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Band application of slurry in orchards using a prototype spreader with an automatic rate controller

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Abstract

A prototype slurry spreader for band application in orchards was designed, constructed, and tested. The spreader comprised several components: 1) 5 m^3 tank, 2) distribution device of trailing hoses to reduce ammonia emissions during application, 3) automatic rate controller to apply nitrogen per crop requirements, and 4) low-pressure, wide-section tyres to mitigate soil compaction and sward damage. The slurry tanker design fitted between tree row spacings accounting for tree shape differences. The spreading system consists of two groups of six trailing hoses; each hose group distributes slurry into two 1.0 m wide bands alongside the machine and 0.5 m from tree rows. Operator input of slurry total nitrogen content, determined by onboard hydrometer in the field, and target application rate in the control unit ensured that nitrogen was applied at a constant rate based on metering pump rotational speed as a function of machine forward speed. The rate control system was tested at different application doses and with rapid changes in machine forward speed (range of 3-9 km h^{-1}). The machine responded promptly (< 2 sec) to forward speed changes, and the spreader evenly distributed slurry in both application bands (D_{ave} < 2.5% on the treated surface). Band application of slurry by the trailing hose device reduced ammonia emissions by 63% compared to the common broadcast application system by splash plate.

Keywords: automatic rate control, orchards organic fertilisation, slurry band application.

Nomenclature

N	nitrogen
NH_3	ammonia
N_2O	nitrous oxide
Q	nitrogen application rate, kgN ha^{-1}
q	pump flow rate, l min^{-1}
W	row spacing - working width, m
F	forward speed, km h^{-1}
ha	hectare
TS	total solids
TN	total nitrogen
D_{ave}	Average deviation
X_i	amount of slurry in one container, kg
n	number of containers of each group of trailing hoses
$\overline{X}$	average amount of slurry in containers of each group of trailing hoses, kg
cv	cultivar

CEC	cationic exchange capacity
cmol	centimole
TKN	total Kjeldahl nitrogen
TAN	total ammonium nitrogen

1. Introduction

The agricultural livestock sector produces large amounts of liquid slurry that possesses substantial potential fertilisation benefits when properly used as manure (Chambers et al., 2000; Schröder, 2005). In Europe, animal slurries are mostly applied on grasslands and cereals (Jackson & Smith, 1997; Sieling et al., 1997; Rotz et al., 2004; Ceotto & Spallacci, 2006), less frequently in horticulture (Cushman & Snyder, 2002; Ribeiro et al., 2007), and uncommonly in orchards (Monge et al., 2000; Domínguez et al., 2010; Cerutti & Beccaro, 2012). Concomitant with its value as a fertiliser, the nitrogen (N) surplus (difference in N between inputs to soil and removals by crops) of the slurry can pose serious environmental risks not only to ground waters from nitrate leakage, but also to the atmosphere from gaseous losses of ammonia (NH_3) and nitrous oxide (N_2O) (Webb et al., 2013).

The western Po Valley of Italy is characterised by high livestock density farms from which most pig farmers wish to export their excess N to other farm areas. Orchards where animal manures are generally not applied represent an opportunity to improve N utilisation in soils that often suffer from progressive reduction of soil organic matter content (Cerutti et al., 2011). In the Piedmont region of northwest Italy, at present there are more than 63,000 ha of orchards that often lie very close, less than 7 km, to intensive livestock farms. Slurry transport to such areas could be feasible by high volume slurry tankers or lorries (Balsari & Airoldi, 1991) and it could be applied with spreaders capable of applying specific, generally low, amounts of nitrogen (< 50 kg [N] ha^{-1}) (Jordan et al., 2011). The slurry spreaders would need to fit within narrowly spaced rows (usually 4 m wide), provide even manure distribution, and minimise nutrient loss and soil compaction (Botta et al., 2008).

Currently, despite the large area of orchard in the region, no existing slurry spreader fulfils these requirements. Low capacity (< 4 m^3) slurry spreaders equipped with a splash plate are occasionally used, but a Department of Agriculture, Forestry and Food Sciences (DISAFA) experiments (internal report) trials have shown their application evenness, rate control, and NH_3 losses all to be very poor. In order to address the need for suitable machinery, a prototype slurry spreader was designed and constructed within the IMPREZA project (Italian acronym for: "Possibility of Reutilising Pig Manure in Fruit Production"), financed in Italy by the Piedmont region. According to the project plan, functional trials were performed to assess the technical and environmental performance (in terms of NH_3 emissions) of the developed prototype.

2. Materials and methods

2.1 Definition of the application surface

Prior to development of the slurry spreader, the available literature was reviewed to identify the target application area among the orchard rows, as well as the target application rate. Tree fertilisation is optimised when slurry is applied for efficient root up-take of nutrients, which Baldini (1986) and Baldoni et al. (1992) indicated is done in a band approximately 1.0 m wide and 0.5 m away from the tree row (s1). Furthermore, band application avoids contact between slurry and trees, which limits the risk of plant disease development.

The literature also revealed that the proper N application rate depends on the orchard cultivar and age (Rufat & Dejong, 2001; Chatzitheodorou et al., 2004). For a peach orchards, widespread in the western Po Valley, it ranges between 50 and 120 kg [N] y^{-1} (PSR, 2006). To obtain maximum organic fertilisation efficiency, about 70% of the rate must be applied in early spring and the remaining 30% in summer (Baldi et al., 2010; Baldi et al., 2012). According to these latter considerations, the slurry spreader was designed to apply slurry in two 1.0 m wide bands beside the machine and 0.5 m from the tree rows. A metering device with the ability to meet the application rates mentioned above was developed later.

2.2 The prototype slurry spreader

The slurry spreader was designed to work autonomously and to operate in the narrow row spacing (4 - 5 m) characteristic of orchards in northwest Italy.

The spreader contains several components (Fig. 2):

- box-section shaped steel frame;
- 5 m^3 galvanized steel tank equipped with a slurry level sensor;
- non-steering axle fitted with wide section and low pressure tyres (500/60 -22.5) to reduce soil compaction and sward damage (Keller & Arvidsson, 2004; Hamzaa & Anderson, 2005);

- hydraulic-driven volumetric lobe pump (Vogelsang R140, made by Hugo Vogelsang Maschinenbau GmbH, Holthöge, Essen, Germany) equipped with a rotation speed sensor;
- band spreading device consisting of a rotary distributor and 12 hoses (6 each side) mounted on a hydraulically-actuated frame to place slurry 0.5 m from tree rows;
- automatic rate controller provided by DICKEY-John® Corporation, Auburn, IL, USA which has three main components (Fig. 3):
  - proximity sensor for determining spreader forward speed, mounted on right wheel rim of the spreader;
  - central electronic unit for operating parameter control and application;
  - control panel to set and verify operating parameters (forward speed, N application rate).

At setup, the operator inputs several parameters into the control panel: row spacing (working width (m)), manure nitrogen concentration (kg [N] m^{-3}), and target application rate (kg [N] ha^{-1}). The manure N content (kg [N] m^{-3}) is estimated indirectly by the hydrometer method (Zhu et al., 2003), which utilises the linear relationships between the density and N content of the slurry as described by Piccinini & Bortone (1991). This method is not only simple, inexpensive, and reliable compared to other methods (Scotford et al., 1998; Saeys et al., 2005), but it is also accurate enough for our purpose.

The on-board computer calculated the application rate of the spreader per the following equation:

$$Q = 0.6 \cdot \frac{q \cdot N}{W \cdot F} \qquad (1)$$

where

Q = is the nitrogen application rate (kg [N] ha^{-1}),

q = is pump flow rate (l min^{-1}),

W = is row spacing or working width (m),

F = is forward speed (km h^{-1}), and

N = is estimated nitrogen content in the slurry (kg [N] m^{-3}).

The automatic controller adjusts the slurry rate according to spreader travel speed and working width. The system verifies that the applied application rate matches the target rate by determining the rotating speed of the volumetric pump and, if necessary, adjusting it by acting on the hydraulic engine linked to the lobe pump shaft. The spreading system consisted of two groups of six trailing hoses, spaced 0.2 m from each other for a total band spread width of 1.0 m for each group. Each hose group is mounted atop a frame and the two frames are actuated by a hydraulic piston, so that they can be spaced up to 1.0 m aside the tanker. This configuration allowed the tanker to be properly positioned for band application to rows of different spacing and trees of various shapes (Fig. 4).

A machine with multiple width settings addresses the needs for slurry application in most of the orchards in the western Po Valley which are characterised by rows spaced 4 m (peach) and 5 m (hazelnut) apart. A band application design also minimises NH_3 emission during land application (Malgeryd, 1998; Smith et al., 2000; Misselbrook et al., 2002). The slurry manure was delivered to the trailing hoses using the volumetric pump (Fig. 5a) through a rotary distributor (Fig. 5b) positioned on the spreading device. Each trailing hose could be closed by a spherical valve to limit distribution to one side of the machine when necessary.

2.3 Functional trials

Transverse and longitudinal distribution uniformity was evaluated following European Standard EN 13406 (2002) requirements. Experiments were carried out to verify the accuracy of the automatic rate controller (Scotford et al., 2001). For these tests, pig slurry from a fattening room of a farrow-to-finish farm was employed with a density of 1014 kg m^{-3}, a total solids (TS) content of 27.2 kg m^{-3}, and a total nitrogen (TN) content of 3.0 kg m^{-3}.

2.3.1 Transverse distribution evenness

The replicated tests were performed on an even, horizontal surface and at three application rates (25, 50, and 100 kg [N] ha^{-1}). To collect the slurry, 0.30 m^3 containers were used. The pump was activated and run until constant slurry was delivered from all the hoses, at which point containers were placed under each hose on both sides of the machine. The time required to fill about 90% of the container capacity was recorded, and the collected slurry quantity was determined by weighing each container on an electronic scale (Kern ECB 50K50, made by KERN & Sohn GmbH, Balingen, Baden-Württemberg, Germany; capacity 50 kg, accuracy 0.05 kg). The data were then processed in order to obtain the distribution pattern of trailing hoses. For each transverse distribution test performed, the average deviation (D_{ave}) was calculated by:

$$D_{ave} = 100 \cdot \frac{1}{n\overline{X}} \sum_{i=1}^{n} \left| X_i - \overline{X} \right| \qquad (2)$$

where

D_{ave} = is the average deviation (%),

X_i = is the amount (kg) of slurry in one container,

n = is the number of containers of each group of trailing hoses and

$\overline{X}$ = is the average amount (kg) of slurry in containers of each group of trailing hoses given by:

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \qquad (3)$$

2.3.2 Longitudinal distribution evenness

Slurry flow was determined by registering changes in unit mass and the associated elapsed time from test start for changes of 5 kg s^{-1} or less. A portable single axle weighbridge scale (Sinergica® model WWSD10T, made by Sinergica Soluzioni S.r.l., Montesilvano, Pesaro, Italy) with a 10,000 kg capacity accurate to 1 kg was used for this purpose. The automatic rate controller was forced to apply 50 and 100 kg [N] ha^{-1} (appropriate for a 4 m working width and a 5 km h^{-1} forward speed), and the scale control device was set to record weight every 5 s during tank emptying. The tests took place on a slurry tank-filling platform near an above ground storage unit as the slurry was discharged into a mixing pit.

2.3.3 Automatic rate controller accuracy

A series of tests was conducted to assess the precision and response time of the automatic rate controller to variations in spreader forward speed. The tests were performed by placing the spreader wheel with a proximity sensor on a hydraulic-driven roller device to simulate forward speeds between 1.0 and 10.0 km h^{-1}. A data logger recorded the signals from the wheel proximity sensor and from the speed sensor mounted on the lobe pump shaft. Three N application rates (20, 40, and 60 kg [N] ha^{-1})

were set on the central unit and tested independently as forward speeds were set to 3.0 and gradually increased to 5.0 km h^{-1}, and then again from 5.0 to 9.0 km h^{-1}. The response of the lobe pump to the forward speed changes was continuously recorded throughout the various settings.

2.4 Slurry application and measurement of ammonia emissions

The prototype was used for slurry application to a peach orchard (cv Spring bright, orchard design 1.80 m ^{x} 3.90 m). Pig slurry was collected from a storage tank at a fattening house of a farrow to finish farm. Prior to field application, the slurry underwent hydrometer analysis to determine its N content. The resulting N content, along with the required application rate and N content, were then input into the central unit. The slurry was applied during the latter half of both April and June on two plots (total surface: 3200 m^2). To confirm that the spreader delivered the required application rate, it was weighed before and after each of the two distributions. Application rates and estimated N content of the slurry are reported in Table 1.

	1st application	2nd application
Nitrogen application rate (kg [N] ha^{-1})	56	10
Nitrogen content of the slurry (kg [N] m^{-3})	4.0	3.1

Table 1 – Peach orchard trials: application rates and estimated nitrogen content of the slurry (hydrometer method).

After the second slurry application, NH_3 emissions were measured using wind tunnels (Dinuccio et al., 2012). The resulting NH_3 emissions were compared from three different application techniques: 1) band application by trailing hoses, 2) band application by trailing hoses followed by immediate soil incorporation, and 3) the common broadcast application system by splash plate. Slurry was incorporated into the soil manually by shovel to a depth of 0.10 m. An adapted slurry spreader equipped with a lateral splash plate was utilised for common broadcast application. The peach orchard soil was silt loamy sub-acid soil with 0.11% TN, 28.7 cmol kg^{-1} cationic exchange capacity (CEC), and pH = 6.4. All treatments were applied in triplicate in a randomised block design. The experimental area used for NH_3 emission trials was 176 m^2, divided into nine, parallel plots of 19.5 m^2 (3.90 m ^{x} 5.00 m) each. Two wind tunnels per plot (n = 6 per treatment) were used. Each wind tunnel covered a surface of 0.32 m^2 (0.80 m length ^{x} 0.40 m width). Immediately following manure application, the wind tunnels were placed over the plots and measurement began. Soil surface air velocity was adjusted to 0.6 m s^{-1} (Dinuccio et al., 2012) and samples were measured daily over 96 h. During the tests, environmental temperatures were recorded daily with a Hobo® Onset (Onset Computer Corporation, Bourne, Massachusetts, USA) data logger. Three samples per load of applied manure (n = 3 per treatment) were taken for laboratory analysis of TS, total Kjeldahl nitrogen (TKN), total ammonium nitrogen (TAN), and pH according to standard analytical methods. Specifically, TS were determined by drying 100 g of fresh material in a oven at 105 °C to a constant weight; TKN and TAN were analysed by the Kjeldahl standard method (AOAC, 1990), and pH was determined by pH-metre HI 9026 (Hanna Instruments, Italy).

Ammonia emission data were processed by ANOVA. When significant, the means were separated using the Tukey post-hoc test. Treatment differences were accepted if $p < 0.05$.

2.5 Slurry spreader productivity

The following were recorded during orchard application:

- effective field time (i.e. time of slurry distribution);
- in-field displacement time (i.e. machine time in the field with the metering system turned off, such as travel within the field and turning time);
- travel time (i.e. travel to and from field, farmstead movement to reach slurry basin);
- loading time (i.e. time required for tank filling);
- time for repair, maintenance, and setting the machine.

Collecting these data allowed determination of field efficiency (%), effective field capacity (ha h^{-1}), and effective material capacity (m^3slurry h^{-1}), according to ASAE Standard EP496.3 guidelines (ASABE Standards, 2010). These data allowed development of a worksheet to value the effect of different operating conditions on machine efficiency, and alternative options for transport and distribution chains suitable for pig slurry delocalisation in orchard areas.

3. Results and Discussion

3.1 Transverse distribution evenness

As shown in Fig. 6, the spreading system produces an even application of slurry while operating with a D_{ave} of less than 3%. The ability to spread slurry uniformly and simultaneously on both sides of the machine is an important advance in spreader technology. The calculated D_{ave} values of 0.30%, 1.89%, and 2.47% for N application rates of 100, 25, and 50 kg [N] ha^{-1}, respectively, was based on total slurry flow rates from both groups of trailing hoses.

3.2 Longitudinal distribution evenness

Test results highlighted the steady flow of slurry (Fig. 7) that was attained during tank unloading under both (50 kg [N] ha^{-1} and 100 kg [N] ha^{-1}) tests conditions. A steady slurry flow during tank emptying produces a longitudinal distribution unaffected by slurry level into the tank, a basic requirement for proper application rate control.

3.3 Automatic rate controller accuracy

The tests also highlighted accurate signal reading by the various control unit sensors, and sufficiently precise management by the control system (solenoid valves that control the hydraulic system) that activates the lobe pump engine. The automatic rate controller demonstrated its ability to adjust pump rotation speed quickly after machine forward speed changes. Indeed, as the slurry spreader forward speed moved from 3.0 to 9.0 km h^{-1}, the system adjusted the pump rotation speed in less than 2 s (Fig. 8).

The system applied slurry at 40.0 ± 0.2 kg [N] ha^{-1}, even with two variations in forward speed that required about 10 s each to restore the proper application rate (Fig. 9). Similar results were obtained with application rates of 20 and 60 kg [N] ha^{-1}.

3.4 Slurry application and measurement of ammonia emissions

The automatic rate controller enabled the operator to apply the desired amount of N regardless of spreader forward speed. Measured N application rates were 2.9% (first test) and 3.8% (second test) higher than those targeted (Table 2).

	Application rate	
	target kg [N] ha^{-1}	measured kg [N] ha^{-1}
1^{st} application	56	57.6
2^{nd} application	10	10.4

Table 2 – Target and obtained application rates obtained during field trials

Table 3 shows the chemical characteristics of the slurry used for NH_3 emissions testing.

	pH	TS kg m^{-3}	TKN kg m^{-3}	TAN kg m^{-3}
Band application	7.5 (0.07)	30.5 (0.66)	2.89 (0.08)	2.09 (0.07)
Band application + harrowing				
Splash plate	7.3 (0.04)	31.2 (0.54)	2.95 (0.06)	2.17 (0.06)

Table 3 – Main chemical and physical characteristics of the slurry used for NH_3 emissions testing (standard error in parentheses, n=3)

During NH_3 emission measurement, the average environmental temperature was 22.4°C (range 16.3-28.8 °C) with an average relative humidity of 78% (range 55-100%). Total N lost as NH_3 from broadcast application by splash plate was 10% of the total N applied (Fig. 10). Band application of slurry significantly reduced NH_3 emissions, and were just below 3.7% of applied N. Slurry incorporation following band application reduced emissions the most, 2.7% of the N applied, although this result was not statistically ($p > 0.05$) different from that obtained by band application (Fig. 10). Harrowing after band application is not always feasible due to the possibility of sward and root damage.

3.5 Slurry spreader productivity

The distance for transport of the slurry between the basin and the field averaged 1450 m. During the first slurry application, 57.6 kg [N] ha^{-1}, the spreader averaged 6.2 km h^{-1}. The effective material capacity was 12.1 m^{3} [slurry] h^{-1} and the effective field capacity was 0.84 ha h^{-1}, equating to a 33.9% field efficiency (Fig. 11). During the lighter second application, 10.4 kg [N] ha^{-1}, the spreader averaged 6.3 km h^{-1}. These values, combined with an effective material capacity of 5.2 m^{3}slurry h^{-1} and an effective field capacity of 1.54 ha h^{-1}, yielded a 61.0% field efficiency (Fig. 11).

The low field efficiency calculated for the higher (57.6 kg [N] ha^{-1}) application rate was mainly due to the impact of time spent travelling to and from the field, as well as moving within (Fig. 10). Optimising spreader runs in the field (i.e., avoiding the down time caused by returning to the slurry storage basin by refilling the tank spreader in the field) may increase field efficiency by 57.2% and 73.1% at application rates of 57.6 kg [N] ha^{-1} and 10.4 kg [N] ha^{-1} (Fig. 12), respectively.

To load the tank spreader in the field, a proper transport chain from the storage basin to the field needs to be created for an effective material capacity, defined as equal to or greater than that of the slurry spreader. In the case of a spring slurry distribution at 57.6 kg [N] ha^{-1}, the transport chain must operate with an effective material capacity of at least 20.4 m^{3} h^{-1}. For the case of a three-axle vacuum tank of 15 m^{3} (the maximum legal gross weight for Italy: 20 Mg) and temporary storage in a field edge slurry mobile container of 20 m^{3}, the transport distance must equal less than 7.7 km (Fig. 13). Similarly, a 16 m^{3} pump tank mounted on a three-axle truck (maximum legal gross weight for Italy: 25 Mg) could operate at a maximum transport distance of 13.1 k.m, and a 26 m^3 pump tank mounted on a three-axle semi-trailer combination (maximum legal gross weight for Italy: 44 Mg) could operate at a distance of 28.0 km.

4. Conclusions

Under our test conditions, the developed prototype slurry spreader was shown to be a reliable machine for slurry application in orchards for three principle reasons: 1) proper nitrogen quantity application due to the efficacy of its automatic rate controller; 2) uniform slurry spread due to the performance of the metering pump and rotary distributor; 3) low environmental impact as a result of reduced ammonia emissions during slurry application. To confirm these results, additional trials shall be performed, using different manure types in orchards planted with different soils and trees of varying training systems. A full evaluation of the machine, including the environmental impact of gases other than NH_3 (e.g., nitrous oxide), slurry nutrient leaching, and soil quality as well as a comparison with manure application costs relative to other techniques, is already under study by our research group.

Under our test conditions, the highest application rate (57.6 kg [N] ha^{-1}) reduced field efficiency as a result of low spreader tank capacity. Field capacity can be increased, however, by filling the slurry spreader in the field, and by choosing a proper transport and temporary storage chain. The need to suitably match the transport chain with specific machines/implements for the greater distances associated with more remote orchards requires agricultural contractors to provide high capacity transport tanker trailer systems and mobile field-edge slurry containers.

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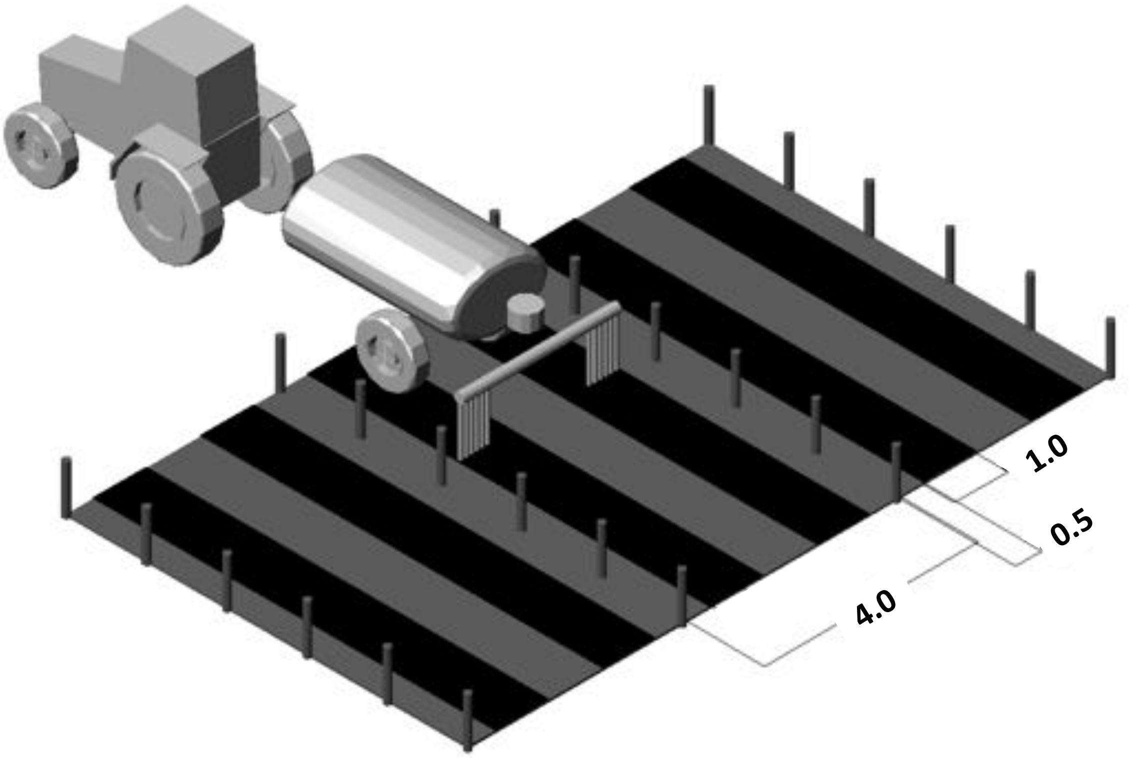


Fig. 1.

Fig. 2

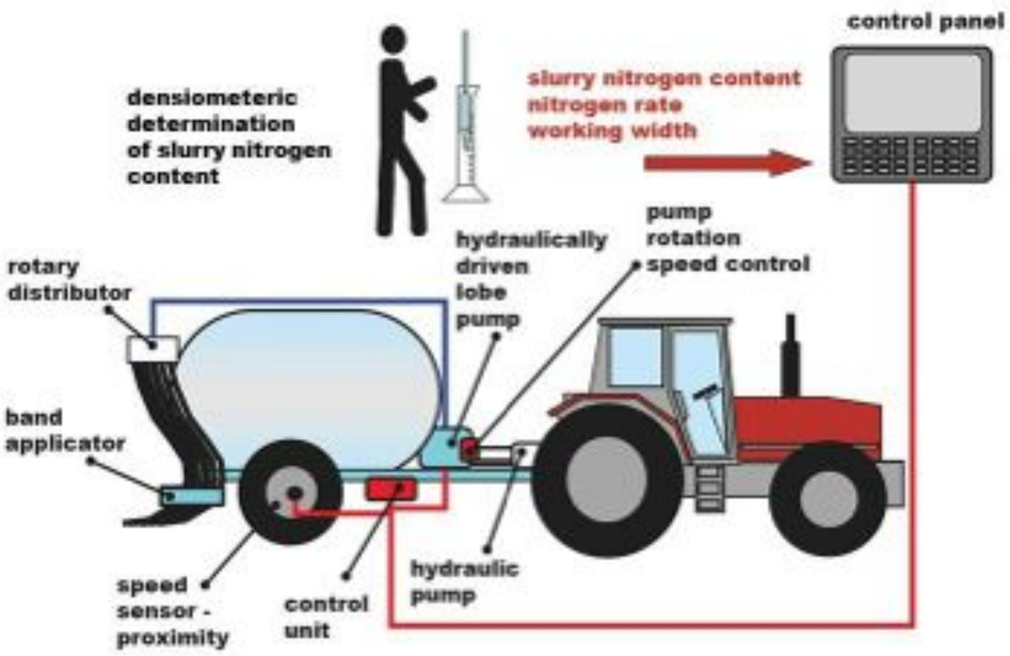

control panel
densiometeric determination of slurry nitrogen content
slurry nitrogen content
nitrogen rate
working width
rotary distributor
hydraulically driven lobe pump
pump rotation speed control
band applicator
speed sensor - proximity
control unit
hydraulic pump

Fig. 3

a b

Fig. 4

a **b**

Fig. 5

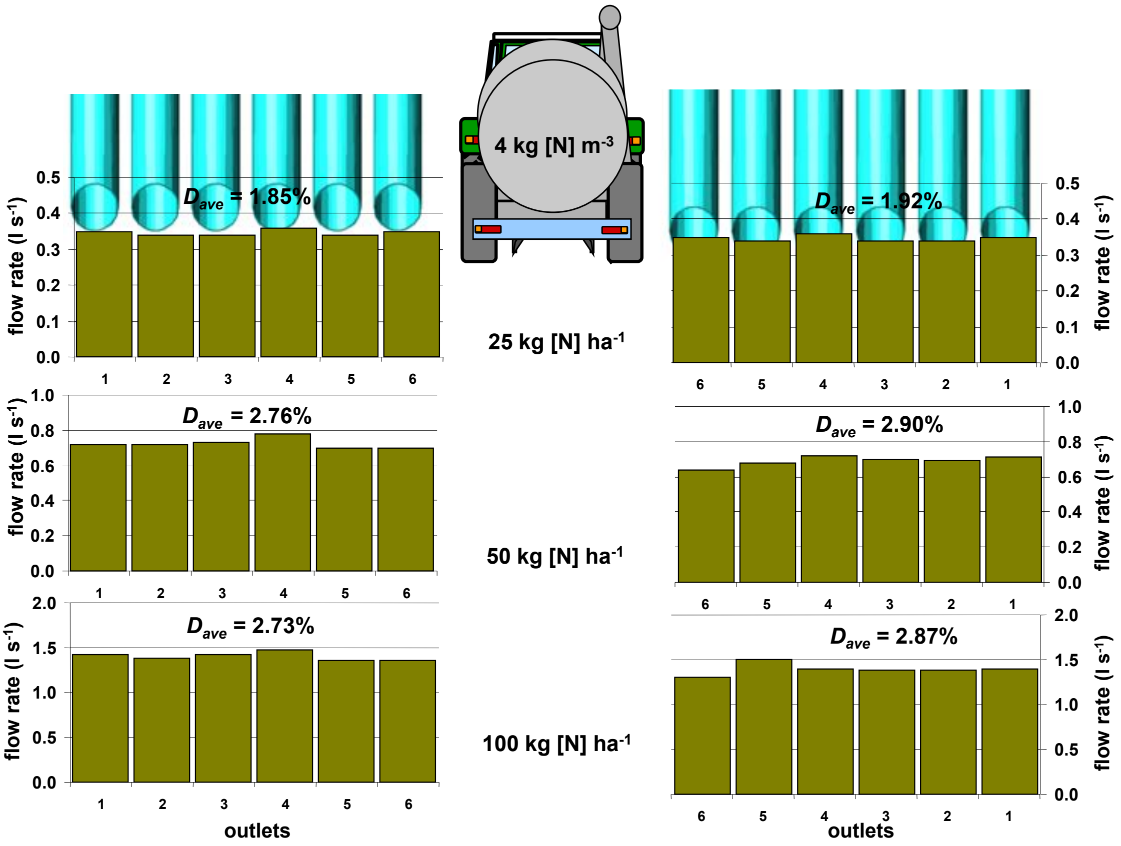
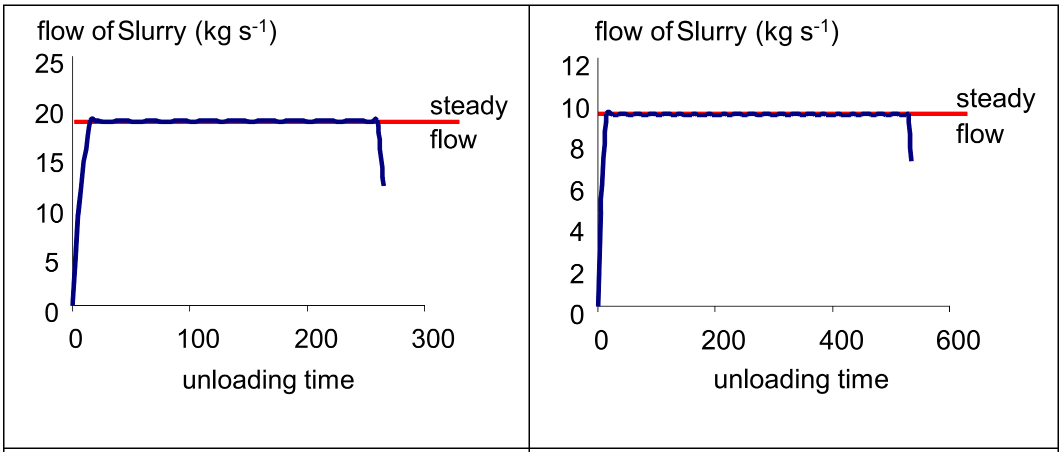
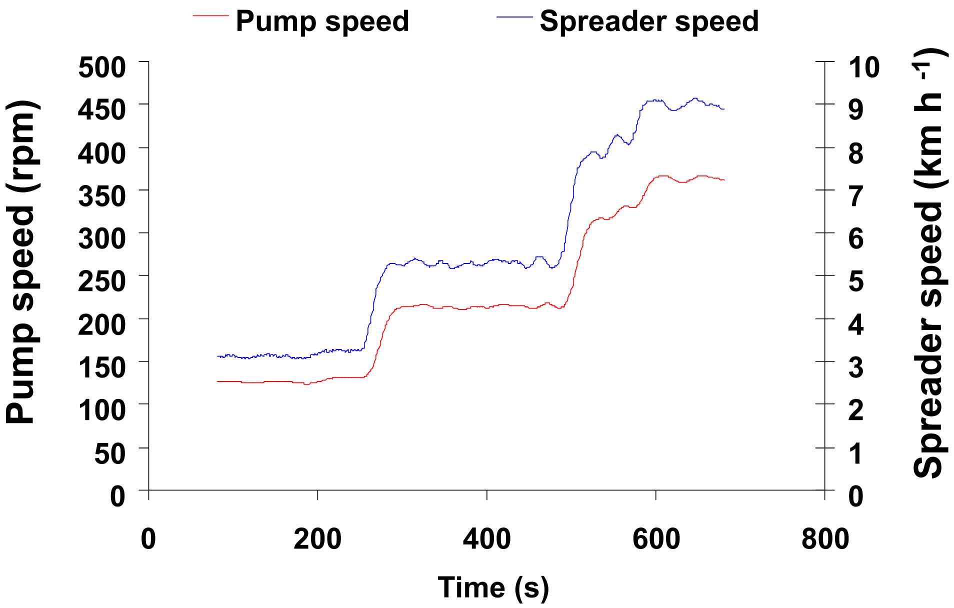

4 kg [N] m-3
25 kg [N] ha-1
50 kg [N] ha-1
100 kg [N] ha-1
D_ave = 1.85%
D_ave = 1.92%
D_ave = 2.76%
D_ave = 2.90%
D_ave = 2.73%
D_ave = 2.87%
flow rate (l s-1)
0.0 0.1 0.2 0.3 0.4 0.5
0.0 0.2 0.4 0.6 0.8 1.0
0.0 0.5 1.0 1.5 2.0
1 2 3 4 5 6
6 5 4 3 2 1
outlets

Fig. 6


flow of Slurry (kg s-1)
25
20
15
10
5
0
0
100
200
300
unloading time
steady flow
flow of Slurry (kg s-1)
12
10
8
6
4
2
0
0
200
400
600
unloading time
steady flow

a b

Fig. 7

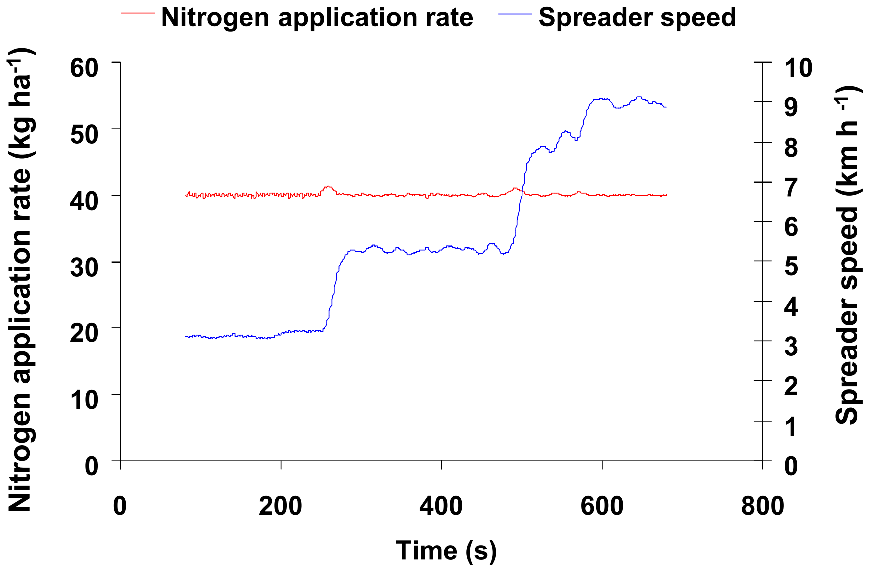


509

510 Fig. 8

511

512



513

514 Fig. 9

515

516

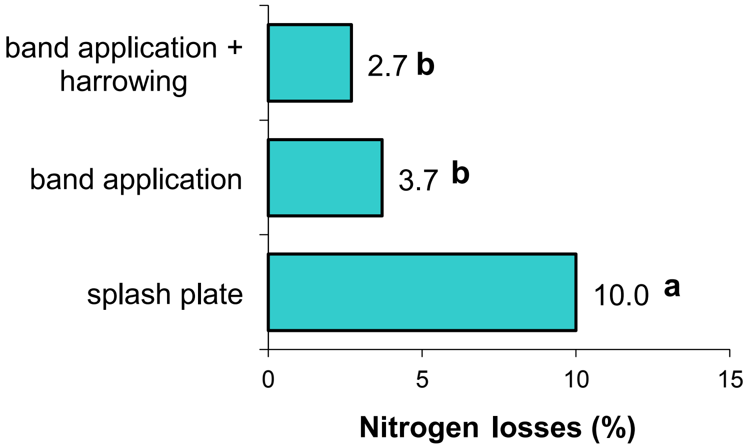

band application + harrowing
2.7 b
band application
3.7 b
splash plate
10.0 a
0
5
10
15
Nitrogen losses (%)

Fig. 10

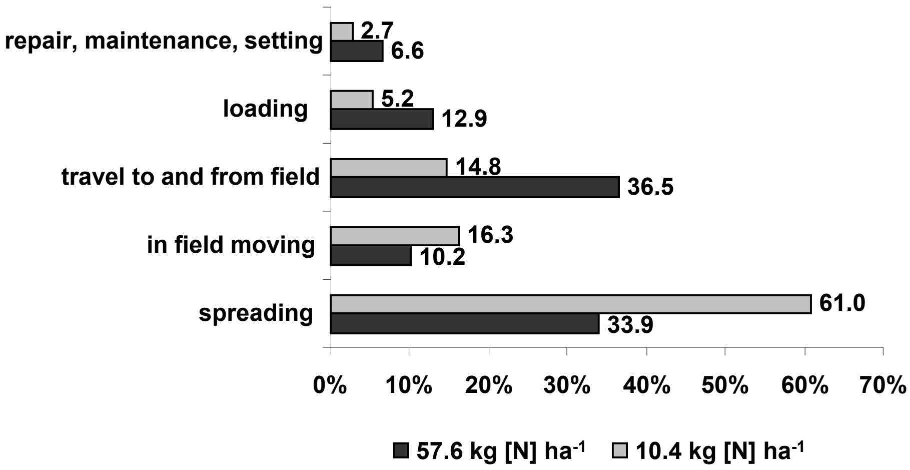

repair, maintenance, setting
2.7
6.6
loading
5.2
12.9
travel to and from field
14.8
36.5
in field moving
16.3
10.2
spreading
61.0
33.9
0%
10%
20%
30%
40%
50%
60%
70%
57.6 kg [N] ha-1
10.4 kg [N] ha-1

Fig. 11

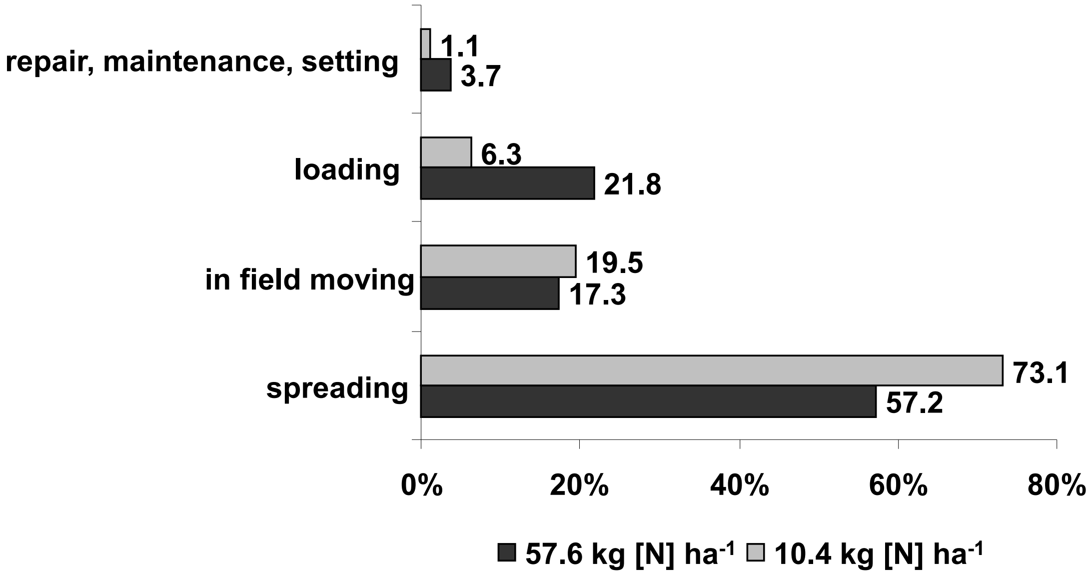

repair, maintenance, setting
1.1
3.7
loading
6.3
21.8
in field moving
19.5
17.3
spreading
73.1
57.2
0%
20%
40%
60%
80%
■ 57.6 kg [N] ha-1
□ 10.4 kg [N] ha-1

Fig. 12

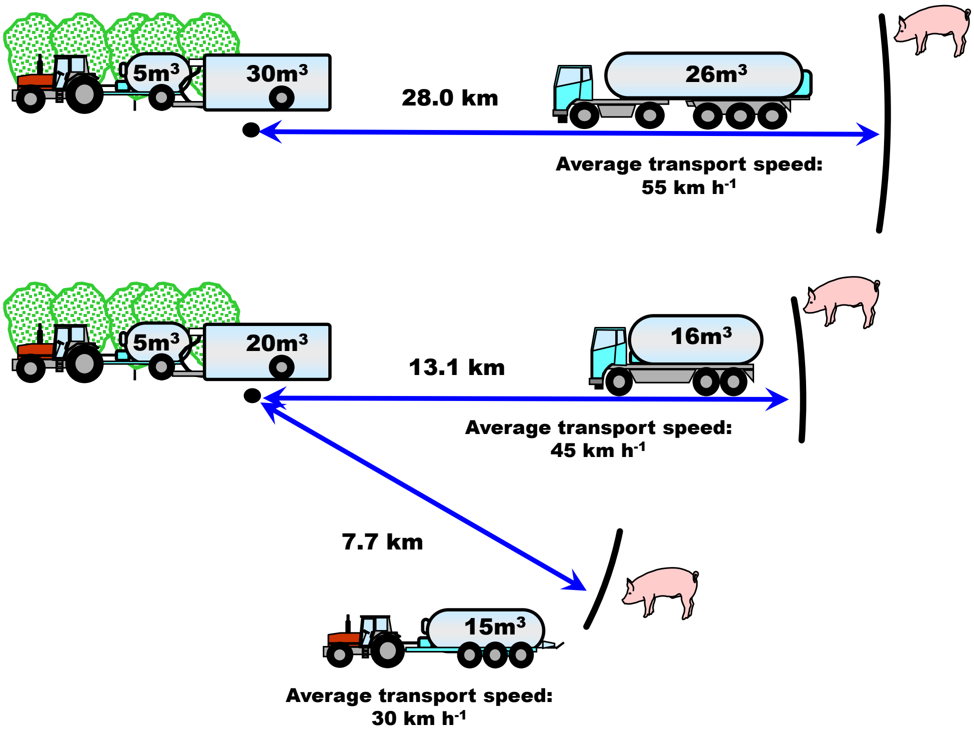

5m³
30m³
28.0 km
26m³
Average transport speed:
55 km h-1
5m³
20m³
13.1 km
16m³
Average transport speed:
45 km h-1
7.7 km
15m³
Average transport speed:
30 km h-1

Fig. 13

Figure captions

Fig. 1 Slurry spreader with application device and bands (dark grey) of manure for tree fertilisation. Distance m.

Fig. 2 Developed prototype slurry spreader with band application distribution system operating in a peach orchard.

Fig. 3 Layout of the automatic rate controller.

Fig. 4 Band application spreader at minimum (a) (transport position) and maximum (b) spacing.

Fig. 5 Lobe volumetric pump (a) and rotary distributor (b) with a spherical valve on each hose.

Fig. 6 Transverse distribution patterns of band applicator hoses on the left (a) and right (b) sides of the spreader.

Fig. 7 Flow of slurry recorded during the longitudinal distribution evenness trial at application rates of 100 kg [N] ha^{-1} (a) and 50 kg [N] ha^{-1} (b).

Fig. 8 Response time of pump rotation speed *versus* machine forward speed.

Fig. 9 Response time of the automatic nitrogen rate controller vs. machine forward speed in the case of an application rate of 40 kg [N] ha^{-1} and a forward speed of the slurry spreader ranging from 3.0 to 9.0 km h^{-1}.

Fig. 10 Nitrogen losses after land application of slurry (data with the same letter are not statistically different - Tukey post-hoc test, $p < 0.05$).

Fig. 11 Different work times under field test conditions. Total time: 71.4 min ha^{-1} at a rate of 57.6 kg [N] ha^{-1}, and 39.0 min ha^{-1} at a rate of 10.4 kg [N] ha^{-1}.

Fig. 12 Different work times of an in-field spreader tank load. Total time: 42.3 min ha^{-1} at the rate of 57.6 kg [N] ha^{-1}; 32.6 min ha^{-1} at the rate of 10.4 kg [N] ha^{-1}.

Fig. 13 Maximum distance between slurry storage and orchard field for different transport chains.