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Design of a slurry injector for use in a growing cereal crop

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ABSTRACT

Soil injection of animal slurry is increasingly being used to mitigate odour and ammonia (NH_3) emissions, but in order to perform injection in fields with growing cereal crops, injectors that have a greater working width than the existing equipment are needed. To reduce crop damage, a disc injector can be used, but due to the need for a high vertical load a simple tine is used in conjunction with the discs, to penetrate the soil more easily. This study investigates how to reduce horizontal and vertical forces when operating the combination of a double disc and tine injector.

An experimental force-measuring system was built with the purpose of making simultaneous force measurements in both field and soil bin studies. Two experiments were carried out in a soil bin facility in order to find the optimal placement of the tine in relation to the discs and the best working depths for the tine and discs. A field study was also done to evaluate the amount of crop damage caused by operating a prototype injector in a growing winter wheat crop.

The measuring system was found to provide very reliable data. To reduce horizontal and vertical forces, as well as crop damage, it was found that running the double discs at approximately 40 mm and the tine at 100 mm below the soil surface gave the best results. The tine should be placed as close as practically possible to the discs, with a rake angle of 40°. At this adjustment the horizontal force demand was reduced to 30–40% of what has been reported for comparable injectors.

1. Introduction

Livestock manure or animal slurry is an important source of odour and atmospheric ammonia (NH_3) (ECETOC, 1994; Hobbs et al., 1995). Both odour and NH_3 emissions have considerable detrimental effects on the environment, and damage the reputation of livestock producers both regionally and nationally (Hansen et al., 2006). NH_3 emission reduces the nitrogen content of the manure, and the deposition of NH_3 contributes both to the eutrophication of surface waters and to terrestrial ecosystems becoming oligotrophic (Houdijk and Roelofs, 1991; Portejoie et al., 2002).

In Denmark, 25% of the national NH_3 emission is derived from the application of livestock manure to the land (Hutchings et al., 2001; Mikkelsen et al., 2006). Improvement of the technology for the land application of livestock manure is therefore an important aspect of reducing NH_3 emission.

Soil injection techniques have been found to produce the lowest emissions of NH_3 and odour following slurry application (Hanna et al., 2000; Smith et al., 2000; Huijsmans et al., 2003). However, due to unacceptably high levels of damage being caused to cereal crops, soil injection is only done on grassland and into uncropped soils. The major problem with using the existing equipment for slurry injection into growing crops is that injection requires a significant additional draught force compared with a trailing-hose application technique (Huijsmans et al., 1998). This results in a small working width; typically 6–8 m for grassland and bare-soil injection, compared with 18–24 m for trailing-hose application. The small working width of existing slurry injection systems results in a high proportion of the area being trafficked with high loads, and therefore there is a high risk of crop damage and harmful soil compaction (Mikkelsen et al., 2004).

The general aim of this study was to optimise the design of a slurry injection system for injection in growing cereals, in order to make it possible to inject slurry at a large working width without significant crop damage. We hypothesised that a combined disc and tine injection system would achieve the desired goals for a new slurry injector.

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2. Slurry injection systems

2.1. Existing systems

Existing grassland injection systems are largely based on disc coulter injection techniques. Disc coulter injection is performed by two discs creating a V-shaped furrow in the soil, or a conical double disc (two-angled disc coulter) creating a similar furrow. A hose following the discs places slurry into the furrow (Rodhe and Etana, 2005). The greatest benefit of using disc coulter injectors is that the discs do not cause significant crop damage when operating in a growing cereal crop (Knudsen, 2005). However, disc coulter injection does have a number of drawbacks. The slurry is not covered by the soil and therefore odour and NH_3 emissions can occur, although at reduced levels compared with surface application. Petersen et al. (2003) found that using disc coulter injection systems reduced permeability of the soil, which could be correlated with a reduced slurry infiltration rate, compared with a harrow tine. Likewise, Munkholm et al. (2003) showed that the use of a disc coulter for direct drilling produced excessive soil compaction below seeding depth. A reduced slurry infiltration rate increases the potential emission of NH_3 and odour (Sommer and Jacobsen, 1999; Sommer et al., 2006). The discs need considerable force to be pushed into the soil, which can create problems in the construction of a wide boom (Godwin et al., 1987b). It can also be difficult to achieve the correct injection depth if the soil is hard, due to dry conditions (Chen and Tessier, 2001). The injection depth is crucial to the ability of the disc injector to reduce NH_3 emission (Chen and Tessier, 2001; Rodhe and Etana, 2005). Rodhe et al. (2004) measured up to 1800 N for the vertical force needed to run a double-disc injector to 8 cm below the soil surface on a silty clay loam. This means that up to $3 \times 1800 = 5400$ N boom m^{-1} or $\sim$550 kg boom m^{-1} of load is needed to ensure the required working depth. Building a slurry injector system more than 8–10 m wide using disc coulter injectors seems to be impossible, due to the high vertical force requirements.

To improve soil coverage of slurry, penetration of the injector, and slurry infiltration rate, it is possible to use tine rather than disc injection. Tine injection is commonly used in bare-soil injector systems, where crop damage is not an issue. Tine systems have been found to produce less soil compaction below the working depth than disc coulters and thus achieve higher infiltration rates (see Munkholm et al., 2003). There are no commercial injector tines for injecting slurry in growing crops as far as we know. Pullen et al. (2004a) developed a tine injector that did not affect the yield of winter wheat and oilseed rape, except when the injection took place very late in the growing season. The Pullen injector was designed with a rake angle of more than 90° in order to minimise soil disturbance and thus crop damage (Pullen et al., 2004b). However, the negative or high rake angle (>90°, with the tine pointing backwards compared to the travel direction) resulted in a high horizontal draught force compared with a tine with a smaller rake angle (<90°) (Godwin, 2007). In an indoor soil bin facility where a sandy loam soil was compacted to approximately 1.5 g/cm^3 ($\pm$0.5 g/cm^3), this injector required approximately 0.7–0.9 kN of draught force at a nominal speed of 0.5 m s^{-1}. Rodhe et al. (2004) tested an injector tine in combination with a single disc. This injector required between 0.5 and 1 kN per tine, depending on soil conditions. Trailing hoses do not require any significant additional draught force except that required for pulling the slurry tanker. Under Danish conditions, a standard 25 tonnes slurry tanker would typically require a 150 kW tractor just to pull the fully loaded tanker and operate the pump (M.H. Jørgensen, Personal communication, 2007). Injector tines with similar draught requirements to those used by Rodhe et al. (2004) and Pullen et al. (2004b) need up to 4 kN m^{-1} boom for operating in a sandy loam. If such injector tines were mounted on a boom of 18 m with a space between the injectors of 250 mm driving 1.66 m/s which is a normal travel speed for soil injection of animal slurry, the total power of the engine (P) needed for pulling such a boom can be calculated using the equation:

$$P\ [\mathrm{kW}] = \frac{T\ [\mathrm{kN}] \times \nu\ [\mathrm{m/s}]}{\eta} = \frac{72\,\mathrm{kN} \times 1.66\,\mathrm{m/s}}{0.5} = 240\,\mathrm{kW} \qquad (1)$$

where T is the horizontal force required for pulling the boom, ν is the velocity, and η is the tractor efficiency. The tractor efficiency is set to 50% here (Guul-Simonsen and Jørgensen, 2001) but can vary considerably depending on wheel-slip. On the basis of these calculations, it can be estimated that a tractor pulling this type of machine would require engine power in the region of 390 kW (240 kW + 150 kW). There are few commercially available tractors in this power band. Therefore it is necessary to develop injection tools which require less draught force than those developed by Pullen et al. (2004b) or Rodhe et al. (2004) in order to increase the potential operating width of the injector boom.

2.2. New systems

Nyord (2008) describes how to modify the Pullen design to reduce the horizontal force requirements. The modified design has the same crop deflector as the original Pullen design, but the wings mounted on a leg are moved forward, which should ensure that the crop deflector is running in loose soil, due to the rupture distance exceeding the distance from the tip of the tine and where the crop deflector cuts through soil surface. This was found to reduce both the horizontal and vertical force requirements significantly compared with the original design. The only problem with the modified design of the Pullen tine was the unacceptably severe crop damage it caused. A test in a winter wheat field in Denmark showed that trash (crop residues) built up in front of the tine, due to the combination of the negative rake angle on the crop deflector and the loose soil in front of the crop deflector. The loosening of the soil in front of the crop deflector to reduce the force requirements meant that the crop deflector had no firm soil surface against which to cut through the trash.

Injectors mounted on a wide boom need to be designed in such a way that vertical force is negative or downward (the so-called "soil suction"). If injectors have positive vertical force it means that injector tines need to be pressed into the soil, which will make heavy demands on the construction of the boom. For narrow tines, the rake angle of the tip of the tine has critical implications for the vertical force (Godwin and Spoor, 1977). However, rake angle also affects the amount of soil disturbance, and therefore crop damage. A small rake angle will create more soil disturbance in a wider band (Pullen et al., 2004a), which may increase the crop damage. The aim of this study was to create a new design of injector tine which produces a negative or neutral vertical force, minimises the horizontal force requirement, and keeps soil disturbance to a minimum.

Because of the problem of trash in front of the crop deflector, it was decided to try a new design (see Fig. 1). Instead of a fixed crop deflector, the crop deflector in the new design was made out of two-angled rolling discs. This should avoid trash building up in front of the crop deflector, while the rolling movement of the discs would prevent a build-up of trash. In the "shadow" of the discs a simple 10-mm-wide tine is placed and, as the tip of the tine is placed deeper than the lowermost part of the discs, the tine will increase the soil penetrating ability for the total injector unit. When the simple tine is placed after the discs, the discs will remove some of the soil in front of the tine. This reduces the risk of operating the simple tine under the critical depth (Godwin and Spoor, 1977), which could be the case when the tine is only 10 mm

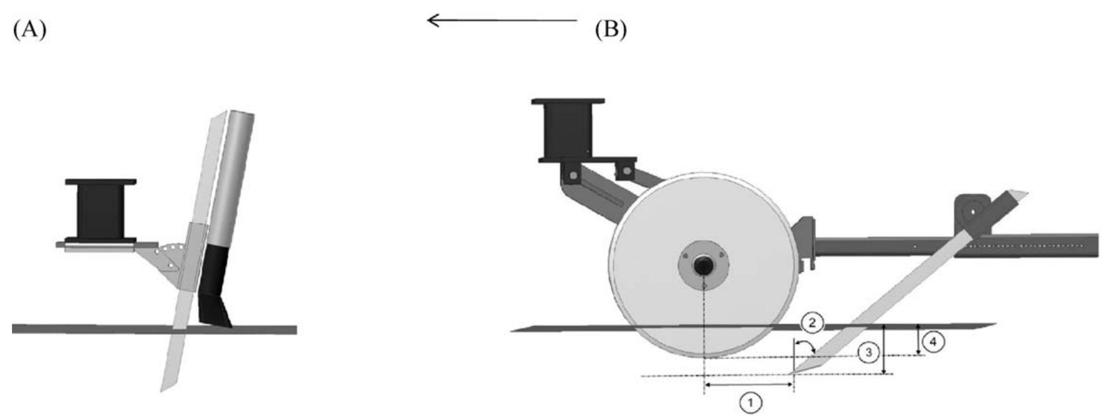

Fig. 1. (A) The simple "Agrodan" tine and (B) the experimental slurry injection system, "Bygholm", used for the study of draught force requirements: (1) distance between discs and tine, (2) 90°-rake angle of the tine, (3) working depth of tine and (4) working depth of discs. Tine operating depth, tine rake angle, distance between tine and discs, and operating depth of discs can be adjusted individually. Array indicates direction of travel.

wide, and therefore the critical depth should be about 60–70 mm operating depth (Godwin, 2007). This overall design raises several questions regarding the detailed design. The new design should have the optimal: (1) distance between discs and tine, (2) rake angle of the tine, (3) depth of tine compared to discs, and (4) depth of discs related to the total working depth. These requirements will be addressed in this paper.

3. Materials and methods

Three experiments were carried out to clarify the effects of injector design on crop damage and the horizontal and vertical forces needed to run the soil injectors.

3.1. Crop damage

The main objective of this experiment was to investigate whether there was any significant influence of the double-disc crop deflector regarding crop damage. The experiment was carried out in a field close to Research Centre Bygholm (55°52′N, 9°49′E). The soil is loamy sand with 12% clay, 15% silt and 70% sand. Total C in the soil was 1.9%. In 2008 the field site was cultivated with winter wheat (*Triticum aestivum* L.). The injection experiment took place on 16 April 2008, when the crop was at growth stage 30 according to the BBCH scale (Lancashire et al., 1991). Two injectors were used; the new injector unit "Bygholm" and the simple injector "Agrodan". Both injectors were mounted on the same experimental plot slurry spreader, but no slurry was applied in this experiment. Both tines were operated at driving speeds of 0.56 and 2.78 m/s the operating depth was 10 cm below the soil surface. The discs on the Bygholm injector were operating at a depth of approximately 4 cm below the soil surface. The simple tine of both injectors had a rake angle of 60°. An important practical question to be addressed was; the risk of blockage with stones and crop residues in the gap between discs and tine increased when the tine was placed close to the discs. Therefore it was decided to position the tine in such a way that the tip of the tine was 300 mm from the centre-line of the discs (see Fig. 1) and thereby reducing the risk of blocking. An untreated crop was also included in the experiment as a control; giving five treatments in all. All treatments were repeated five times, thus using 25 plots, each 20 m^2 (2.5 m × 8 m) in size. The plots were divided into five blocks including all treatments, which were placed randomly within the block.

Each plot was harvested at maturity using an experimental plot combine harvester, and grain dry matter was determined. Ratio vegetation index (RVI) was measured four times in the growing season with a hand-held Viscan instrument (for more details, see Berntsen et al., 2006). The RVI parameter is strongly related to the green leaf area and therefore indicates the present plant biomass. One RVI measurement was taken before and three after the soil injection in order to monitor the biomass production of the crop.

3.2. Force measurements

3.2.1. Instrumentation

To measure the draft force requirements of the different combinations and adjustments of tines and discs, a specially made measuring frame attached to a tractor's three-point linkage system was used. The width of the frame was 3.0 m and it had three transverse girders for the attachment of different soil-engaging implements (see Fig. 2).

The frame was designed to restrain the load with minimum deflection. At maximum load the deflection at the bottom point of soil interaction was less than 5 mm due to the total deflection of the full structure. The system was modularised so that it was possible to mount the transducer to measure the total force for one tine system. By reorganising the mounting unit and the transducers, it was possible to measure partial forces from different elements in the tine system, e.g. a disc section and a tine section working together in the same track. Measuring transducers were located between the frame and the tested implement. A total of eight implements could be tested simultaneously. The working depth of the implements was controlled and adjusted by means of two trailing wheels mounted beneath the frame. The measuring frame was linked to a special wide-wheeled tractor, allowing the tractor wheels to run outside the soil bins.

The transducers used for the measurement of the draft force were of the extended octagonal ring (EOR) type. The design and location of the strain gauge and the strain gauge bridge circuits were as described by Godwin (1975) and O'Dogherty (1996). Each transducer was rated for maximum horizontal and vertical loads of 62.0 and 85.2 kN, respectively. The rated maximum moment of force was 14.3 MNm. Using this transducer design, simultaneous and independent recording of the horizontal draught force, the vertical force, and the resulting moment was possible (Godwin et al., 1987a).

The working speed of the slurry injectors was measured by using radar mounted on the measuring frame and pointing at the soil. An MGCplus data-logger (Hottinger Baldwin Messtechnik) was used to record the data. In the field the logger was powered with 12 V DC from a tractor battery. The logger had two modules

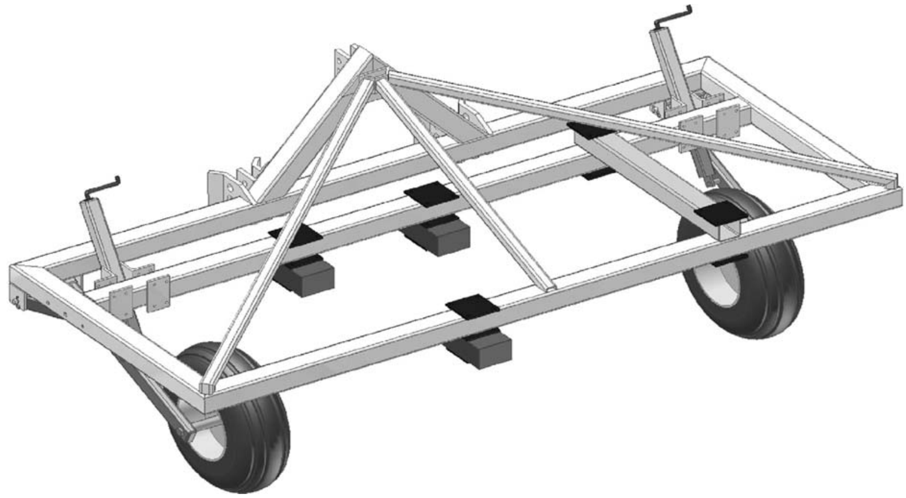

Fig. 2. Tractor mounted measuring frame to study the force requirements for the soil-engaging implement, e.g. a slurry injector. The frame is shown with three transducers.

(type Ml 801), each with eight channels for measuring an analogue input range of 0–10 V and a module (type Ml 460) with four channels for measuring frequencies. The analogue channels were used for force sensing, while a frequency channel was used for measuring the working speed. A sampling rate of 600 Hz was used.

3.3. Design of the test injection implement

To study the design and set-up of the implement, four experimental injector implements were made at the workshop of Research Centre Bygholm. The injectors were made in such a way that it was possible to adjust the distance between the discs and the tine, the rake angle of the tine, the depth of the tine compared with the discs, and the depth of the discs relative to the total working depth (see Fig. 1). The diameter of the two sharpened discs was 400 mm and the tine had a rectangular cross-section of 10 mm × 40 mm. The discs were mounted with a tilting angle of 5° with respect to both the horizontal and vertical directions, thus opening up to the rear and upwards. The discs touched each other.

3.4. Site and experimental conditions

The draft force measurements taken in spring and fall 2008 were made in the semi-field facilities at Research Centre Foulum, Denmark (Schjønning, 1994). The semi-field facilities included four lanes of soil bins each 40 m long, 2.7 m wide and 1.5 m deep. The bins were filled with soil in 1993. The soils were excavated from three Danish locations with different soil types and textures. The filling of the bins was done so as to retain the vertical pedological differentiation in the soil at the original location. The soils were packed to the bulk density found in the field. After this the soil was exposed to several years' freeze–thaw and dry–wet cycles as well as tillage performed to a depth of 0.2 m, allowing the soil structure to develop. The three soils were coarse sand (Jyndevad), a loamy sand (Foulum) and a sandy loam (Rønhave). Soil data are shown in Table 1.

The semi-field facilities made it possible to investigate soil type differences under identical, well-defined climatic conditions. Furthermore, the soil variations within each of the soil types were minimised. The soil shear strength was monitored at 5 cm depth using a commercial hand-held vane shear strength tester (Serota and Jangle, 1972).

3.5. Force measurements spring 2008

The experiment of spring 2008 was carried out in the semi-field facility. Only the lane with the coarse sand soil type (Jyndevad) was used. The horizontal and vertical draft forces were measured for different combinations of operation depth of the tine below the discs, distance between the discs and tine, and rake angle of the tine. We used two distances between the centre of the discs and the front tip of the tine, 0 and 300 mm (tine 300 mm behind discs); three rake angles of the tine, 20°, 40° and 60°; and four operation depths of the tine below the discs, 0, 20, 40 and 60 mm. Operation depth was measured for each run. For each combination, four replications were made. The replications were made by having four identical implements mounted on the measuring frame at the same time. The distance between the individual injectors was 250 mm. The working depth of the double disc was 40 mm, giving a total working depth (depth of the tine) of 40, 60, 80 or 100 mm.

Table 1
Soil texture, density, moisture content and shear strength in topsoil (0–100 mm).

Experiment	Soil	Soil type	Dry bulk density, $g\,cm^{-3}$	Organic matter, $g\,100\,g^{-1}$	Moisture content (v/v), $g\,[H_2O]/100\,g$ [dry soil]	Vane shear strength, kPa (SE)	Texture, $g\,100\,g^{-1}$				Rupture distance, cm		
							<2 μm	2–20 μm	20–200 μm	>200 μm	Rake angle 40° (SE)	Rake angle 60° (SE)	Rake angle 80° (SE)
Spring 2008	Jyndevad	Coarse sand	1.5	2.0	8.8	4.3 (1.7)	4	4	18	72	–	–	–
Fall 2008	Jyndevad	Coarse sand	1.5	2.0	5.1	7.2 (1.6)	4	4	18	72	16.8 (0.9)	10.1 (1.0)	6.7 (0.5)
	Foulum	Loamy sand	1.5	2.5	11.8	11.6 (2.9)	9	11	45	33	17.9 (1.5)	14.2 (1.1)	8 (0.8)
	Rønhave	Sandy loam	1.5	2.5	13.6	16.2 (3.3)	18	13	47	20	18.6 (1.3)	14.7 (1.4)	10 (1.1)

All the tests were conducted at a working speed of 1.4 m s^{-1}. Soil density, soil water content and shear strength were determined. Differences between settings and the influence of the three factors (distance, depth and rake angle) were analysed using the generalised linear model in the statistical package SAS version 9.1.

3.6. Force measurements fall 2008

The experiment of fall 2008 was also carried out in the semi-field facility. Measurements were conducted in all three soil types, coarse sand (Jyndevad), loamy sand (Foulum) and sandy loam (Rønhave). The horizontal and vertical draft forces were measured for different combinations of the working depth of discs and rake angle of the tine. Four operation depths of the discs (0, 33, 67 and 100 mm) were used and the simple tine operates at 100 mm below the soil surface at three different rake angles (40°, 60° and 80°) except when the discs are operating at a depth of 100 mm, where the tine is not included in the measurements, since the discs operates at the same depth as the tine and therefore the tine do not influence the forces for the injector. Additional measurements for the vertical and horizontal forces where discs and tine were attached separately on different transducers were carried out in the loamy sand. In these measurements the rake angle of the tine was 60° and the tine was operated directly after the discs as the "Bygholm" injector. For each combination, four replications were made. The replications were made by having four identical implements mounted on the measuring frame at the same time. The distance between the individual injectors was 250 mm. In all tests the working depth of the tine was 100 mm. All the tests were conducted at a working speed 1.4 m s^{-1}. After the tests, soil density, soil water content and shear strength, cross-section area, and the surface disturbance created by the injector were measured. For all treat treatment in *Foulum* and *Rønhave* soils, measurements of surface disturbance and cross-section area were carried out. Surface disturbance was estimated by the width of the band of disturbed soil across the furrow, and the cross-section area was measured with a profile meter similar to that described by Pullen et al. (2004b). Each profile was traced on to paper and subsequently the area was measured with a planimeter. Differences between soil types and settings and the influence of the factors operation depth of discs and rake angle of tine were analysed using the generalised linear model in the statistical package SAS version 9.1.

4. Results

4.1. Crop damage

At injection time very little crop biomass was recorded, which indicates that crop growth was negligible at that time (see Fig. 3). It appears that the crop started growing in the period between 16 and 21 April. There were no significant effects of the treatments on the RVI measurements but there seemed to be a tendency for reduced crop growth when operating the Agrodan tine at 2.78 m/s compared with the other treatments ($P = 0.12$). The yield results (Table 2) support this statement; but although the Agrodan tine at 2.78 m/s resulted in the lowest grain yield, it was only significantly lower than Bygholm at a speed of 2.78 m/s. No other significant effects of driving speed were observed.

4.2. Force measurements spring 2008

Rather low forces and large variations between the replicates were observed and therefore it was not possible to identify a few easily explainable significant differences between treatments (see Fig. 4). However, there was a significant increase in horizontal force when the operating depth of the tine increased from 20 to 60 mm ($P < 0.0001$) below the discs. However, when the tine was operating 20 mm deeper than the discs (compared with operating the discs alone) an unaltered or even a moderate decrease in horizontal force was observed. There was a tendency for a reduction in force as a consequence of distance between tine and discs where Distance 0 resulted in the lowest mean value of horizontal force, which was about 6% lower on average than that for Distance 20 ($P = 0.10$). Regarding vertical force, a tendency for increased force requirements when operating the discs at depth 100 mm compared with a position of the tine 20, 40 or 60 mm deeper than the discs was observed ($P = 0.087$). There was also a very weak tendency for reduced vertical force requirements when the tine was operated at a rake angle of 40° compared with 20° and 60° ($P = 0.067$ and $P = 0.11$, respectively) but in this case the variation was very high and therefore no clear conclusion can be drawn. No significant effect of distance between tine and discs was observed with respect to vertical force ($P = 0.85$).

4.3. Force measurements fall 2008

When discs were operating alone at a depth of 100 mm differences in rake angle of the tine were not investigated (see Fig. 5). A tendency towards significant differences between the four replicates was identified in this experiment, regarding both horizontal and vertical forces ($P = 0.11$ and $P = 0.10$, respectively), which can probably be explained by a difference in soil density across the soil bin, where a reduced soil density was observed close to the sides of the bin. The statistical analysis showed that the differences between replicates were similar across all treatments, and therefore replicate was included as a covariate and was treated as a random factor to explain some of the variation between the

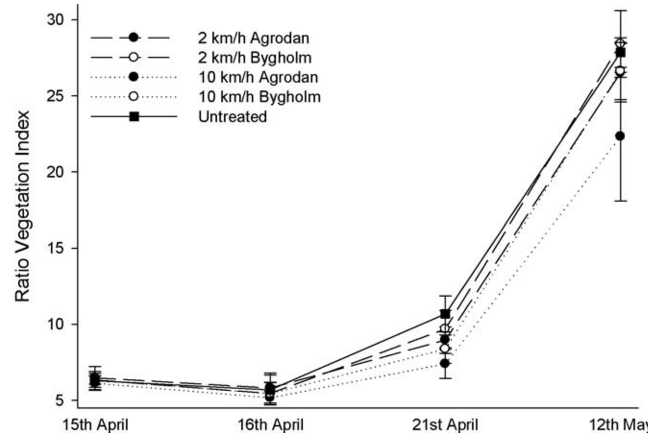

Fig. 3. Ratio vegetation index (RVI) results, measured in winter wheat. Soil injection took place on the morning of 16 April and the measurement was taken afterwards. *Dots* and *squares* indicate means ($n = 3$) and *error bars* indicate standard error of the mean. *Note:* Due to an experimental error, RVI was not recorded later in the growing season.

Table 2
Average winter wheat grain yield (in t ha^{-1}) after operating two different soil injection tools in the growing crop ($n = 5$).

Treatment	Grain yield (t ha^{-1})
0.56 m/s Agrodan	9.7
0.56 m/s Bygholm	9.7
2.78 m/s Agrodan	9.3
2.78 m/s Bygholm	10.0
Untreated	9.7
LSD	0.45

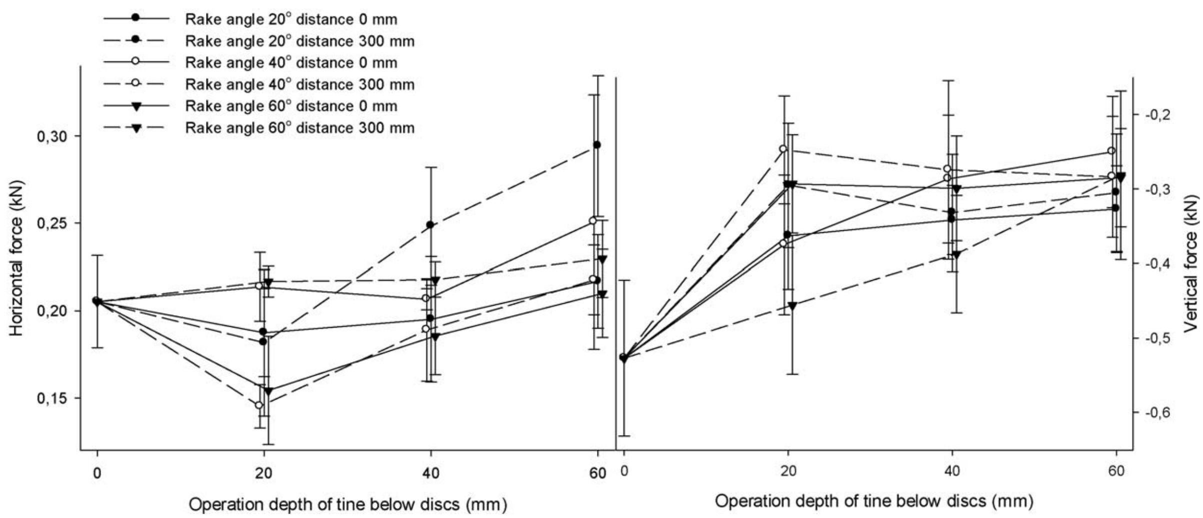

Fig. 4. *Left panel*, average horizontal forces; *right panel*, average vertical forces. The rolling discs were operated at 40 mm depth and the attached tine was working at three different depths. The simple tine operated at three different rake angles. Only one point is given for operating the tine 0 mm below the discs, since rake angle for the discs are fixed. *Error bars* indicate standard deviation ($n = 4$).

systematic factors. In addition, cross-section area was measured in order to investigate whether some of the differences in horizontal and vertical forces could be explained by differences in how much soil was loosened by the tine and discs; therefore the results of the cross-section area measurements were initially included in the statistical analysis. No significant effects due to cross-section area were seen, and therefore cross-section area was subsequently excluded from the statistical analysis. In general the forces increased significantly with increased clay content of the soil ($P < 0.0001$). No significant depth effect was identified ($P < 0.0001$). The smallest horizontal force was measured for tines alone (operation depth of discs = 0) and, when compared with 33 and 66 mm operation depths of discs, a significant effect was recorded ($P = 0.018$ and $P < 0.0001$, respectively). An operation depth of 100 mm resulted in the highest average horizontal force requirement, but in coarse sand and loamy sand no significant effect was recognised down to 66 mm. Rake angle also influenced the horizontal force significantly ($P < 0.0001$). A rake angle of 80° induced significantly higher forces than an angle of 40° or 60°. The difference between rake angles of 40° and 60° was not significant across soil types and operating depths ($P = 0.077$) but there was a tendency towards the lowest forces for a rake angle of 40°, and in the sandy loam and loamy sand there were almost significant differences between rake angles of 40° and 60° ($P = 0.18$ and $P = 0.087$, respectively).

Two statistical interactions were identified in the analysis of the vertical force measurements: (1) between operating depth and rake angle ($P = 0.036$) and (2) between soil type and rake angle (0.031). This was most probably due to insignificant and non-systematic differences between rake angles of 40° and 60° in the sandy soil and no difference between rake angles 60° and 80° in the loamy sand and the sandy loam. There was a significant effect of depth and soil type regarding vertical forces (both $P < 0.0001$). Increasing the operation depth of discs increased the vertical force across all soil types and rake angles; as an example, the force was increased by up to 10 times in sandy loam from slightly positive values (which indicate a downward movement—the so-called soil suction) when the tines were operating alone, to about 1 kN when the discs were operating alone; increased clay content of the soil increased the vertical forces across all rake angles and depths. Statistical analysis showed that the reason for the interaction between rake angle and depth was due to there being no differences at depths of 0 and 33 mm between rake angles 40° and 60° ($P = 0.085$ and $P = 0.16$, respectively), but significant differences at 66 mm across all soil types. The interaction between soil type and rake angle was identified as resulting from there being no significant differences between vertical forces at rake angles of 40° and 60° in sandy soil ($P = 0.89$) but significant differences between rake angles of 40° and 60° in the two other soil types—loamy sand and sandy loam ($P < 0.0001$ and $P = 0.0052$, respectively). A rake angle of 80° did, in all cases in this experiment, result in higher vertical force requirements than the two other rake angles, even though the difference in the sandy loam between rake angles of 60° and 80° was very small and that at a depth of 66 mm and a rake angle of 60° was, for some unexplained reason, slightly higher than with a rake angle of 80°.

An experiment where the horizontal and vertical forces of the discs and the tine were measured separately was carried out, and the results are shown in Fig. 6. The results show that even though the discs were operated at 33 or 66 mm, more than two-thirds of the total horizontal as well as the vertical forces can be attributed to the operation of the discs.

Fig. 7 shows the measurements for two soils and three rake angles of the width of the band of disturbed soil across the injection slit created by the injection tines; a significant effect of operating depth ($P < 0.0001$) and an interaction between rake angle and soil type ($P = 0.049$) were recorded. The lowest average bandwidth across soil types and rake angles was achieved at 33 mm operating depth of the discs, although operating the tines alone with a rake angle of 80° showed the narrowest band of disturbed soil for all treatments.

5. Discussion

5.1. Crop damage

We are unable to explain why the operation of the Bygholm injector at 2.78 m/s resulted in a non-significantly higher yield than the untreated control, and this is probably due to chance. Because of this, the results of this experiment should be treated with caution. However, there seemed to be a tendency for higher grain yields when operating the Bygholm injector compared with the simple Agrodan tine, although the only significant difference appeared at a speed of 2.78 m/s. This could be an effect of the discs opening up the soil in front of the tine, thereby reducing the width of the cross-section area at the soil surface, so that fewer crop roots

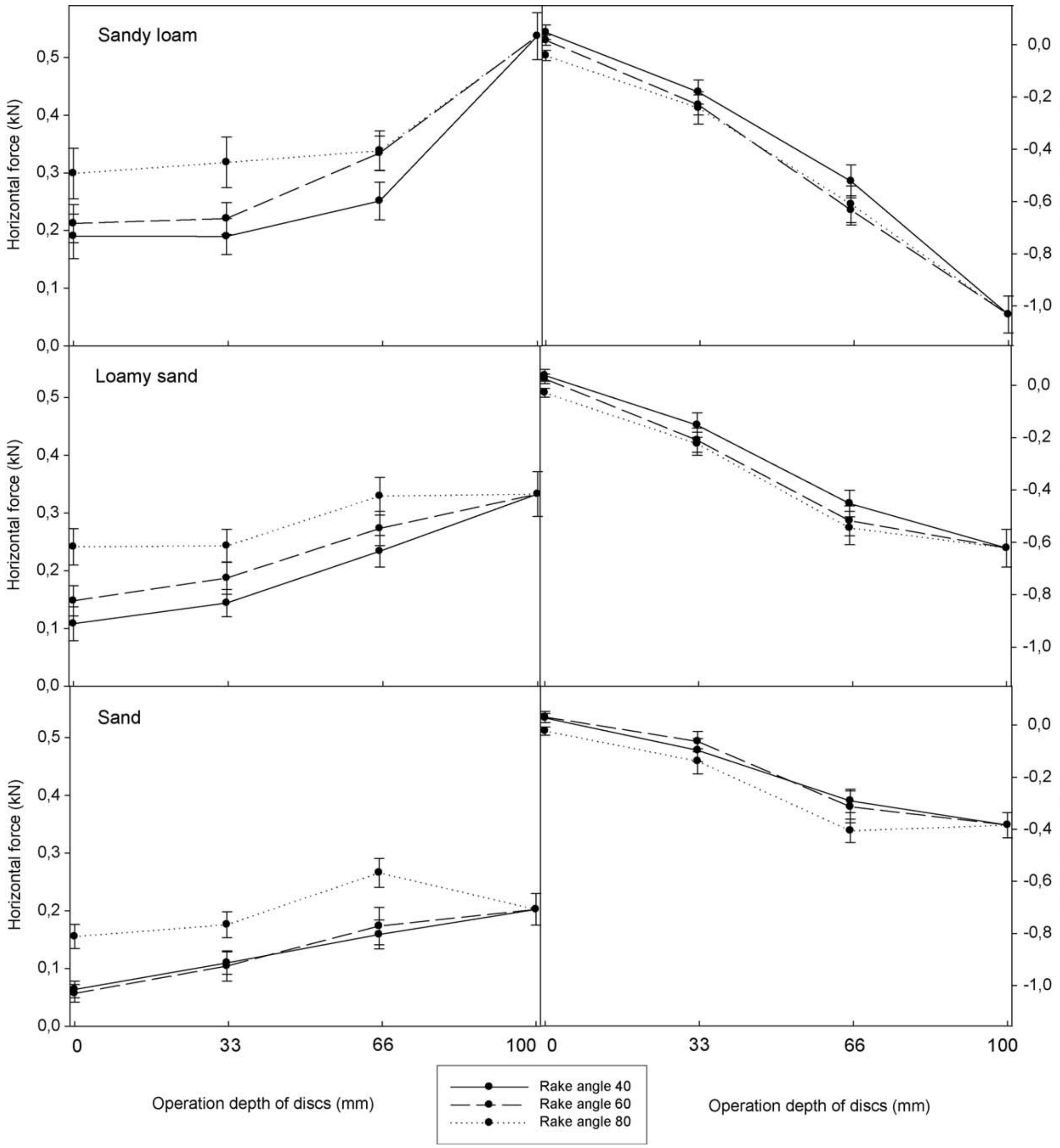

Fig. 5. The *left column* shows average horizontal forces and the *right column* shows average vertical forces. Measurements were done in three different soil types at four operation depths of the discs. The simple tine operates at 100 mm below the soil surface at three different rake angles except when the discs are operating at a depth of 100 mm, where the tine is not included in the measurements; *error bars* indicate standard deviation ($n = 4$).

would be affected by the soil loosening. The results are supported by the assumption that if the travel speed is increased, the width of the cross-section area following the tine will also increase. This effect was also identified in the fall 2008 experiment, where the bandwidth was found to be at the minimum when the discs operated at 33 mm depth compared with tines working alone with a rake angle of 60° or 40° or when compared with discs operating at a greater depth (see Fig. 4). The discs also significantly reduced the build-up of trash (crop residues) on the tine because the discs created a slit in the soil surface where the crop was "cleared away", creating a "ploughing effect". This kind of effect was also found by Rodhe and Etana (2005). Pullen et al. (2004b) reported a similar effect of a fixed crop deflector which was cutting through the soil surface so as to prevent traction on the attached wings.

5.2. Force measurements

5.2.1. Discussion of the method applied

At calibration of the transducers mounted on the measuring frame, a very high degree of linearity between applied forces and electrical output was found (data not shown). The stiffness of the measuring frame to applied forces was very high and resulted in only small deflections at the implement. The degree of hysteresis between loading and unloading characteristics was less than 0.4% and therefore acceptable (data not shown). In the force measurements of spring 2008, the low shear strength of the soil implied very low values of horizontal as well as vertical forces and this made it difficult to see any differences between treatments. However, measurements carried out in the fall 2008 experiment

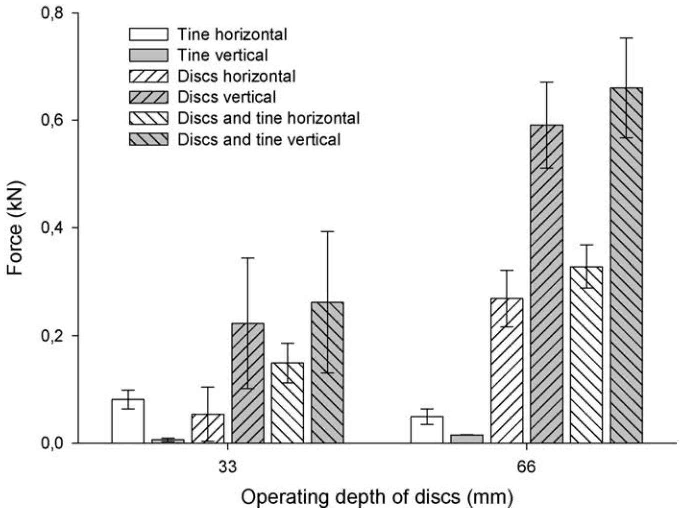

Fig. 6. Average force measurements of tine, discs, and the combination of tine and discs; *error bars* indicate standard deviation ($n = 3$). Tines were operated 100 mm below the soil surface with a rake angle of 60°.

showed very consistent results, with a covariance value of about 5% between replicates, which indicates that the experimental set-up was appropriate for this purpose.

5.2.2. Depth of tine compared to discs (spring 2008 results)

The observed increase in horizontal force with increased working depth of the tine following the discs is, not surprisingly, due to the increased cross-section area (Godwin, 2007). However, it was unexpected to find that the mean of horizontal force across rake angles was lower when the tine was operating 20 mm below the discs compared with operating the discs alone. We expected increased horizontal force with increased volume of disturbed soil. One explanation of this could be that a reduced downward vertical force reduce the rolling resistance on the discs and thereby reduces the horizontal force as well. The vertical forces are reduced by placing the tine 60 mm below the discs compared with 20 mm (and to some extent also 40 mm), even though this is only a tendency between 40 and 60 mm. This could be due to increased

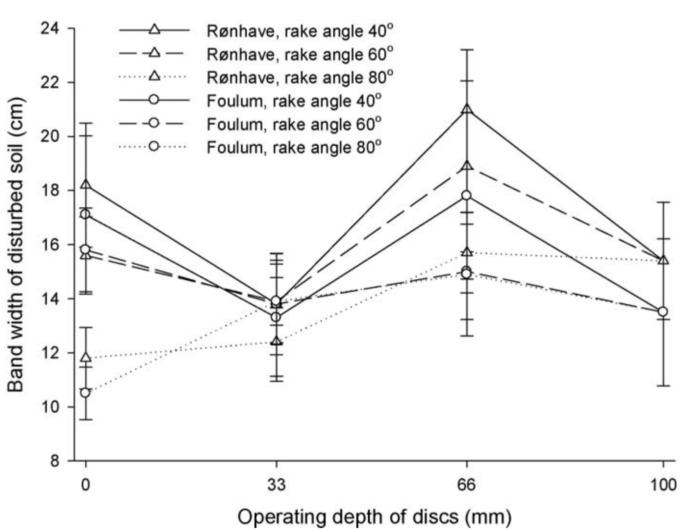

Fig. 7. Average bandwidth of the disturbed soil surface across the injection slit, measured for two soils at three rake angles of the tine. For disc operating depths of 0, 33 and 66 mm, the connected tine was operated in the soil bin at 100 mm depth, but an operating depth of 100 mm means that only the discs were running in the soil. *Error bars* indicate the standard deviation ($n = 20$).

soil resistance and thereby increased downward movement of the tine, as described by Godwin and Spoor (1977), and therefore the total vertical forces of the injector will be reduced.

5.2.3. Distance between discs and tines (spring 2008 results)

No significant effect of distance from the tine to the discs was apparent. This could be due to very low force measurements in general in the spring 2008 experiment and the consequent difficulty in detecting differences between treatments. However, there could have been an indirect effect of loosening the soil and thereby degrading the soil structure in front of the rolling discs, while no differences in average horizontal forces were observed between operating the discs alone or with the tine attached 20 mm below the discs. This would usually increase the horizontal force due to increased cross-section area. Especially at rake angles of 20° and 40°, and a distance of 0, low forces were observed at 20 mm tine depth, which are also the settings where the longest rupture distance was observed.

5.2.4. Rake angle of the tine (fall 2008 results)

Godwin and O'Dogherty (2007) described how the rake angle of a simple tine would influence the vertical forces of the tine. When the rake angle is less than approximately 70° then the forces will be downward (so-called soil suction), but if the rake angle is set to more than 70° then an upthrust will occur. This was also found in the fall 2008 force experiment, where the tine operating alone in all three soil types at a rake angle of 40° or 60° resulted in positive vertical forces, which means a downward movement, and a rake angle of 80° produced a negative force. The finding of lower horizontal forces at a rake angle of 40° compared with rake angles of 60° or 80° agrees with the theory proposed by Godwin (2007) and Godwin and O'Dogherty (2007). It was expected that the horizontal force would increase by combining cutting disc and tine compared with operating the tine alone, because studies done on the forces associated with working discs in soil have concluded that discs require both more horizontal and more vertical force than tines with low rake angle in order to create a similar degree of soil failure (Godwin and O'Dogherty, 2007). This was not the case when operating the discs at 33 mm depth with the attached tine 100 mm below the soil surface. This is most probably due to reduction in the vertical force component which also results in a reduction in the total draught force.

5.2.5. Depth of discs related to the total working depth (fall 2008 results)

When the discs remove some of the soil, the "actual working depth" of the simple tine is reduced by 20–30 mm and thus the real operating depth is reduced to 70–80 mm. This depth has to be compared with the potential critical depth of a 10-mm-wide simple tine, which will be around or below 60–70 mm working depth (Godwin and Spoor, 1977). This means that using the discs to remove some of the topsoil from the tine can possibly reduce the risk of operating the tine below the critical depth which increases the horizontal force significantly. In this case, it is more or less free to attach the tine to the discs, since the extra force needed to pull the tine does not exceed the additional force which is necessary if operating the tine below the critical depth. It should theoretically be possible to reduce the operating depth of the tine or increase the width of the tine to reduce the depth/width ratio of the tine. However, neither of these possibilities is practically feasible: an increased width of the tine would increase the crop damage, and the operation depth is needed to create a furrow in the soil to receive the animal slurry. The horizontal force in the sandy loam did not increase at all when tines were operating alone and when discs were operated at 33 mm depth, but a tendency towards an increase in forces was registered in the loamy sand and the sandy soil. This slight difference can possibly be explained by the difference in rupture distance which, at all rake angles, was greater in the sandy loam than in the two other soil types.

5.3. Does the optimal design meet the practical demands of the task?

On the basis of the above-described experiments, no clear answer to the question of the optimal distance between tine and discs regarding draught force can be given, but it seems that the distance should be at least 250 mm in order to reduce the risk of blockage. The optimal rake angle was found to be 40° according to the lowest vertical and horizontal forces measured. The best position of the tine was identified to be 60 mm below the discs, while this position implies the biggest reduction in vertical force. The final question raised was which operating depth of the discs was preferable: 33 mm was found to be optimal regarding both horizontal and vertical forces.

Using the horizontal force measurements taken in the fall 2008 experiment in the sandy loam soil, where the injector was set to a rake angle of 40°, operating the discs at a speed of 0.56 m/s at a depth of 33 mm and with the tine at 10 cm below the soil surface, a horizontal force of 0.2 kN was required. Wheeler and Godwin (1996) found that horizontal force increased by 25% as a consequence of increasing the speed from 0.56 to 1.67 m/s, which means that 0.2 kN at 0.56 m/s is equivalent to 0.25 kN at 1.67 m/s. A calculation, similar to that in Eq. (1), of the energy input needed to pull an 18-m-wide slurry-injector machine mounted with such injectors as described, with an individual distance of 300 mm gives the following result:

$$P\ [\mathrm{kW}] = \frac{(0.25\ \mathrm{kN} \times 3\ \mathrm{injectors/m} \times 18\,\mathrm{m}) \times 1.66\,\mathrm{m/s}}{0.5} = \frac{13.5\,\mathrm{kN} \times 1.66\,\mathrm{m/s}}{0.5} = 45\,\mathrm{kW} \tag{2}$$

Compared with the results of other studies such as those of Rodhe and Etana (2005) and Pullen et al. (2004b), this injector reduced the draught force to about 30–40% and this would theoretically make it possible to pull an 18-m-wide injector after a regular slurry spreader with a 220 kW tractor. It must be borne in mind that the measurements were done in a soil bin where no heavy traffic took place and that the measurements were carried out on relatively sandy soils.

6. Conclusions

The method used for determining the horizontal and vertical forces required when working this type of injector in soil was found to be useful, especially if the measurements are carried out in dry or semi-dry soil with shear strength of 7 kPa or above. The results appear to be consistent and comparable with results from similar studies.

The combination of discs and tine reduces the damage to a growing winter wheat crop when the discs are operated at a depth of approximately 40 mm and the tine is 100 mm below the soil surface, compared with operating the tine alone. No significant crop damage was found compared with the untreated control crop.

The optimal design and set-up of the proposed soil injector with respect to horizontal and vertical forces seems to be as follows: (1) the discs operate at a depth of 30–40 mm, (2) the tine is placed as close as practically possible to the discs in order to degrade the soil structure in front of the discs and (3) the tine operates with a rake angle of about 40°.

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