P surpluses continuing in the long term, this can cause accumulation of P in soil with associated adverse environmental effects.

The large N surplus in 2017 at both sites demonstrated that crop N demand was lower than the fertiliser N input, and this could increase the risk of NO_3^--N leaching. In 2018, slightly more N was removed than applied to the crop (Table 9), which could be due to omission of supplementary broadcast mineral fertiliser dressing of 70 kg N ha^{-1} at V6 this year in combination with a high N uptake. The DM yield at harvest in 2018 was higher than in 2017, which indicates that the plant growth was not severely limited by N in 2018 despite the lower N fertiliser input, probably because the plants were able to benefit from the soil N pool. The high DM yields in 2018 at Foulum were related to the uncommonly high temperatures in May, June and July (Fig. 1), which were favorable for maize growth.

In the present study, we observed no adverse effects of placed slurry on growth of young maize plants, which agrees with some earlier studies (e.g. Bittman et al., 2012). However, some studies report restricted maize root growth near the slurry zone (Pedersen et al., 2020b; Sawyer and Hoeft, 1990). For that reason appropriate injection machinery should ensure precise depth control to safely avoid slurry being placed too close to the maize seed.

5. Conclusions

Placement of cattle slurry in combination with slurry acidification or addition of a nitrification inhibitor increased the initial leaf P concentrations, which could be as high as when mineral P starter fertiliser was applied. However, increased leaf P concentration at the early growth stage did not always result in yield increases at harvest. At both locations, the highest dry matter yields were obtained when slurry was placed in a broad band below the maize row, but on the Foulum site only if the broad-banded slurry was combined with a nitrification inhibitor or slurry acidification. Farmers on intensive livestock farms can hereby reduce their expenditure on mineral P fertiliser and at the same time reduce the P surplus on the fields without compromising final yields in silage maize cropping.

CRediT authorship contribution statement

Ingeborg F. Pedersen: Conceptualization, Formal analysis, Methodology, Visualization, Writing - original draft. **Gitte H. Rubæk:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Tavs Nyord:** Conceptualization, Methodology, Resources. **Peter Sørensen:** Conceptualization, Funding acquisition, 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.

Acknowledgements

We thank the technical staff, especially Jens Bonderup Kjeldsen, Arne Grud, Tiina Pedersen, Marianne Ahrenfeldt M Stevenson at the Department of Agroecology, Aarhus University, and Peter S. Nielsen at the Department of Engineering, Aarhus University for technical assistance. The study was financially supported by the Ministry of Environment and Food of Denmark (Green Development and Demonstration Programme (GUDP) project “Gylle-IT”).

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