LANDTECHNIK 70(6), 2015, 238–252
DOI:10.15150/lt.2015.3114

LANDTECHNIK
AGRICULTURAL ENGINEERING

Development of a direct injection system without time lag for application of plant protection products

Mathias Krebs, Dirk Rautmann, Henning Nordmeyer, Jens Karl Wegener

Earlier systems for direct injection of plant protection products (PPP) did not satisfy the requirements of practical farming because of time lag between dosing of PPP and its application and because of cleaning problems. To offer solutions in this respect, a prototype field sprayer with direct injection for site-specific application was conceived, constructed and tested. This prototype has three separate nozzle lines, each with its own direct injection unit capable of preloading with individual spray mixture so that no time lag occurs in application. Calculated were the theoretically achievable working widths possible with the applied direct injection dosing pumps. Test stand measurements were carried out to determine dosing precision. The results show that good dosing precision is achieved in the different settings. Hereby, attention should be paid to the working range of the dosing pumps. The results show that practically-applicable systems for direct injection without time lag based on the developed prototype are possible offering the ability to apply PPP more precisely and site-specifically.

Key words
Direct injection, field sprayers, plant protection products, precision farming, site-specific application

Current conventional application of tank mixes for heterogeneous crop pests leads to relatively high amounts of plant protection products (PPP) being applied in specific areas where the crop treatment threshold is not reached and, in fact, no application is required. Using direct injection systems means individual PPP can be separately applied site-specifically, thereby reducing respective consumption without foreseeable yield penalty, thus increasing the economic return from crop production through saving PPP and also reducing impact on the environment (Wartenberg 2000).

The term site-specific application involves, on the one hand, matching application (amount of active ingredient) to requirement and, on the other, treatment on a specified area of the field (yes/no = treatment or no treatment). To reduce spraying operations over the crop, the usual practice so far is to prepare tank mixes of different PPP, which in turn means that site-specific application of individual PPP is impossible. Required here are alternative solutions such as direct injection or multi-tank sprayers whereby individual spray mixtures are in separate tanks. Gerhards (2004) reported trial results with a GPS-steered three-tank sprayer with boom section control (3 m) whereby herbicide was selectively and site-specifically applied.

received 29 July 2015 | accepted 23 October 2015| published 7 December 2015

Thus, in 2003 this technique achieved savings in various locations for dicotyledonous and grass weed control in small grain cereal, sugar beet and maize crops. These savings in spray material application were up to 96 % in small grain cereals, as much as 61 % in maize and up to 64 % in sugar beet, illustrating well the potential of this form of site-specific crop protection. However, the multi-tank sprayers increased the problem of residual spray amounts and reduced operational speed, so that further development of the three-tank Cerberus field sprayer from Rau was stopped (Holtmann 2010).

The direct injection concept with field sprayers is actually over 30 years old, premiered as early as 1989, following several years of development, by the Swiss Ciba-Geigy firm in cooperation with the dosing pump manufacturer MSR (Neunaber 1989). However, this system failed to establish itself on the market because of poor practicability. Despite this, a functioning system for direct injection continued to be sought by farmers and agricultural advisors (Garrelts 2013, Rimpau 2006). At Agritechnica 2007 the manufacturer Lechler won a silver medal for development of a direct injection system for spray applications from 0.2 to 5.0 l/ha (Eikel 2007). Further development of this system was, however, also halted. The improvement and development of direct injection systems was also worked on by different manufacturers outside Germany such as Berthoud in France, which won a “SIMA Innovation Award 2013” for development of a cyclone-mixer for direct injection of up to three different PPP into the water flow (Berthoud 2013). Although this is still not available on the market, its presence infers that many manufacturers work on the theme of direct injection and that there remains a demand on the market for practicable systems, or that such a demand is at least expected by many manufacturers. In North and South America established manufacturers such as AGCO (RoGator) and John Deere already offer direct injection sprayers ex-works (Wehrspann 2013) although, so far, they do not do so in Europe. In northern Europe, there are manufacturers, such as Kyndestoft or Danfoil, offering direct injection systems ex-works (Kyndestoft 2015, Danfoil 2015). Their market share is, however, small. Problematical with the systems developed so far is either the dosing precision, the cleaning, or the too long time lag.

If a plant protection product is pumped via direct injection into the water flow at a central point, it took too long for the required concentration to be delivered to all the nozzle exits in the systems available in the past. The effect is also described by manufacturer Lechler in the operator manual for the Lechler VarioInject-System (Lechler 2007). This time lag is caused by the direct injection point in the nozzle line being too far away from the actual nozzles and by the markedly different distances from injection point to the various nozzles. This leads to the butterfly effect as shown in Figure 1: the water-PPP mix produced by direct injection does not arrive at all the nozzles at the same time. Instead, there occurs a time lag before delivery along the entire boom.

With central injection into the nozzle pipeline, Vondricka and Schulze Lammers (2009) speak of a more than 20 seconds time lag. Further problems, which have already appeared in trials of different direct injection systems, concern the dependence of dosing precision on rheological properties (elasticity, viscosity, plasticity) of the crop spray product under different pressures and temperatures and also the cleaning of the system, as well as the handling of the flushing water.

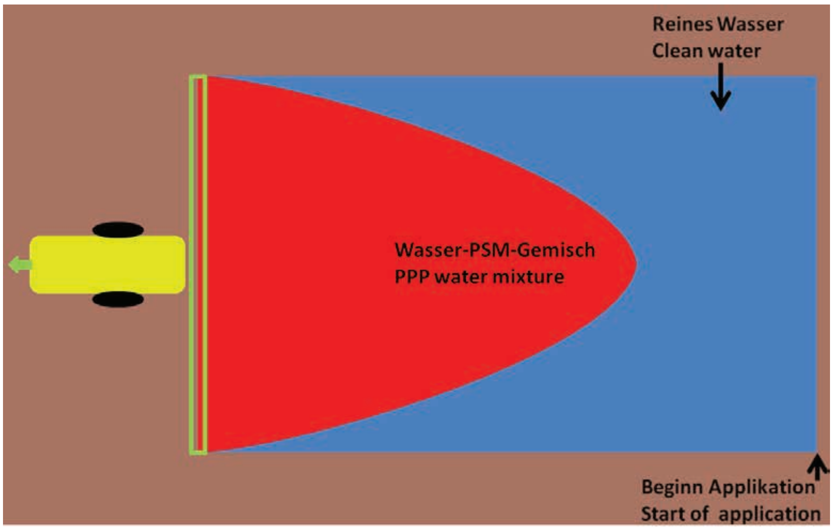

Figure 1: Diagram of the butterfly effect created through direct injection of spray material without preloading

Towards solving these acknowledged problems, a joint project was initiated between the firm Herbert Dammann GmbH and the Julius Kühn-Institute (Institute for Application Techniques in Plant Protection and Institute for Plant Protection in Field Crops and Grassland). An innovative field sprayer prototype with direct injection of PPP was developed, constructed and tested. During the first trials, two test questions were researched:

- Can the direct injection pumps manage to dose at a precision ± 7 % of the reference value while delivering different amounts of spray within the working range given by the manufacturer?
- Which working widths (sectional widths) can be covered by both sizes of pumps used for the direct injection in association with the spray application amount at working speeds 6, 8, 10 and 12 km/h?

Product specifications

At the beginning of the project, analysis was carried out on where the previous direct injection system problems lay and why these had led to field sprayers with direct injection being comparatively rare in European farming. As already mentioned, main reasons for this were the long reaction periods, the imprecise dosing and the cleaning problems. Additionally, the sprayers of this type offered up until now were substantially more complicated in operation. For this reason, the future system should offer direct injection without time lag, site-specific application and should have the capability of applying at least three different sprays independently of each other. Thereby, dosing precision should lie in the range with a maximum ± 7 % of reference value. System operation should suit the demands of practical farming and an effective cleaning of the entire system should be possible.

Functional specifications

Because length of time lag in previous central direct injection systems is caused by the injection point being too far from the nozzle exits, this leaves only two solutions: injection as directly as possible at the nozzle, or “preloading“ of the nozzle line. Decentral injection as near as possible to the nozzles was rejected. Work at the University of Bonn has shown that precise dosing of sprays of different viscosity in very small amounts, as is required for individual nozzles, and maintaining maximum deviations ± 7 % of reference value is currently technically not realizable (Walgenbach 2014). The prototype was therefore fitted with separate lines for each of the three direct injection systems. Thus, each nozzle line can be filled with its own mix of water and PPP. The advantages will be described in detail later in the paragraph headed “Preloading”.

At the beginning of the project, a supplier for the dosing pumps for direct injecting had to be selected. International suppliers of direct injection systems are mainly to be found in the USA, e. g. TeeJet and Raven Industries. Evaluation of the systems took place parallel to conception of the prototype and led to the Raven Industries system “Sidekick” being selected.

Concept variations

In the conception phase, there were various designs possible for the different component groups and functional areas such as carrier liquid tank, plant protection product tank, tank cleaning, pumps and drives, nozzle lines on the booms and nozzle switching system, spray application regulation, injection point for PPP, etc. For every component group, or each functional area, advantages and disadvantages were listed. Consideration of the different points was part of preparation for the first prototype design.

Prototype construction

The realized prototype (Figure 2) has a maximum working width of 27 m and comprises a main tank divided into five single tanks. Three of these tanks have different capacities supplying the spraying system (system I with 4,500 litres, system II 1itres, 500 l and system III 500 litres). The water tank from system I is additionally equipped with a mixing unit and cleaning nozzles, so that here there is also the possibility to work conventionally with a tank mixture instead of the direct injection. For this purpose, the sprayer is equipped with an induction lock. Thus, solid formulated PPP can also be used and applied with system I. The tanks from system II and III are only for water and are not fitted with

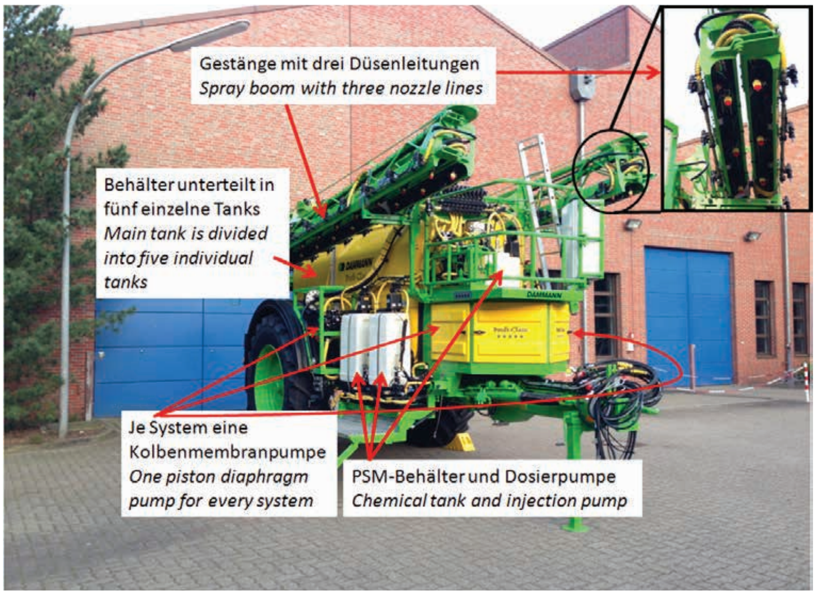

Figure 2: Crop sprayer prototype with direct injection (Photo: M. Krebs)

cleaning nozzles. The further tanks comprise a 500 litres fresh water container and a flushing liquid collection tank for liquid from the circuit-flushing line if preloading and for the cleaning liquid before final cleaning if direct injection is used. This has 200 litres capacity and – as the tank in system I – also cleaning nozzles. The booms feature three parallel nozzle pipelines. Every nozzle line is assigned a direct injection unit comprising spray tank and dosing pump as well as individual hydraulically driven piston diaphragm pump for moving the carrier liquid.

This concept gives three application systems on one vehicle that are fully functional independently from one another. Additionally, two further hydraulically driven pumps are built into the prototype, which are necessary for pumping cleaning water and for pumping out flushing liquid.

Direct injection pumps

The system injects the plant protection product into the carrier liquid stream directly before a mixing chamber built into the nozzle line. Figure 3 is a schematic representation of the function principle in the system used by Raven.

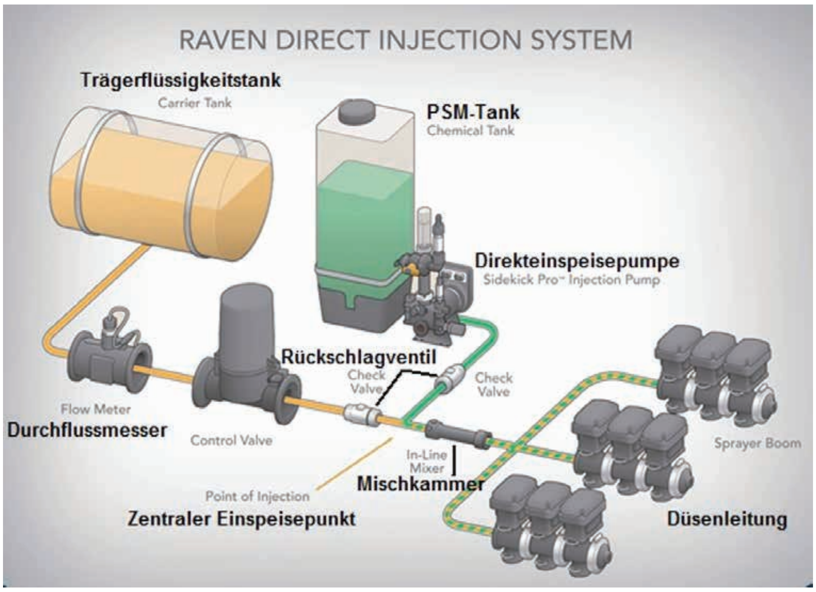

Figure 3: Diagram of Raven direct injection, altered (Raven 2015b)

The system controls receive information on current flow from the carrier liquid flow meter. Based on this, the system doses PPP in decilitres per litre of carrier liquid. If there is no carrier liquid flow, no PPP injection takes place.

For systems I and II, direct injection pumps with a working range of 0.15–5.9 l/min are used. Figure 4 shows both injection units installed on the right side of the sprayer, each with a 90 litres capacity tank for plant protection product. The advantage of large spray tanks is that enough crop protection spray can be carried for high area performance. A disadvantage is that these are not exchangeable tanks. Thus, when PPP is changed, residue from the previous operation has to be poured back into the original containers and the tanks cleaned. For this reason both spray tanks on the prototype were retrofitted with cleaning nozzles.

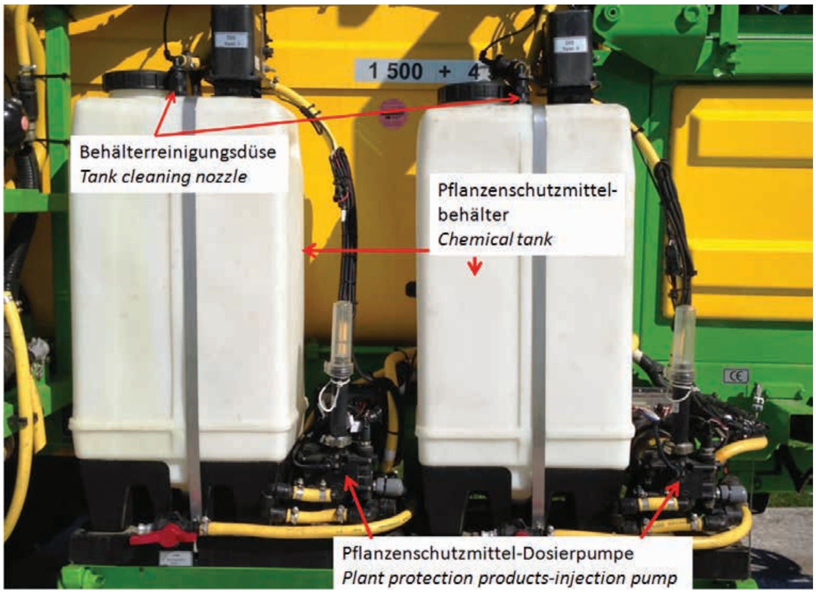

Figure 4: Spray chemical tanks and dosing pumps from systems I and II (Photo: M. Krebs)

For system III, installed on the front of the crop sprayer, a smaller direct injection unit from Raven with a capacity range of 0.03–1.18 l/min was selected (Figure 5). The spray tank here is a 28 litres TeeJet interchangeable container. Contrary to the system I and II PPP tanks, the system III tank is not equipped with a cleaning nozzle. The background to this solution is that this tank is only used for one PPP and is removed from the sprayer after use and placed in chemical store. In practice, having different exchangeable tanks permits very rapid changeover of PPP.

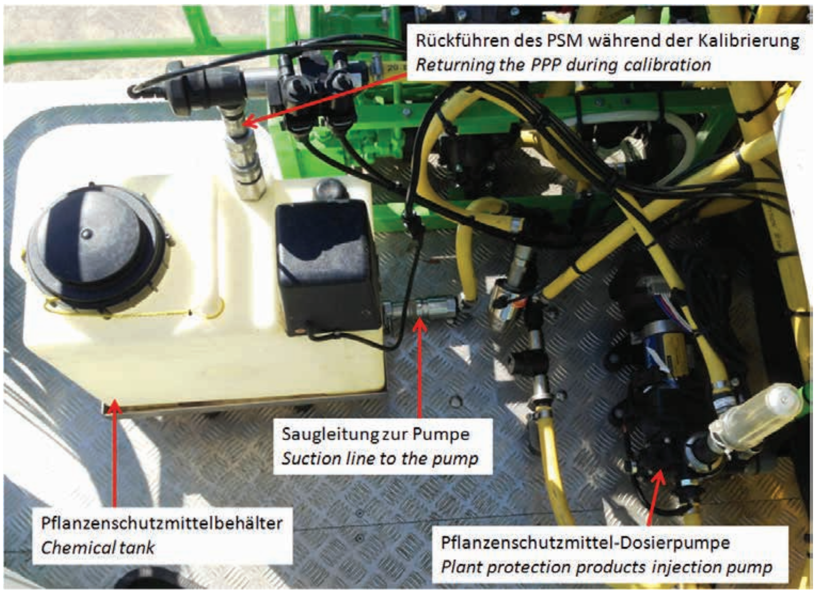

Figure 5: Spray chemical tank and dosing pumps from system III (Photo: M. Krebs)

Calibrating direct injection pumps

All three direct injection pumps are electrically powered piston pumps that can be calibrated without the operator coming into contact with PPP. Figure 6 shows the calibrating procedure according to the Raven operator manual. The injection pump is set at recirculation into the spray tank. The operator screws off the transparent cap with the calibration scale and presses the calibration piston downwards. Then the cap is screwed back on. Next, the calibration procedure is started at the control terminal. If the calibration piston remains within the markings on the cap, the pump is correctly calibrated. When not, the calibration value can be matched at the operating terminal and the procedure repeated until the piston settles within the scale marks (Raven 2015a). The required time for the calibration is very short and can, for instance, be done during water refilling.

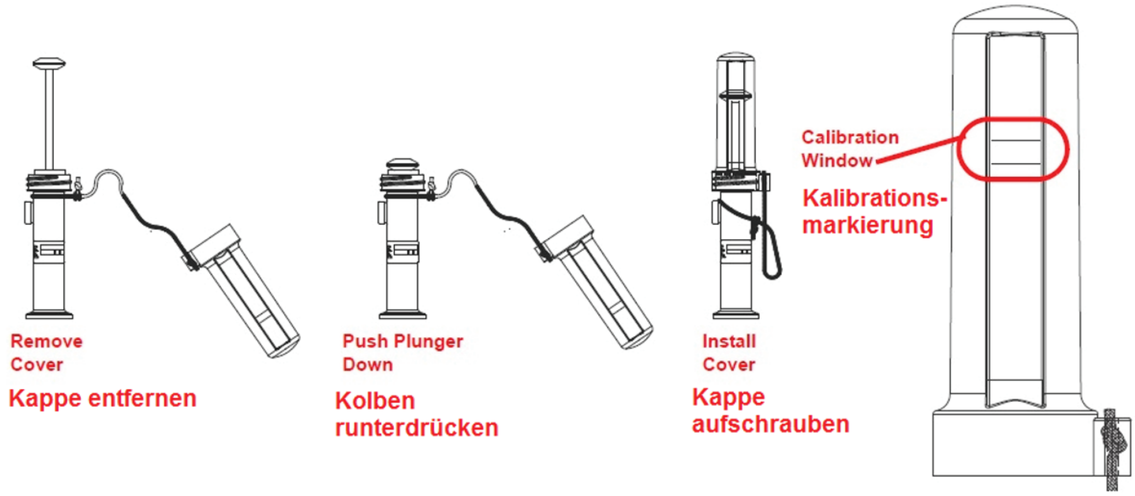

Figure 6: Calibrating the direct injection pump (Raven 2015a)

Preload

To avoid time lag with direct injection, every direct injection unit on the prototype is assigned an own nozzle line with circle flushing line that can be preloaded. Preloaded means that the circle flushing line normally closed during spraying is, before application start, opened just long enough to allow the full reference concentration to be reached in the nozzle line. Hereby, the circuit flushing line does not run back into the respective system tank but instead into the flushing water collection tank. Figure 7 shows a section from the prototype fluid circuitry diagram.

For preloading, the water pump, as well as the direct injection pump, must be set at the desired value. The water pump transports water continually, even with closed nozzles, up to the constant pressure valve located in front of the flow meter. As long as the nozzles remain closed, the water flows back into the tank at this point. If the program "Preload" is started, the circuit flushing line opens for a predetermined period of time depending on the set pumping rate of the carrier liquid pump (water pump). The direct injection unit gets via the reading for carrier liquid (water) on the flow meter, the signal to inject the PPP (see Figure 3). The time set for preloading is so measured that, from the injection point to the furthest nozzle, the water-PPP mixture lies in the reference concentration. Closure of the circuit flushing line means no more water passes through the flow meter and so PPP injection stops. Only during spraying, when the nozzles are opened, does water once again flow through the

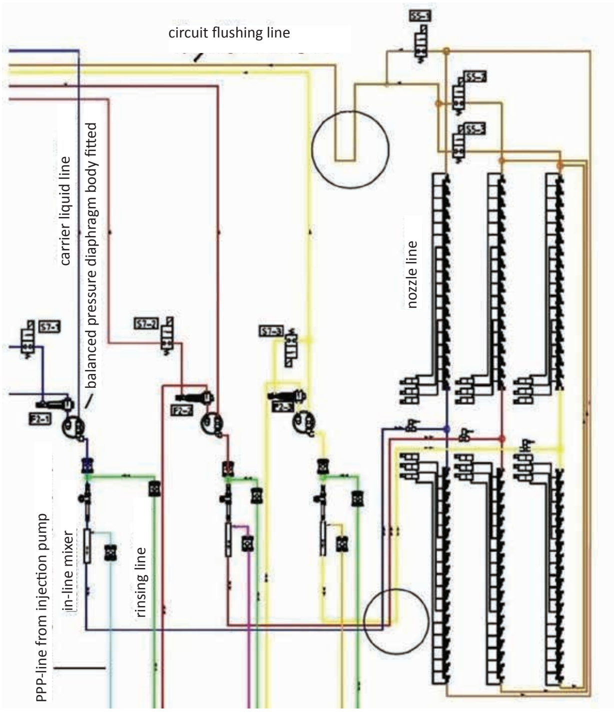

Figure 7: Section of fluid circuitry diagram from the prototype with three nozzle lines, altered (Dammann 2013)

flow meter and PPP is then again injected into the line. With this procedure, the full application concentration is available immediately at every nozzle when every boom section is opened.

Prototype controls

For operating all three systems, seven terminals are still required currently. A terminal per system for controlling and regulating the carrier liquid flow and a further one for each direct injection system along with a seventh terminal for cleaning procedures and for activating the required program (spraying, calibrating, preloading, etc.). The number of terminals will be reduced for future practical work.

Material and methods

To measure dosing pump precision, as well as work quality of the PPP-water mixing chamber, a solution with the fluorescent dye Brilliantsulfoflavin (BSF) is used. System precision is assessed through measuring the fluorescence of the BSF-water-mix (spray liquid) leaving the nozzle exits. Before every alteration to dosing level, the measurement instrument is calibrated using a calibration solution representing the reference concentration. An indicated value of 100 % represents the desired reference concentration.

The working width or boom section width with which the prototype can be operated in association with the output ranges of the applied dosing pumps, as well as the respective sprayer operational speeds, were calculated. The theoretically possible working width b_A [m] was calculated through the equation 1:

$$b_A = \frac{\frac{\dot{V}}{A}}{v_a} \times 600 \qquad \text{(Eq. 1)}$$

Table 1: Formula symbol

	Formula symbol	Units
Possible working width	b_A	m
Application amount	A	l/ha
Working speed	v_a	km/h
Dosing output	$\dot{V}$	l/min

The calculation involved the already mentioned working speeds at differing spray application amounts. For the variable "dosing output", four factors were calculated depending on the two pump sizes with different minimum and maximum outputs.

Results and discussion

Figures 8 and 9 show the results of the test stand measurements with the small pump (work range 0.03–1.18 l/min) as well as with the large pump (work range 0.15–5.9 l/min). Presented in each case are measurements in five different dosing levels within the working range of the pump. The figures alongside the blue points represent the arithmetical average from 180 recordings for every dosing level. The box emphasises the interquartile intervals within which 50 % of all measurements lie.

As shown by the results for the small dosing pump in Figure 8, the deviation of dosing precision from reference value lies on average at not more than ± 4 %. The highest value of the actual dosing was 106.8 % for the small output pump at a recorded output of 0.8 l/min, which was still within the predetermined tolerance of ± 7 % of reference value. Lowest value recorded was 95 % at an output of 0.054 l/min which also lies within the predetermined tolerance area. Alongside the average, which should be as near as possible to the reference value, important for dosing quality is also as small as possible scatter of results. The largest scatter was recorded at the lowest dosing amount (0.054 l/min).

The results from the large pump in Figure 9 show that, here too, the largest scatter of results is evident in the lower dosing range. The extreme values with the large pump lie, when all five dosing areas are observed, between 97.8 % in the lower area and 106 % in the upper area and therefore within the tolerance of ± 7 % around the reference value. Comparing the distribution of results within each dosing level shows that the scatter produced by both pump sizes is greatest within the dosing levels at the lower threshold of the working range. Thus, dosing precision is more to be expected at the lower end of the respective dosing areas. Whether the dosing precision measured with the BSF-solution can also be achieved with liquid formulated plant protection products available on the market, remains to be seen in practice. If the operator carries out for every PPP the written, easy to follow, calibration of the direct injection pumps, which can be completed in just a few minutes, than it can be expected that no great problem with application precision will appear. The reasons for the better dosing precision with the pumps used, compared with systems tested in the past, is based in their design. The electrically powered piston pumps now used enable a more precise dosing compared with the peristaltic pumps used earlier. The piston pump doses with every piston stroke a defined amount of spray product and can be exactly controlled via the electricity drive.

A further reason for the prototype's higher dosing precision is the positioning of the injection point. With central injection into the nozzle line before the booms, the higher volume being pumped means the dosing precision is substantially more exact in comparison with decentral dosing direct at the individual nozzle with the help of rapid reaction valves (RRV). The very small amounts of spray that are necessary with decentral single-nozzle dosing are technologically almost impossible to be precisely managed (Walgenbach 2014). The disadvantages of long time lag periods with central injection of spray into the nozzle line as discussed by Sökefeld et al. (2005) are eliminated through the procedure of preloading with the developed prototype. Thus, by using three nozzle lines, each with its own direct injection system, the PPP can be changed without time lag or, where required, all three systems used for application simultaneously.

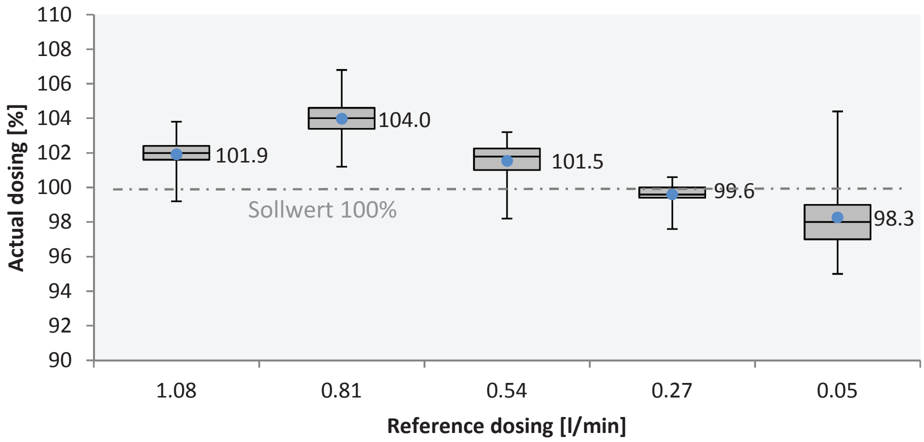

Figure 8: Dosing precision at different outputs for the small pump with a range of 0.03–1.18 l/min (n = 180)

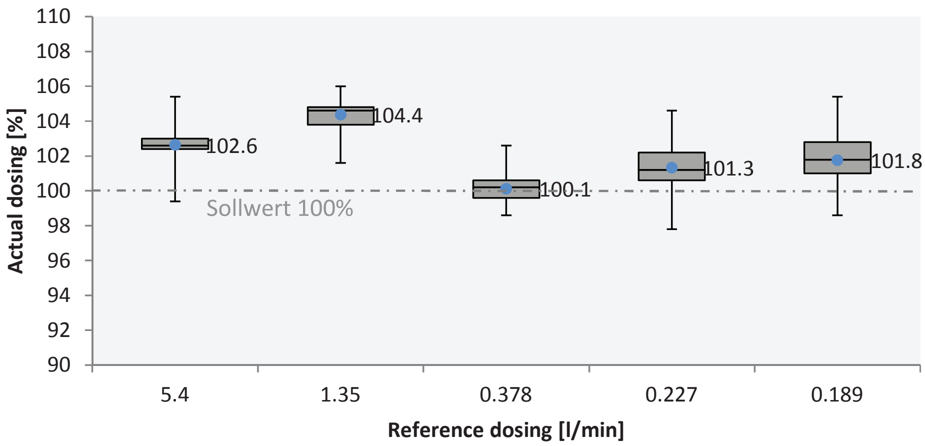

Figure 9: Dosing precision at different outputs for the large pump with a range of 0.15–5.9 l/min (n = 180)

Presented in tables 2 to 5 are the calculated theoretically possible working widths for different PPP application rates of 6, 8, 10 and 12 km/h. To be noted is that the prototype has a maximum working width of 27 m. Space between nozzles is 0.5 m. With the nozzle line from system I, an individual nozzle switch is fitted, allowing free selection of boom sections for different working widths bearing in mind that these widths can be limited by the direct injection pump capacities. The nozzle lines of both further systems are divided into 7 sections of six times 4 m and one 3 m section.

Table 2: Theoretical working widths (b_A) of the direct injection system in dependence of pump size used at 6 km/h working speed

Working speed 6 km/h	**Dosing rate [l/min]**			
	Small direct injection unit		**Large direct injection unit**	
	min.	**max.**	**min.**	**max.**
	0.03	1.18	0.15	5.9
Spray amount PPP [l/ha]	**Theoretical working width [m]**			
0.1	30.0	1,180.0	150.0	5,900.0
0.2	15.0	590.0	75.0	2,950.0
0.5	6.0	236.0	30.0	1,180.0
1	3.0	118.0	15.0	590.0
2	1.5	59.0	7.5	295.0
3	1.0	39.3	5.0	196.7
4	0.8	29.5	3.8	147.5
5	0.6	23.6	3.0	118.0
7	0.4	16.9	2.1	84.3
10	0.3	11.8	1.5	59.0

From table 2 it can be seen that, at 6 km/h working speed with the small pump, a minimum working width of 30 m is necessary to realise a spray output of 0.1 l/ha. This means that the crop sprayer prototype at this working speed (v_a) with its 27 m working width cannot apply 0.1 l/ha of spray. With increasing application amounts per hectare, the required minimum working width reduces so that in the case of large application amounts, switching to boom sectional width spraying is enabled. If the maximum possible working width exceeds the actual working width of the prototype, the larger pump must be used. Thus, for instance, with a PPP application rate of 5 litres the maximum theoretical working width with the small pump is 23.6 m and is thereby smaller than the actual working width of the prototype at 27 m. Under the same conditions, the large pump gives theoretical working widths (b_A) between 3 and 118 m. The following tables 3 to 5 show the theoretically possible ranges of working widths at higher speeds.

Table 3: Theoretical working widths (b_A) of the direct injection system in dependence of pump size used at 8 km/h working speed

Working speed 8 km/h	**Dosing rate [l/min]**			
	Small direct injection unit		**Large direct injection unit**	
	min.	**max.**	**min.**	**max.**
	0.03	1.18	0.15	5.9
Spray amount PPP [l/ha]	**Theoretical working width [m]**			
0.1	22.5	885.0	112.5	4,425.0
0.2	11.3	442.5	56.3	2,212.5
0.5	4.5	177.0	22.5	885.0
1	2.3	88.5	11.3	442.5
2	1.1	44.3	5.6	221.3
3	0.8	29.5	3.8	147.5
4	0.6	22.1	2.8	110.6
5	0.5	17.7	2.3	88.5
7	0.3	12.6	1.6	63.2
10	0.2	8.9	1.1	44.3

Table 4: Theoretical working widths (b_A) of direct injection system in dependence of used pump sizes at 10 km/h working speed

Working speed 10 km/h	**Dosing rate [l/min]**			
	Small direct injection unit		**Large direct injection unit**	
	min.	**max.**	**min.**	**max.**
	0.03	1.18	0.15	5.9
Spray amount PPP [l/ha]	**Theoretical working width [m]**			
0.1	18.0	708.0	90.0	3,540.0
0.2	9.0	354.0	45.0	1,770.0
0.5	3.6	141.6	18.0	708.0
1	1.8	70.8	9.0	354.0
2	0.9	35.4	4.5	177.0
3	0.6	23.6	3.0	118.0
4	0.5	17.7	2.3	88.5
5	0.4	14.2	1.8	70.8
7	0.3	10.1	1.3	50.6
10	0.2	7.1	0.9	35.4

Table 5: Theoretical working widths (b_A) of direct injection system in dependence of the used pump sizes at 12 km/h working speed

Working speed 12 km/h	**Dosing rate [l/min]**			
	Small direct injection unit		**Large direct injection unit**	
	min.	**max.**	**min.**	**max.**
	0.03	1.18	0.15	5.9
Spray amount PPP [l/ha]	**Theoretical working width [m]**			
0.1	15.0	590.0	75.0	2,950.0
0.2	7.5	295.0	37.5	1,475.0
0.5	3.0	118.0	15.0	590.0
1	1.5	59.0	7.5	295.0
2	0.8	29.5	3.8	147.5
3	0.5	19.7	2.5	98.3
4	0.4	14.8	1.9	73.8
5	0.3	11.8	1.5	59.0
7	0.2	8.4	1.1	42.1
10	0.2	5.9	0.8	29.5

From tables 2 to 5 it can be seen that the theoretical working widths (b_A) decrease with increasing working speed. This enables the switching to smaller boom sectional working widths at higher working speeds. In the case of the dosing pump with smaller working range, however, the limit to the maximum possible working width would quickly be reached with higher application amounts. Thus, with the smaller direct injection unit at a working speed of 12 km/ha and an application amount of 5 l/ha means a maximum theoretical working width of only 11.8 m is possible. With the large direct injection unit under the same conditions, the theoretical working width realizable lies between a minimum 1.5 and maximum 59 m. The four tables with the different working speeds emphasize why it is necessary for the future user to have the capability with direct injection field sprayers of selecting different sizes of pumps. Because of the wide range of permitted PPP application amounts in crop production, from 0.05 l/ha with insecticides up to 6.25 l/ha with herbicides (BVI. 2015), one pump size alone is unable to cover the required range. On the other hand, where the operator has different sizes of pump available, most possible situations in practical farming can be covered.

The developed prototype can be seen as an important step for precision farming in crop protection because it shows that the application of individual PPP with direct injection, with higher dosing precision and without time lag, is possible. Site-specific treatment with individual sprays as "Yes/no-decisions", or through adjustment of water amount or site-specific adjustment of active ingredient applied, are all possible with the prototype. Thereby, PPP can be used more precisely according to the situation. A few steps have still to be taken (e. g. sensors for pathogen identification), before site specific crop protection with differentiated application of individual plant protection products achieves wider application in practical farming. The results achieved confirm the statement of Ganzelmeier (2012), that precision farming in crop protection advances only step by step, although in the future the concept will have great influence.

Conclusions

The investigations show that the field sprayer prototype with direct injection is capable of applying liquid formulated plant protection products with high dosing precision within the working range of the dosing pumps. The plant protection products can be applied site-specifically and without time lag. Within the project, it was not possible to test all the liquid formulated PPP on the market. Only wide-ranging practical trials can establish whether all formulations are applicable without problems under different environmental conditions. Problematical are small application amounts per hectare where work is only able to be carried out in small section working widths and at low speeds. The operation and the cleaning process with the prototype must be simplified in a further development step. Additionally, future improvements such as, e.g., reduction of the number of operating terminals are intended. Further field trials on farms for demonstration of the system's suitability in practical farming are planned, or are in some cases already being carried out. The test results and experience so far with the field sprayer prototype show, that practically applicable systems for direct injection without time lag are realizable.

References

Berthoud (2013): Direkteinspritzungssystem BERTHOUD: „CLEAN SPRAYER“. http://www.berthoud.com/allemand/news-und-messen/news/direkteinspritzungssystem-berthoud—clean-sprayer–5208.aspx, accessed on 5 June 2015

BVL (2015): Pflanzenschutzmittel-Verzeichnis 2015, Teil 1 Ackerbau – Wiesen und Weiden Hopfenbau – Nichtkulturland. Hg. Bundesamt für Verbraucherschutz und Lebensmittelsicherheit, Braunschweig, 63. Auflage

Dammann (2013): Fluid-Schaubild D-I-S PSM, unpublished

Danfoil (2015): Vorteile des danfoil MultiDose Injection Systems. http://www.danfoil.dk/de/produkte/injection/vorteile_des_danfoil_multidose_injection_systems.htm, accessed on 5 June 2015

Eikel, G. (2007): Direkteinspeisung für bis zu vier Pflanzenschutzmittel. profi 19(11), S. 8

Ganzelmeier, H. (2012): Nachhaltiger und schlagkräftiger Pflanzenschutz. In: Jahrbuch Agrartechnik 2012. Hg. Frerichs, L., Braunschweig, Institut für mobile Maschinen und Nutzfahrzeuge, S. 1–9, http://www.digibib.tu-bs.de/?docid=00043448, accessed on 18 June 2015

Garrelts, J. (2013): Aktuelle Entwicklungen zur Direkteinspeisung von Pflanzenschutzmitteln in einer Feldspritze. In: Norddeutsches Marktfruchtforum 2013, Hg. Kage, H., Sieling, K., Huesmann, S., Schriftenreihe des Instituts für Pflanzenbau und Pflanzenzüchtung Christian-Albrechts-Universität zu Kiel 84, S. 49–53

Gerhards, R. (2004): Precision Farming im Pflanzenschutz. In: Landinfo 3: Informationen für die Landwirtschaftsverwaltung/Baden-Württemberg, Hg. Landesanstalt für Entwicklung der Landwirtschaft und der Ländlichen Räume (LEL), S. 10–15

Holtmann, W. (2010): Was wurde eigentlich aus ... der Cerberus-Feldspritze von Rau? profi 22(1), S. 112

Kyndestoft (2015): Kyndestoft Injection. http://kyndestoft.eu/onewebmedia/injektion%20%28ny%20adr%29.pdf, accessed on 5 June 2015

Lechler (2007): Lechler VarioInject Bedienungsanleitung. Hydraulisch angetriebenes Direktdosiersystem mit zentraler Einspeisung auf dem Gestänge

Neunaber, M. (1989): Pflanzenschutz: Wasser und Mittel endlich getrennt. profi 1(12), S. 9

Raven (2015a): Installation & Operation Manual Sidekick Pro™ Manual No. 016-0171-391 Rev. C. http://ravenhelp.com/~/media/Product%20Information/Service%20Manuals/Application%20Controls/016-0171-391%20Rev%20C%20-%20Sidekick%20Pro%20-%20Installation%20and%20Operation%20Manual.ashx, accessed on 11 June 2015

Raven (2015b): Sidekick Pro™ Funktionsschema. http://ravenprecision.com/products/application-controls/sidekick-sidekick-pro/, accessed on 4 June 2015

Rimpau, J. (2006): Innovationsbedarf für den zukünftigen praktischen Pflanzenschutz: Anforderungen an die Wissenschaft. In: Schriftenreihe der Deutschen Phytomedizinischen Gesellschaft. Band 8. Biotechnologie – Innovationsmotor für den Pflanzenschutz, Hg. von Tiedemann, A.; Feldmann, F., Stuttgart, Eugen Ulmer KG, S. 118–122

Sökefeld, M.; Hlobe, P.; Schulze Lammers, P. (2005): Entwicklung einer Versuchseinrichtung zur Untersuchung der Verzögerungszeiten von Direkteinspeisungssystemen für die teilflächenspezifische Applikation von Herbiziden. Agrartechnische Forschung 11(5), S. 145–154

Vondricka, J.; Schulze Lammers, P. (2009): Real-time controlled direct injection system for precision farming. Precision Agric 10, pp. 421–430

Walgenbach, M. (2014): Aufbau und Untersuchung eines Versuchsträgers zur Direkteinspeisung an der Düse. Dissertation, Rheinische Friedrich-Wilhelms-Universität Bonn

Wartenberg, G. (2000): Teilflächenspezifisches Spritzen von Pflanzenschutzmitteln. Landtechnik 55(6), S. 438–439, DOI: http://dx.doi.org/10.15150/lt.2000.1992

Wehrspann, J. (2013): Direct injection for sprayers is back. http://farmindustrynews.com/sprayers/direct-injection-sprayers-back, accessed on 5 June 2015

Authors

Dr. Henning Nordmeyer is senior scientific councilor and head of the herbology department at the Institute for Plant Protection in Field Crops and Grassland of the Julius Kühn-Institute, **M. Sc. Mathias Krebs** is member of the scientific staff, **Dipl.-Ing. Dirk Rautmann** is scientific director and deputy institute director and **Dr. Jens Karl Wegener** is director and professor and head of the Institute for Application Techniques in Plant Protection of the Julius Kühn-Institute, Messeweg 11/12, 38104 Braunschweig, E-Mail: dirk.rautmann@jki.bund.de

References/Acknowledgements

This project was supported by funds from the Federal Ministry of Food and Agriculture (BMEL) on the basis of a resolution of the German Federal Parliament. Project sponsorship took place via the Federal Office for Agriculture and Food (BLE) within the program for innovation support (FKZ 2815404010). Additionally, we thank our colleagues in the Institute for Application Techniques in Plant Protection and Institute for Plant Protection in Field Crops and Grassland within the Julius Kühn-Institute, Braunschweig for their support during the conducting of the investigation. We would also like to give our thanks to our project partner Herbert Dammann GmbH for the productive cooperation.