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REGULAR ARTICLE

Placement depth and distribution of cattle slurry influence initial maize growth and phosphorus and nitrogen uptake

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Abstract

Background: Placed cattle slurry (CS) provides essential nutrients such as nitrogen (N) and phosphorus (P) to young maize (*Zea Mays* L.) plants and may substitute the use of mineral starter fertilizers. However, placement depth and distribution of slurry may influence the plant growth response.

Aims: The objective was to evaluate the effects of slurry placement depth and distribution on initial maize growth, and N and P uptake on loamy sand and coarse sandy soil.

Methods: In a pot experiment, CS spiked with $(^{15}NH_4)_2SO_4$ was placed either 2, 5, or 8 cm below the seed in a thick layer covering 50% of the central pot area or 5 cm below the seed in a thinner layer covering the whole pot area.

Results: In the loamy sand soil, maize biomass and P uptake at the five-leaf stage were higher when slurry was placed in a thick-centered layer 2 or 5 cm below the seed than at 8 cm. In the coarse sandy soil, maize biomass increased by 21%, when slurry was placed in a thinner layer covering the whole pot area, compared to slurry placed in a thick layer, whereas slurry placement depth had no effect on this soil type. Nitrogen use efficiency (NUE) and ^{15}N recovery (^{15}NRE) were not affected by slurry placement depth, but the application of slurry in the thick layer increased NUE and ^{15}NRE in loamy sand soil as compared to the thin slurry layer at the same depth.

Conclusions: Placed CS could replace starter N and P fertilizer for the early growth of maize. The beneficial effect of placed slurry depended on slurry placement depth in the loamy sand soil and slurry distribution in the coarse sandy soil, and distribution of slurry in broader bands seems a promising strategy in coarse sandy soils.

KEYWORDS
^{15}N-labeling, nitrogen use efficiency, slurry distribution, slurry to seed distance, root distribution and growth

1 | INTRODUCTION

Among cereal crops, maize (*Zea Mays* L.) occupies the second-largest area globally (FAOSTAT, 2019). It is expected that the demand for maize will increase further due to similar yields as highly productive grass and since it is a treasured feed for livestock and substrate for bioenergy (Baral et al., 2019; Manevski et al., 2017). The deficiency of plant nutrients such as nitrogen (N) and phosphorus (P) at early growth stages may limit maize yields. Ammonium-N has limited mobility in soil due to adsorption, but after nitrification to nitrate-N, it becomes mobile in soil (Giehl & von Wirén, 2014). In contrast, P is more immobile in soil, and often N and P fertilizers are placed near to the maize seeds at sowing as a starter fertilizer to avoid the reduction in maize yield due to P deficiency at early growth stages (Grant et al., 2001; Lauzon

& Miller, 1997; Westerschulte et al., 2018). Rock phosphate, which is the source for mineral P, is a non-renewable resource, and excessive P applied with manure and mineral fertilizers on many farms may cause environmental problems by increased P losses to aquifers (Sørensen & Jensen, 2013). A better utilization of manure P would thus be beneficial to avoid excessive build-up of P reserves in soils (Withers et al., 2019).

Animal manures are rich in N and P and have the potential to replace mineral starter fertilizers *via* precision application techniques. Positive effects of slurry placement on N and P use efficiency (NUE and PUE) in maize have already been shown in different field trials (Eghball et al., 2005; Pedersen et al., 2017; Schröder et al., 2015; Westerschulte et al., 2017; Tauchnitz et al., 2018). Several studies reported that P uptake can be improved by precision placement of manure close to the seed (Bittman et al., 2012; Pedersen et al., 2017) because placement alleviates the problems related to the immobility of P in soil (Chatterjee et al., 2014; Ma et al., 2013). Slurry placement close to the maize seeds (≈ 5 cm below and beside) may ensure proper early contact between lateral roots and P fertilizer (Bittman et al., 2012). However, a major challenge associated with the placement of slurry near the seeds is the potential toxic effect of slurry for early root growth and development. The unfavorable environment for root growth may arise from combinations of high ammonia, moisture or nitrite concentrations (Sawyer et al., 1990), changes in pH (Whalen et al., 2000), and depletion of oxygen during slurry decomposition (Petersen et al., 1996; Sawyer et al., 1990). In contrast, the placement of slurry far from maize seeds reduces final dry matter yields (Pedersen et al., 2020a). Therefore, the optimum vertical distance between seeds and slurry needs to be determined to avoid toxicity and improve early growth and final yields in maize.

In a pot experiment, on a coarse sandy soil, Pedersen et al. (2020) applied cattle slurry (CS) at different vertical distances to the maize seeds covering the whole soil area in pots. They observed that the placement of slurry 1.5 cm below the seed restricted growth of the primary root and lowered the early plant biomass production. Root injuries may be avoided by allowing the root to grow outside the highly concentrated slurry layer. On the other hand, Pedersen et al. (2017) showed that maize plants might benefit from CS placed in a broad band. Since the turnover of slurry components (e.g., organic and mineral N, P, carbon, sulfur), root development, and nutrient uptake may depend on soil properties (Fang & Su, 2019), the importance of slurry placement depth and width of the slurry layer may also differ among soil types. Therefore, a pot experiment was conducted under climate-controlled conditions using two soil types: loamy sand and coarse sandy soil. These soils are commonly used for maize cropping in Northern Europe. We assessed the effect of the vertical distance between CS and maize seeds and the effect of thick versus thinner slurry layers on the early growth of maize as well as on N and P uptake. We hypothesized that: (1) placement of slurry close to the seed reduces root and shoot biomass, (2) plant growth benefits from slurry placed in a thick layer covering 50% of the central pot area instead of the entire pot area, allowing roots to evade the slurry layer but still benefit from the nutrients in the slurry, and (3) CS can substitute mineral N and P as a starter fertilizer, leading to similar biomass production by proper placement.

TABLE 1 Selected properties of soils used in the experiment

	Unit	Loamy sand	Coarse sand
Texture			
Clay (< 2 μm)	%	8.6	3.2
Silt (2–63 μm)	%	12.0	5.2
Fine sand (63–200 μm)	%	46.6	16.1
Coarse sand (200–2000 μm)	%	32.8	75.5
Total nitrogen (N)	g kg^{-1}	1.15	1.19
Ammonium (NH_4^+-N)	mg kg^{-1}	0.02	0.01
Nitrate (NO_3^--N)	mg kg^{-1}	1.8	3.4
Total carbon (C)[a]	g kg^{-1}	14.4	12.3
Bicarbonate-extractable phosphorus (P; Olsen-P)	mg kg^{-1}	59	40
pH (KCl)	–	4.7	5.0
Water holding capacity	g g^{-1}	0.26	0.24

[a]Soils carbonate content is very low and thus total organic C (TOC) and total C are identical.

TABLE 2 Properties of cattle slurry (CS) used in the experiment

	Unit	CS
Dry matter	g kg^{-1}	86.0
Total N	g kg^{-1}	3.3
Ammonium-N	g kg^{-1}	1.6
Total P	g kg^{-1}	0.61
pH		7.9

2 | MATERIAL AND METHODS

2.1 | Soils and manure

Two soil types were used in a pot experiment (Table 1), loamy sand and coarse sandy soil. The soils were collected from the plow layer in arable fields at Foulumgaard (56°30′N, 9°35′E) and Jyndevad (54°90′N, 9°13′E) experimental stations, Aarhus University, respectively. These soils had sufficient extractable P (Olsen-P) for plant growth and development according to common recommendations (Jordan-Meille et al., 2012). After collection, the soils were sieved (6 mm) to remove large stones and plant residues and then homogeneously mixed.

Fresh CS (Table 2) was collected from a storage tank at Research Center Foulum, five weeks before the start of the experiment and stored at 2°C until it was applied. Prior to application, the ammonium (NH_4^+-N) pool of the CS and an ammonium sulfate [$(NH_4)_2SO_4$] fertilizer was enriched to 0.608% and 0.696% atom fraction ^{15}N, respectively, by adding $(^{15}NH_4)_2SO_4$ (60% atom fraction ^{15}N). A nitrification inhibitor Vizura® (BASF) with the active compound 3,4-dimethylpyrazole phosphate (DMPP) was added to the slurry at a rate of 2 L 50 Mg^{-1} slurry, resulting in 4.5 mg DMPP pot^{-1}, except in

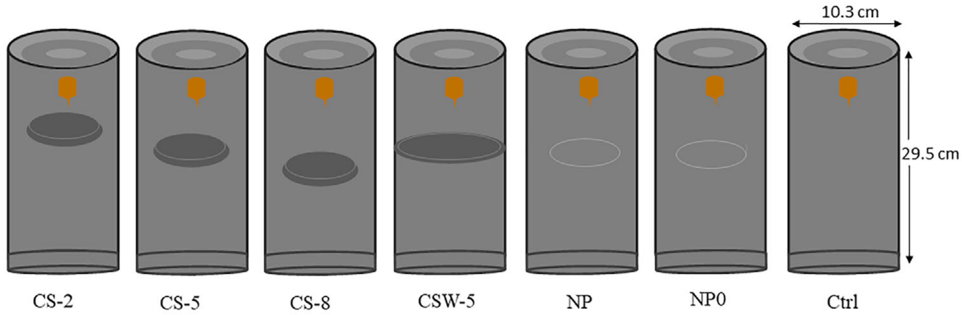

FIGURE 1 Experimental setup. Liquid cattle slurry (CS) was applied at 2cm below the seed, covering the central 50% of the pot area (CS-2); 5 cm below the seed covering center 50% pot area (CS-5); 8 cm below the seed covering center 50% pot area (CS-8); 5 cm below the seeds covering whole soil area (CSW-5); application of mineral nitrogen (N) and phosphorus (P) fertilizer (NP); application of only N fertilizer (NP0), and without N and P amendment (Ctrl).

control treatment. A similar rate of DMPP was added with the $(NH_4)_2SO_4$ fertilizer.

2.2 | Experimental setup

In a pot experiment, CS was placed 2, 5, or 8 cm below maize seeds covering 50% of the central pot area or the whole area of the pots (83.3 cm^2). Slurry covering 50% of the central pot area simulated slurry placement with a narrow-bandwidth (thick layer), which could allow roots to evade the slurry layer if the slurry zone was unfavorable for root growth. Slurry covering the whole area should represent slurry placement with a broad band-width (thinner layer). This treatment was supposed to simulate conditions by injection in a 30 cm broad layer using a goosefoot as tested by Pedersen et al. (2020b). The experiment was conducted in a climate-controlled chamber as a completely randomized design with four replicates. The pots were arranged in four blocks; the position of pots was randomly changed within each block every second day to minimize positional effects. For each soil type, the following treatments (Figure 1) were applied:

- CS-2: CS applied 2 cm below the seed, covering the central 50% of the central pot area.
- CS-5: CS applied 5 cm below the seed, covering the central 50% of the central pot area.
- CS-8: CS applied 8 cm below the seed, covering the central 50% of the central pot area.
- CSW-5: CS applied 5 cm below the seed, covering the whole pot area.
- NP: Mineral fertilizer applied equal to slurry NH_4^+-N and total P at 5 cm below the seed, covering center 50% of the central pot area.
- NP0: Mineral fertilizer applied equal to slurry NH_4^+-N at 5 cm below the seed, covering center 50% of the central pot area.
- Ctrl: Reference with no amendment.

Sieved soils were packed in 29.5 cm high polyvinyl chloride (PVC) cylinder (10.3 cm inner diameter) leaving ≈ 2 cm on top for watering and 2 cm below for plastic caps (Figure 1). The loamy sand and coarse sandy soils were packed to densities of 1.27 and 1.23 g cm^{-3}, respectively, to simulate field conditions. The soil for each pot was divided into three portions. The first portion was filled to the lower 12.5 cm, the second portion up to the slurry application layer, which was an additional 6 cm for CS-2, and 3 cm for CS-5, CSW-5, NP, and NP0 treatments, and the final portion after fertilization. Fertilizers (both slurry or mineral fertilizer) and seed distance were measured from seed to upper part of the fertilizers. After fertilization, a part of the remaining soil was added immediately to reduce the volatilization loss of NH_4^+-N, but compression was delayed by 1 h to avoid spreading of slurry out of the designated area. A nylon mesh (8 mm mesh size) at the top of the slurry layer was used as a marker for later identification of the position of the fertilizer application.

For pots receiving slurry, 91 g slurry pot^{-1} was applied in a ≈ 22 mm thick layer covering 50% of the central pot area (CS-2, CS-5, and CS-8 treatments) or in a ≈ 11 mm thick layer covering the entire pot area (CSW-5 treatment). The ≈ 11 mm thickness of slurry is the expected average thickness in practice when applying a realistic rate of 45 Mg slurry ha^{-1} (corresponding to 27 P ha^{-1}) by broad banding in 30 cm broad bands with 75 cm distance between maize rows (Pedersen et al., 2020). The 22 mm thickness would be achieved by application of the same amount of slurry in 15 cm broad bands under each plant row. By the latter treatment, there will always be less than 7.5 cm from the seed to the edge of the slurry band. As a result, each pot received 146 mg NH_4^+-N, 56 mg P, and 140 mg potassium (K). The mineral fertilizer treatments received, N (as $(NH_4)_2SO_4$), P [as potassium dihydrogen phosphate (KH_2PO_4)], and K [as potassium sulfate (K_2SO_4)] in an aqueous solution at similar rates as in the slurry treatments. For all pots, manganese, zinc, boron, copper, cobalt, and molybdenum were applied with irrigation water 10 days after sowing at a rate of 1.15, 0.85, 0.16, 0.48, 0.01, 0.19 mg kg^{-1} dry soil, respectively. Soil moisture was maintained at 60% water holding capacity (WHC) of the pots during the initial 3 weeks, at 70% WHC for the following 2 weeks, and then at 75% WHC until harvest. The soil moisture was adjusted by gravimetric method adding demineralized water in 2-day intervals.

Hybrid maize seeds (cv. Conclusion, FAO 190) were soaked in a wet-paper towel 2 days after slurry application to simulate a realistic timing between manure application and sowing. To synchronize the emergence of plants, sprouted seeds with uniform radicles were planted at 3 cm below the soil surface with the embryo facing upward. The pots were placed in a greenhouse until maize seed plumules appearance on the surface and then transferred to a climate chamber. The average daily temperature, relative humidity, and light intensity of the climate chamber were adjusted to 15°C, 75%, and 385 μmol photons m^{-2} s^{-1}, respectively (Figure S1). The air temperature increased by 0.1°C d^{-1} starting 10 days after sowing.

2.3 | Plant and soil sampling

The maize plants were harvested 47 days after planting at five-leaf stage (V5) by cutting 1 cm above the soil surface. The biomass was chopped and oven-dried at 60°C until constant weight.

After the removal of aboveground biomass, the soil columns were pushed out of the pots using a hydraulic pusher. Each soil column was divided into three layers; the first layer corresponded to the top 0–5 cm, the second layer to the middle 5–16 cm, and the third to the 16–25 cm layer. The middle layer was further divided into three subsections. First, a sample was collected from the fertilizer placement area by inserting a 5 cm long PVC cylinder with a diameter of 7.3 cm starting at the nylon net marking the top of the slurry layers. The cylinder had the exact diameter of the slurry patch, covering 50% of the central area of pots (hereafter, “inside ring”). A second sample was obtained from the soil outside the inserted cylinder (hereafter, “outside ring”), and the remaining soil in the 5–16 cm column was collected as a separate sample (hereafter, “middle 5–16 cm”). The soil samples were stored at 2°C until the separation of root and soil.

Within 2 days after harvest, roots were separated from soil by sieving (2 mm). Subsequently, the roots were washed with water placing in a 200-μm sieve. Soil, stones, and particulate organic matter were removed with the help of forceps and repeated decantation. Roots were oven-dried for three days at 60°C.

2.4 | Soil analyses

Immediately after the separation of roots from the soil, a subsample of the sieved soil was used for extraction of mineral N ($NH_4^+ + NO_3^-$), soil pH, and soil water content. Approximately 10 g soil subsamples were transferred to 50-ml extraction tubes followed by 40 mL potassium chloride (KCl; 2 M) solution and then shaken end-over-end at 25°C at 32 rpm for 60 min. Soil pH was measured in the suspension of soil and KCl with a pH meter (CyberScan PC 300, EUTECH Instruments). The suspension was filtered through 1.6-μm glass microfibre filters (VWR Int.) and the filtrate was stored at –18°C until analyzed. Soil mineral N concentrations were analyzed by flow analysis (Auto Analyzer III, Bran + Luebbe GmbH) using standard colorimetric methods. Gravimetric soil water content was determined in separate 10 g subsamples after drying at 105°C for 24 h.

2.5 | Plant analyses

The aboveground plant material was ground to < 0.8 mm using a grinding mill (SM 2000, Retsch GmbH) for total P determination. Total P content was determined by digesting 300 mg plant material with 3 mL hydrogen peroxide and 6 ml nitric acid in a microwave digestion system (Anton Paar GmbH). The digestate was diluted with ultra-pure water, and P concentrations were measured using inductively coupled plasma-optical emission spectroscopy (iCAP 6000, Thermo Fisher Scientific).

For total N and ^{15}N determination, plant material was further ground by ball milling (MM 400, Retsch GmbH), and approximately 3 mg of the finely milled samples were packed in tin capsules (5 × 9 mm; S€ANTIS Analytical AG). Analyses of total N and ^{15}N were done using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd.) at the Stable Isotope Facility, University of California, Davis.

2.6 | Calculations and statistics

The percentage of ^{15}N derived from applied $^{15}NH_4^+$-N fertilizer (N*dff*) in shoot biomass was calculated as

$$Ndff\ (\%) = \frac{a-c}{b-c} \times 100, \tag{1}$$

where *a* is the atom fraction ^{15}N of maize in the treatment plots, *b* represents the atom fraction ^{15}N of the labeled NH_4^+-N pools, and *c* represents atom fraction ^{15}N in the reference maize grown without amendment.

The percentage of ^{15}N-labeled fertilizer recovery (^{15}NRE) by maize was calculated as

$$^{15}NRE\,(\%) = \frac{N\ Uptake \times \%Ndff}{N\ applied} \times 100, \tag{2}$$

where *N uptake* is N uptake by maize and *N applied* is NH_4^+-N content of ^{15}N-labeled fertilizer.

Nitrogen use efficiency (NUE) and phoshorus use efficiency (PUE) of maize were calculated according to

$$UE_x\ (\%) = \frac{Uptake_x - Uptake_{Ctrl}}{Total_x} \times 100, \tag{3}$$

where $Uptake_x$ and $Uptake_{Ctrl}$ are, respectively, the uptake of N or P in the fertilized and unfertilized control treatment by maize. $Total_x$ is the total amount of N or P in applied fertilizers.

Statistical analyses were performed using the R-software version 3.4.2 (R Core Team, 2018). Data were analyzed with a linear mixed effect (*lme*) model under the *nlme* package using the restricted maximum likelihood method. Replicates were treated as a random factor. The model assumptions, normality of residuals, and homogeneity of variance, were tested using diagnostic plots. Aboveground biomass and root density data were log-transformed before analysis due to violation of the model assumptions. Mean differences between treatments

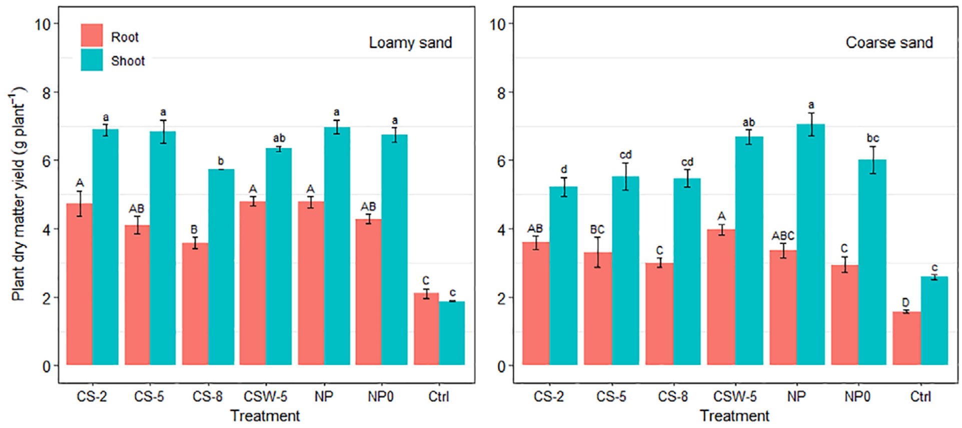

FIGURE 2 Maize shoot and root dry matter yield at the five-leaf stage (V5) in the loamy sand and coarse sandy soil. Bars represent mean and the error bars represent standard errors ($n = 4$). Different letters represent the significant difference ($p < 0.05$) within the shoot and root biomass. Refer to Figure 1 for treatment abbreviations.

were tested using the Tukey HSD method available in function *lsmeans*, where $p < 0.05$ was used as the threshold for hypothesis rejection.

3 | RESULTS

3.1 | Maize shoot and root biomass

On the loamy sand soil, the root and shoot biomass did not differ in the NP and NP0 treatments (Figure 2) suggesting that placement of mineral P fertilizer did not significantly affect early maize growth on this soil. Slurry placed at 2 and 5 cm depth covering 50% of the central pot area resulted in similar shoot biomasses, while placement at 8 cm depth resulted in lower shoot biomass, compared to the mineral fertilized treatments and treatments with slurry placed closer to the seed. Root biomass was also lower when slurry was placed 8 cm below the seed than CS-2 and NP treatments. Slurry placed in a layer 5 cm below the seed covering the entire pot area had a similar shoot and root biomass as the slurry placed at the same depths or closer to the seeds covering 50% of the pot area, and thereby thick layers and mineral fertilizers. On the coarse sandy soil, the shoot biomass was higher in the NP treatment than in the NP0, CS-2, CS-5, and CS-8 treatments. When slurry was placed 5 cm below the seed, the shoot biomass benefitted from slurry placed in a layer covering the entire pot area (CSW-5), compared to the slurry covering 50% of the pot area (CS-5), and shoot biomass was similar to the treatment with mineral NP fertilizer. For slurry placed in a thick layer covering 50% of the central pot area, placement depths did not influence shoot biomass on the coarse sandy soil, though higher root biomass was observed in CS-2 than CS-8 treatment.

3.2 | Root distribution

Root density was significantly different among soil layers, soil types, and fertilizer treatments. The density was higher outside the ring than inside irrespective of fertilizer treatments and soil type (Figure 3). On the coarse sandy soil, root density outside the ring was higher in treatments receiving slurry than in the mineral fertilizer treatments (NP and NP0), whereas the root density did not differ among fertilized treatments on the loamy sand. On both soils, the root density was higher in the middle 5–16 cm layer when slurry was applied in a thinner layer (CSW-5 treatment) than in a thick layer (CS-5 treatment). In general, root densities decreased with increasing distances between seed and slurry in both soils, excluding the bottom 16–25 cm layer.

3.3 | N and P uptake

On both soil types, N concentrations in shoots were higher for treatments receiving slurry than for treatments receiving mineral fertilizers, with lower N concentrations in the loamy sand than the coarse sandy soil (Table 3). On the loamy sand, shoot N uptake was the highest for treatments with slurry placed in a thick layer regardless of placement depth in comparison to slurry placed in a thinner layer, whereas shoot N uptake was highest in the two treatments with slurry placed 5 cm below the seed (i.e., CS-5, CSW-5) on the coarse sandy soil.

NUE ranged from 34% to 39% after slurry application and 53% to 59% after mineral fertilizer application on the loamy sand. The NUE was 30%–35% for slurry and 48%–56% for mineral fertilizer on the coarse sandy soil (Table 3). Based on the recovery of labeled N, slurry contributed 34% to 36%, while mineral fertilizer contributed 43% to 46% in the shoot biomass N. Recoveries of labeled N (NREs) from applied fertilizers in shoots ranged from 31% to 36% across both soil types (Table 3).

P uptake by maize plants and PUE were significantly higher on the loamy sand than on the coarse sandy soil. On the loamy sand soil, P uptake and PUE increased with slurry application closer to seeds covering 50% of the central pot area. Shoot P uptake and PUE were also higher when slurry was placed in a thick layer covering 50% of the central pot area than when placed in a thinner layer covering the whole pot area (CSW-5), but the trends were not consistent in the coarse

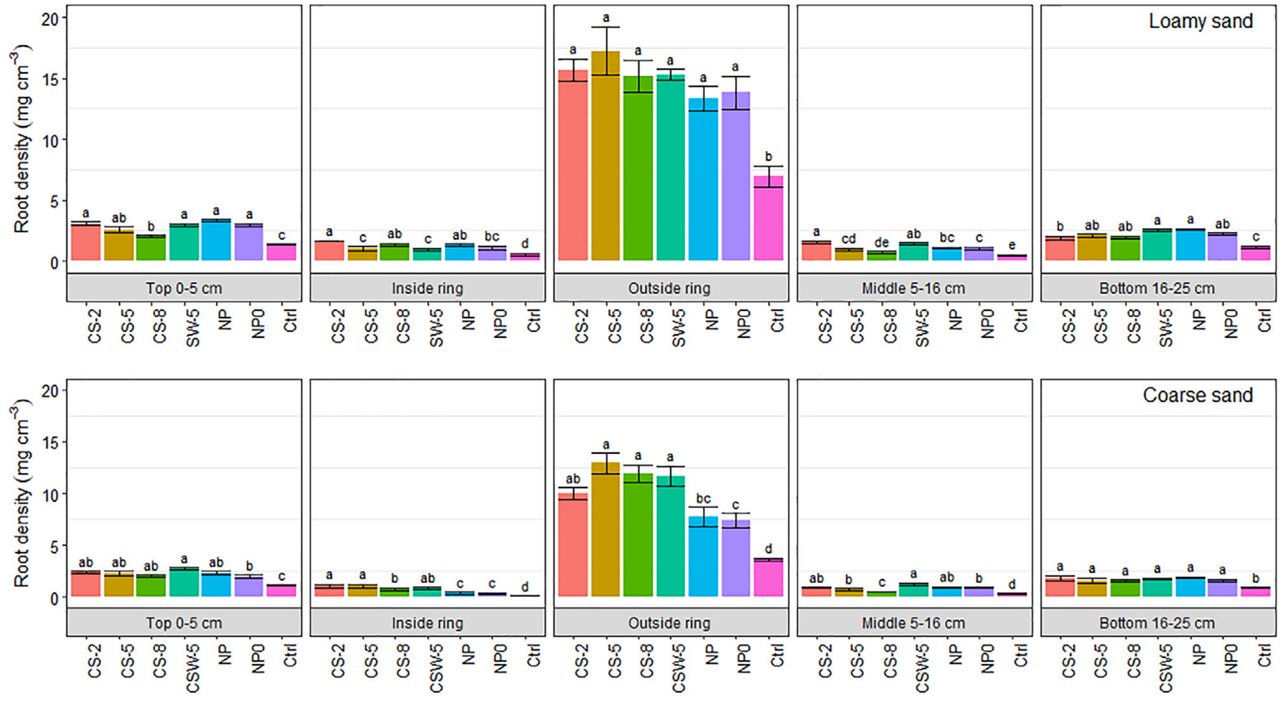

FIGURE 3 Maize root density in different soil layers at the five-leaf stage (V5). Bars represent mean, and the error bars represent standard errors ($n = 4$). Top 0–5 cm refers to the upper 5 cm soil layer of each pot; inside ring refers to the soil that was obtained by inserting a 5 cm long cylinder of 7.3 cm diameter from the place of fertilization covering the central half of the soil area; outside ring represents soil collected outside the inserted cylinder; middle 5–16 cm refers to the remaining soil in this layer when the 5 cm layer around the fertilizer string (= inside ring and outside) was removed; bottom 16–25 cm refers to soil layer below 16 cm to the bottom. Refer to Figure 1 for the treatment legends.

TABLE 3 Concentrations of N and P, N and P uptake in maize shoots, N and P use efficiency (NUE and PUE), N derived from applied fertilizer (N*dff*), and recovery of labeled N (^{15}NRE) in aboveground biomass at the five-leaf stage. The numbers represent mean values, and numbers in parentheses denote standard errors ($n = 4$). Different letters represent the significant difference ($p < 0.05$) within each soil type. For treatment abbreviations, see Figure 1

	(%)			(mg plant^{-1})		(%)			
Treatment	N conc.	P conc.	N:P ratio in shoots	N uptake	P uptake	NUE	PUE	N*dff*	^{15}NRE
Loamy sand									
CS-2	2.02 b	0.23 bc	9	139 a	16 ab	39 c	17 ab	34 b	35 ab
CS-5	1.98 b	0.22 cd	9	135 a	15 bc	38 c	16 bc	36 b	35 a
CS-8	2.38 a	0.22 cd	11	137 a	13 d	38 c	12 de	35 b	36 a
CSW-5	1.94 b	0.20 e	10	123 b	13 d	34 d	12 e	36 b	33 cd
NP	1.31 c	0.24 b	5	91 d	17 a	53 b	19 a	46 a	31 d
NP0	1.48 c	0.21 de	7	99 c	14 c	59 a	–	46 a	33 bc
Ctrl	1.02 d	0.32 a	3	19 e	6 e	–	–	–	–
Coarse sand									
CS-2	2.57 ab	0.19 b	14	134 b	10 bcd	32 cd	7 bcd	34 b	33 b
CS-5	2.64 a	0.20 b	13	143 a	11 bc	35 c	8 bc	34 b	36 a
CS-8	2.37 bc	0.17c	14	129 b	9 d	30 d	5 d	34 b	32 b
CSW-5	2.14 cd	0.17 c	13	143 a	11 b	35 c	9 b	35 b	36 a
NP	1.46 e	0.19 b	8	102 d	13 a	48 b	13 a	43 a	32 b
NP0	1.88 d	0.16 c	12	112 c	10 cd	56 a	–	43 a	35 a
Ctrl	1.39 e	0.24 a	6	36 e	6 e	–	–	–	–

sandy soil. On both soil types, the highest P uptake was observed in the NP treatment, except in CS-2 in loamy sand. Application of mineral P with N (NP treatment) increased the P uptake by 20% and 38% in the loamy sand and the coarse sandy soils, respectively.

3.4 | Soil mineral N and pH

Soil NH_4^+-N concentrations were below the detection limits in most of the cases and thus it is not reported here. Soil NO_3^--N concentrations were higher on the coarse sand than on the loamy sand soil, and the concentrations were higher for treatments applied with slurry than with mineral fertilizer. The NO_3^--N accumulation was higher in the lower soil layer (16–25 cm) in both soil types, though higher in coarse sand when slurry was applied 50% of the central pot area at 8 cm below the seed (CS-8 treatment), compared to the other treatments (Table 4).

For treatments receiving slurry, soil pH inside the ring increased by 0.8 and 1.0 units in the loamy sand and the coarse sandy soil, respectively, compared to the unfertilized control treatment (Table 4). When slurry was placed in a thick layer covering 50% of the central pot area, soil pH outside the slurry zone did also increase, but the effect on soil pH was always more pronounced inside the slurry zone. Soil pH decreased in mineral N applied treatment compared to the control.

4 | DISCUSSION

4.1 | Slurry placement depth

Maize shoot biomass at V5 was highest on the loamy sand when slurry was placed in a 22 mm thick layer at 2 or 5 cm below the seed covering 50% of the central pot area, while no effect of placement depth was observed on the coarse sandy soil. Root biomass also increased when the distance between slurry layer and the seed was reduced on both soil types. In a similar experimental setup on a similar coarse sandy soil, Pedersen et al. (2020) found that growth of the primary root was restricted when CS was placed 1.5 cm below the seed in a 2 cm thick layer covering the entire pot area. Possible mechanisms to explain nontoxic effects of placed slurry to young maize plants in the present study are: (1) the roots could avoid the slurry patch and utilize the peripheral area for growth and nutrient uptake in case of toxicity because slurry only covered 50% of the central pot area, and (2) the NH_4^+-N rate was only half of the rate applied in Pedersen et al. (2020), and possibly below toxic levels. Sawyer and Hoeft (1990) also reported a toxic effect of CS to maize roots with an application rate of 325 g plant^{-1}, which is several folds higher than used in this experiment.

The lower recovery of labeled N (^{15}NRE) in CS-2 than in the CS-5 treatment in the coarse sandy soil may indicate minor root injury, but since the shoot and root biomass was not reduced in the CS-2 treatment, it suggests that the lower recovery of fertilizer N was not important for early plant growth.

The lower shoot biomass and P uptake in treatments with slurry placed 8 cm below the seed on the loamy sand indicate that the slurry was placed too far from the seed to allow the roots to exploit the slurry nutrients during early growth. This suggests that slurry placed in a thick centered layer should be placed less than 8 cm below the seed on this soil type. Since there was no response to mineral P fertilizer in this soil, the negative effect of the deepest placement was due to inadequate N or other nutrients in this soil.

4.2 | Slurry layer width

We expected that plants would benefit more from the slurry placed in a thick centered layer since roots could grow outside the concentrated slurry layer. The root density inside and outside the rings was not different between the slurry applied in the centered 50% of the pot area (CS-5) or covering the whole pot area (CSW-5). This indicates that roots did not escape from the slurry layer due to any unfavorable conditions, and thus the width and thickness of the slurry layer did not affect the root growth. Irrespective of slurry width and thickness, the root density was highest near the pot wall (Figure 3) as reported by Poorter et al. (2012). The preferential root growth toward the pot walls could be related to the rootst' tendency to grow in a horizontal direction to explore resources (Giehl & von Wirén, 2014) until reaching pot walls.

In the coarse sandy soil, root and shoot biomass at V5 was higher when slurry was placed at 5 cm depth covering the entire pot area (CSW-5) than when placed in a centered layer (CS-5). Pedersen et al. (2020b) also observed higher plant biomass with the application of slurry in thinner layers below the seeds, compared to application in thick layers beside the seeds in a field experiment on a similar coarse sandy soil. In the loamy sand soil, the width of the slurry layer did not affect the plant biomass. This indicates that on coarse sandy soils, application of slurry covering the whole pot area may give better access of maize roots to slurry nutrients (Pedersen et al., 2017), compared to more concentrated thick slurry layers. This experimental setup, however, does not allow us to distinguish whether the positive effect of a broader slurry layer in the coarse sandy soil was related to differences in soil P status, soil texture, or other soil properties.

4.3 | Fertilizer value of slurry P and N

On the loamy sand soil, P uptake and PUE were similar for slurry placed at 2 cm distance (CS-2) and for mineral P fertilizer (NP) treatment, suggesting that slurry has the potential to replace mineral P fertilizer. On both soils, shoot P uptake decreased with increasing distance between slurry and seed, indicating that slurry placement close to the seed increased the P availability. On the coarse sandy soil, P uptake and PUE were lower in the slurry treatments, compared to the mineral P reference (Table 3), which is in accordance with other studies (e.g., Pedersen et al., 2017).

Slurry pH was 7.9, and pH increased significantly in soil affected by slurry application, compared to the corresponding zone applied with mineral fertilizer (Table 4). Barrow et al. (2020) suggest that the availability of P in soil is highest around pH 5.5 and lower at pH levels

TABLE 4 Soil nitrate (NO_3^-) and $pH_{KCl\,(2\,M)}$ in different soil layers at the end of the experiment. Mean values below the instrument detection limit are shown as "< 0.1." The values in parentheses are standard errors, which are not reported for pH as the values were ≤ 0.1. The different letters represent statistical differences among the fertilizer treatments within a soil type. See Figure 1 for treatment abbreviations

		NO_3^--N (mg kg^{-1})		pH	
Soil layer	**Treatment**	**Loamy sand**	**Coarse sand**	**Loamy sand**	**Coarse sand**
Top 0–5 cm	CS-2	0.3 (0.1)	1.1 (0.1)	4.7 ab	4.8 b
	CS-5	0.5 (0.3)	1.2 (0.3)	4.8 a	4.9 a
	CS-8	0.3 (0.2)	0.6 (0.1)	4.8 a	4.9 a
	CSW-5	0.1 (0.1)	0.9 (0.1)	4.7 ab	4.9 a
	NP	< 0.1	< 0.1	4.6 b	4.7 c
	NP0	< 0.1	< 0.1	4.7 ab	4.8 b
	Ctrl	< 0.1	0.3 (< 0.1)	4.7 ab	4.9 a
Inside ring					
	CS-2	0.5 (0.2)	5.8 (0.1)	5.4 a	5.9 b
	CS-5	0.4 (0.1)	5.7 (1.6)	5.5 a	5.8 b
	CS-8	0.7 (0.2)	7.5 (1.3)	5.5 a	5.7 b
	CSW-5	0.4 (< 0.1)	4.5 (0.2)	5.5 a	5.9 a
	NP	< 0.1	< 0.1	4.2 c	4.5 d
	NP0	< 0.1	< 0.1	4.2 c	4.5 d
	Ctrl	< 0.1	< 0.1	4.7 b	4.9 c
Outside ring					
	CS-2	0.4 (0.1)	5.0 (0.7)	5.1 b	5.7 b
	CS-5	0.3 (< 0.1)	4.9 (1.3)	5.2 b	5.6 b
	CS-8	0.5 (0.1)	4.4 (0.5)	5.1 b	5.5 b
	CSW-5	0.4 (0.1)	4.2 (0.3)	5.5 a	5.8 a
	NP	< 0.1	1.1 (< 0.1)	4.1 d	4.4 d
	NP0	< 0.1	0.7 (< 0.1)	4.2 d	4.4 d
	Ctrl	< 0.1	0.2 (< 0.1)	4.7 c	5.0 c
Middle 5–16 cm					
	CS-2	0.2 (< 0.1)	5.8 (1.6)	4.8 a	4.8 ab
	CS-5	0.4 (0.2)	4.1 (1.5)	4.6 bc	4.7 bc
	CS-8	0.5 (< 0.1)	2.9 (0.6)	4.6 bc	4.7 bc
	CSW-5	0.4 (0.3)	2.4 (1.2)	4.5 c	4.6 c
	NP	< 0.1	1.4 (< 0.1)	4.3 d	4.4 d
	NP0	< 0.1	1.1 (< 0.1)	4.3 d	4.4 d
	Ctrl	< 0.1	< 0.1	4.7 ab	4.9 c
Bottom 16–25 cm					
	CS-2	1.5 (0.5)	9.1 (2.1)	4.8 a	5.1 a
	CS-5	0.6 (0.2)	9.0 (< 0.1)	4.8 a	5.1 a
	CS-8	3.8 (0.6)	20.2 (2.9)	4.8 ab	5.0 ab
	CSW-5	1.0 (0.1)	4.3 (1.1)	4.7 bc	4.9 bc
	NP	0.5 (0.2)	0.6 (< 0.1)	4.7 c	4.7 c
	NP0	0.7 (0.3)	2.4 (< 0.1)	4.7 c	4.8 c
	Ctrl	< 0.1	< 0.1	4.7 ab	5.0 ab

above and below. Thus, the change in soil pH after manure application could well have affected P availability in our treatments. However, it is impossible to distinguish this effect on P uptake from other effects such as the effect of the release of manure P in soluble form and its adsorption in soil.

Similar ^{15}N recovery between mineral N treatments and slurry treatments suggests that slurry can also be effectively used as starter N fertilizer, if applied in a sufficient amount. In accordance with our findings, Ketterings et al. (2013) also concluded from a field study with differently textured soils that manure can replace starter mineral N fertilizers. According to Sørensen (2004), however, the recovery of ^{15}N-labeled ammonium-N is expected to be lower after slurry application than after mineral fertilizer application due to microbial immobilization of N during slurry decomposition, which was not observed here. A significantly higher NUE of the mineral N than the corresponding ^{15}N recovery indicates that significant "added N interactions" took place (Jenkinson et al., 1985). This can be explained by the preferred microbial use of ammonium, compared to nitrate. It means that soil microbes immobilize labeled ammonium-N instead of unlabeled nitrate-N that would have been used otherwise (Jenkinson et al., 1985). Because of the addition of a nitrification inhibitor in our experiment, the added mineral N remained on ammonium form for a prolonged period and probably caused a higher "added N interaction" than normally seen after application of ammonium-based mineral fertilizer. Importantly, this discrepancy does not influence the comparison of shoot biomass between different slurry placement depths and distribution in soil.

5 | CONCLUSION

Appropriate methods of slurry application may improve plant uptake of P and N and thereby initial maize growth, which often is a prerequisite for obtaining high final yields. In the loamy sand, initial P uptake and plant biomass were improved by placement of CS in a narrow layer 2 or 5 cm below the seed, compared to the placement of slurry 8 cm below the seed, while the shoot N uptake at the V5 was not affected by placement depth, but only by slurry distribution. In the coarse sandy soil, initial maize growth and P uptake responded positively to mineral P fertilizer and slurry placed in a broad thin layer 5 cm below the seed. This study thus confirmed that CS can replace mineral N and P starter fertilizers for maize by appropriate placement of the slurry and that appropriate placement depends on soil properties.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are in the article itself.

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