agriculturalengineering.eu 79(3), 2024, 164–179
DOI:10.15150/ae.2024.3317

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# Comparison of different nozzle types and their constellation at the boom of field sprayers for not treating tramlines in cereals

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Chemical plant protection takes an essential role in the production of quality food. However, the use of plant protection products is currently under critical discussion due to possible negative influences on the environment caused by unintentional inputs. In this research article, a new innovation in crop protection equipment is presented, which makes it possible to save crop protection agents by recessing the tramlines. The nozzle types and the nozzle constellation in the tramline area were modified on the spray boom. In laboratory and field tests, two suitable variants were investigated that enabled the tramline to be recessed and then compared with the whole area application that is customary in practice. In these tests, only the qualitative and quantitative effects of the spray liquid distribution, which could arise due to the change in nozzle types and nozzle constellation, were examined. The results show that through the appropriate choice of nozzles and the correct nozzle constellation, a recess in the tramline is possible with the aim of saving crop protection agents, and that the quality and quantity of the spray liquid distribution is almost as good as with a conventional whole area application.

**Keywords**
Tramline deactivation, field sprayer, plant protection, spray boom, spray distribution

During application, plant protection products not only reach the desired target sites but can also contaminate surrounding sensitive environmental areas through various entry pathways (UBA 2015). These unintentional inputs can have negative effects on the environment and lead to limit values being exceeded in ground and surface waters (BMEL 2017). In addition to the possible ecological risk, chemical plant protection is expensive. For this reason, farmers go to great lengths to pursue the principles of „integrated pest management“. This pretends to limit the use of chemical-synthetic plant protection products to the necessary extent by combining plant cultivation measures, technical advances and biological plant protection (Hallmann et al. 2009).

In the course of precision farming and the digitalisation of agriculture, technical progress takes an important role in resource efficiency and environmental protection (BMEL 2017). These developments lead to new approaches in plant protection technology by reducing the consumption of plant protection products. Many of these new approaches in plant protection technology are moving away from a general, whole-area and rigidly terminated treatment of the areas, in the direction of a targeted, partial-area-specific and timed treatment (Hallmann et al. 2009, Pohl et al. 2020). For example,

received 28 November 2022 | accepted 9 August 2024| published 19 August 2024

there are GPS controlled automatic section control or the section specific application with the aid of a direct injection system on field sprayers (Wegener et al. 2016). The GPS controlled automatic boom section control makes it easier to turn the individual boom sections of the field sprayer on or off. This significantly reduces unintentional double treatments in wedge areas and headlands in the crop. In addition, it eases treatments at dusk and night or with field sprayers with large working widths and many small sections (Ganzelmeier and Nordmeyer 2008).

The crops often show heterogeneous plant diseases, pests and weeds and often in nests arise (Gerhards et al. 1997, Hallmann et al. 2009). By using a site-specific application with direct injection system and sensor technology, these areas are detected and specifically treated. Such techniques are already ready for series production, but are not yet widely used in practice (Pohl et al. 2021). In addition to these techniques, crop protection systems are currently being developed for row crops that are a combination of hack and band sprayer. These techniques control the weeds between the rows mechanically. A herbicide is then applied in the crop row with a band sprayer. This system is often supported with camera guidance. This combination leads to a reduction in herbicide use (Herrmann et al. 2021).

Tramlines guide to avoid over- or underdosing due to incorrect spacing (Moismann et al. 2007, Webb et al. 2004). By cut-outs in seed drills during sowing, tramlines are already established by omitting the appropriate subareas. On the one hand, this practice leads to less mechanical damage and twig growth. On the other hand, it saves seed grain (Diepenbrock et al. 2016, Hallmann et al. 2009). A technology for field sprayers that also allows the tramline to be omitted, is an innovation that takes up this savings approach and allows the crop free tramline to be omitted during the application of plant protection products. Not only does this reduce the direct input of plant protection products into soil, groundwater, surface waters and other sensitive environmental systems but also saves costs and resources (von Hörsten et al. 2016, Withers et al. 2006). As part of a joint research project between the JKI and Horsch Leeb Applications Systems GmbH, research into tramline deactivation for field sprayers has been underway since 2018.

In initial investigations, it has already been possible to direct the spray fans out of the tramline and reduce the amount of spray liquid entering the tramline by using different nozzle types, constellations and articulated nozzle holders. It was also possible to reduce the overall application rate (Bröring and von Hörsten 2019). The challenge for the development of such a system is that the lateral distribution of the spray liquid must comply with a legal standard (EN16119 -2). This standard contains environmentally relevant requirements for field sprayers. It also specifies requirements for the design and performance of field sprayers to minimise the risk of environmental pollution, as well as the procedures for verifying these requirements.

In addition to meeting the challenge of complying with the legal standard, the effectiveness at the edge of the tramline when using a tramline deactivation system is also important. An even distribution of the spray liquid is a prerequisite for a successful effect of the plant protection product in the crop (Kifferle and Stahli 2001). The JKI specifies legal test requirements for this. In the test specifications, the coefficient of variation of the spray liquid distribution is a key assessment criterion. For field sprayers in use, this coefficient of variation must not be greater than 10 % (JKI 2019).

In addition to the distribution of the spray liquid quantity, the quality of the distribution, e.g. the deposition of the spray liquid on the crop, is also an important parameter for the effectiveness of the plant protection product. The droplet size is a key factor for the distribution quality and influences droplet deposition and drift (Chen et al. 2020). A characteristic derived from the droplet size for nozzles used in crop protection is the droplet spectrum. The droplet spectrum is often specified as the volumetric droplet diameter (Kifferle and Stahli 2001, Privitera et al. 2023). Based on the results of the initial investigations by Bröring and von Hörsten (2019), this study used technical derivations to analyse possible statements about the effectiveness of various plant protection products in the edge area of the tramline. This was done in the form of spray distribution measurements (in the laboratory and in the field). It was examined whether the use of tramline deactivation for field sprayers shows significant differences with regard to the distribution quantity and quality on the cultivated area compared to the whole-area application that is common in practice. From this, conclusions were drawn about the effectiveness of the plant protection products.

## Material and methods

### Experimental procedure

In the following paragraph various test methods were employed to record and evaluate the quantity and quality of the spray liquid distribution. The spray distribution in the laboratory and field, the change in droplet size, as well as the influence of the boom movement and the accumulation of the spray liquid in the crop were analysed. Three variants were in comparison (Figure 1).

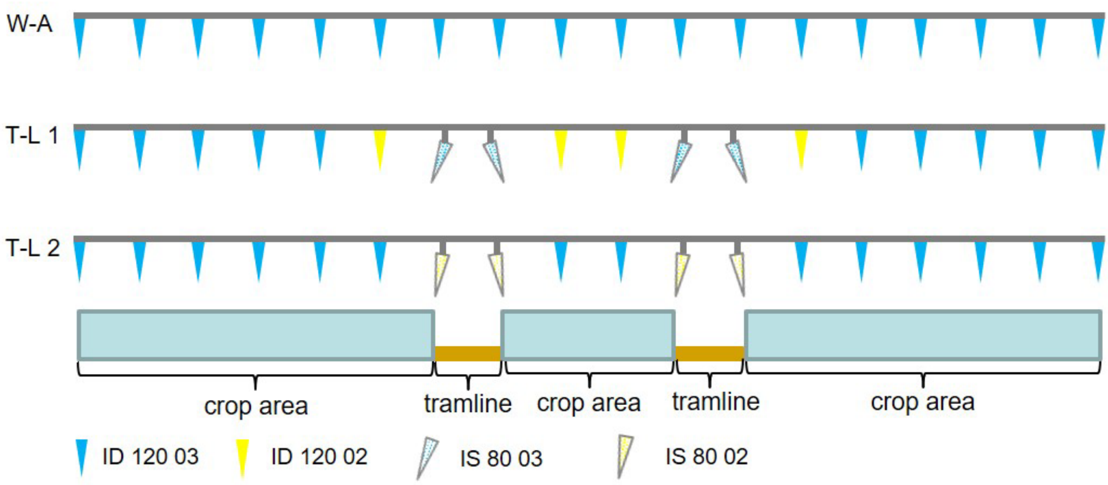


Figure 1: Layout of the test variants: W-A = whole area application, T-L 1 = tramline deactivation variant one, T-L 2 = tramline deactivation variant two, nozzle spacing: 50 cm

The first variant W-A was a standard whole area application of plant protection products without changing the nozzle constellation in the tramline area. The nozzle configuration is based on the blue injector flat-fan nozzles from Lechler (ID 120 03). The nozzle constellation of the other two variants T-L 1 and T-L 2 is different in the tramline area, so that the tramline was omit during the application of plant protection products. In the T-L 1 variant, a total of eight nozzles were replaced from the basic configuration of the nozzle assembly. Four ID 120 02 nozzles and four IS 80 03 edge nozzles were used. In addition, the target area distance of the edge nozzles (IS 80 03) was reduced from 50 to 40 cm and additionally tilted 20° to the left or right with an articulated nozzle holder. In the second variant T-L 2, only four nozzles were replaced from the basic equipment with edge nozzles (IS 80 02). The target area distance is reduced by 10 cm as well, but the nozzles just tilted 10° to the left or right with an articulated nozzle holder. In standard nozzle cluster for field sprayers, the single ones were rotated by 7°–10° to the boom axis to avoid interference of the nozzle spray fan. Furthermore, this was implemented in the three variants with the exception of the IS 80 02 in the T-L 2 variant. The IS 80 02 of the T-L 2 variant were rotated by 50° to the boom axis. The nozzles on the boom had a distance of 50 cm for all three variants. The nozzles were selected and adjusted in order to direct the spray liquid out of the tramline as close to the edge as possible and at the same time save spray liquid.

## Quantitative distribution measurements

### Lateral distribution

The quantitative spray distribution was recorded in a static lateral distribution measurement in the laboratory and a dynamic one in the field. In the static distribution measurement, all three variants were set up in an arrangement of 24 nozzles with the corresponding nozzle constellations using a horizontal spray patternator. However, only the range of 16 nozzles was taken into account for the subsequent analyses. Horizontal spray patternator consists of a channel pattern with a resolution of 10 cm, which guided the collected spray liquid into a cylinder assigned to each channel. An ultrasonic sensor detected the fill level of the bottles and generated a distribution pattern. The measurement duration of the spraying process was limited to 310 seconds to achieve an ideal filling condition of the measuring cylinders for quantity recording. The spraying pressure was set to 5 bar, which is usually used for this type of nozzle in practice. The measurements of the individual variants were repeated six times.

The dynamic distribution measurements were carried out in the field using the fluorescent dye pyranine, collectors and a field sprayer (Horsch Leeb LT 5). The concentration of pyranine in the tank filling of the field sprayer amounts 0.2 %. Filter paper (width 8 cm) and Petri dishes (D = 94 mm) served as collectors. The field trial took place on a short-cut grass field at the JKI. The collection containers were positioned close to the ground.

In order to ensure the technical feasibility of the distribution measurements, the nozzle constellations of the individual variants were not placed in the originally intended positions directly in the tramline area of the field sprayer but offset parallel to it (Figure 2). The collectors were installed in parallel offset positions as well. This was necessary to avoid a direct crossing and thus damage to the collectors. Each variant was repeated three times with filter paper and Petri dishes as collectors. Each repetition records a total spray width of 8 m, allowing the spray pattern of 16 nozzles to be recorded. The filter papers were split up in 10 cm pieces after the pass. For the passages with Petri dishes as collectors, these were placed at distances of 10 cm between them. Thus, per repetition, 80 collection points with a measuring range of 10 cm were recorded and later on evaluated individually. Hereby the same gutter grid as in the static lateral distribution measurement in the laboratory was obtained. The driving speed of the field sprayer was 7.5 km $h^{-1}$ and the spraying pressure was set to 5 bar. The boom of the field sprayer was equipped with an automatic height guide, which always kept a uniform target area distance of 50 cm. After each crossing, the collectors were collected and the spray deck was dried. Due to the tendency of pyranine to degrade under the influence of light, the collectors were always shielded from the light. After drying, the dye was washed with a certain amount of distilled water. These samples were analysed by a fluorometer (Spectrophotometer SFM 25, Biotec-Kontron Instruments, Germany).

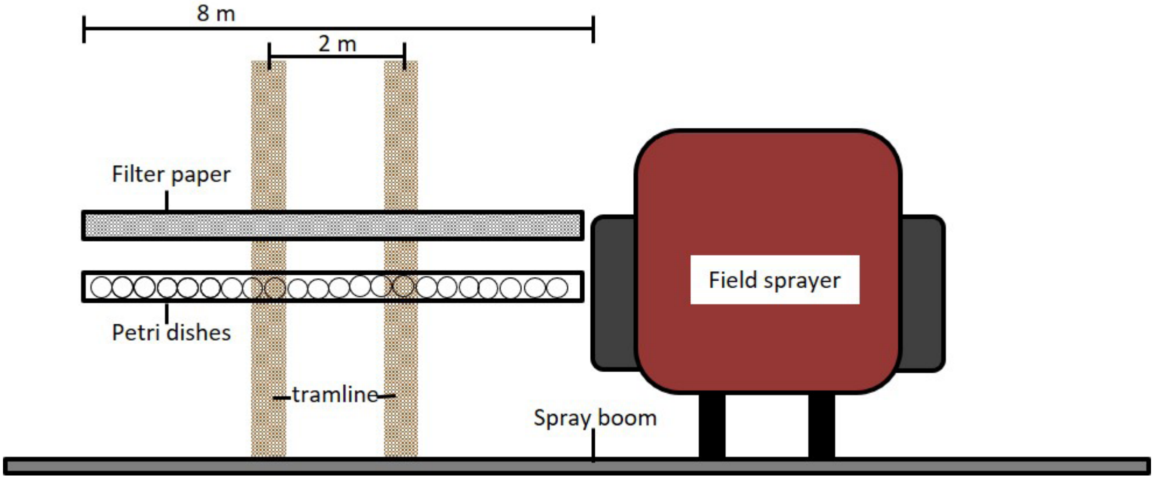


Figure 2: Layout of dynamic distribution measurement in the field.

## Spray boom movement

The influence of the boom movement on the quantitative spray liquid distribution was determined in two steps. First, it was examined how a change in position of the boom in horizontal and vertical direction affected the coefficient of variation of the lateral distribution. For this purpose, the static distribution measurements described in point 2.2.1, were repeated on the horizontal spray patternator in a different position. In the vertical direction, the lateral distribution of the respective variants was measured at a target area distance of the nozzle assembly of 40 cm, 45 cm, 55 cm and 60 cm. In the horizontal plane, the nozzle arrangement was shifted by 5 cm and 10 cm to the right and left from the zero point (tramline position). In the second step, it is examined how much the position of the boom moved during application in field from the zero point. This is achieved by two laser rangefinders (CheckTec GmbH, Germany). They record a measuring point every 0.02 s. To determine the vertical movement of the spray boom, a laser rangefinder is set up on the boom above the track with the measuring direction towards the ground. For the lateral movement, a laser rangefinder is installed in the middle measuring in the direction of a wooden wall set up parallel to the tramline (Figure 3).

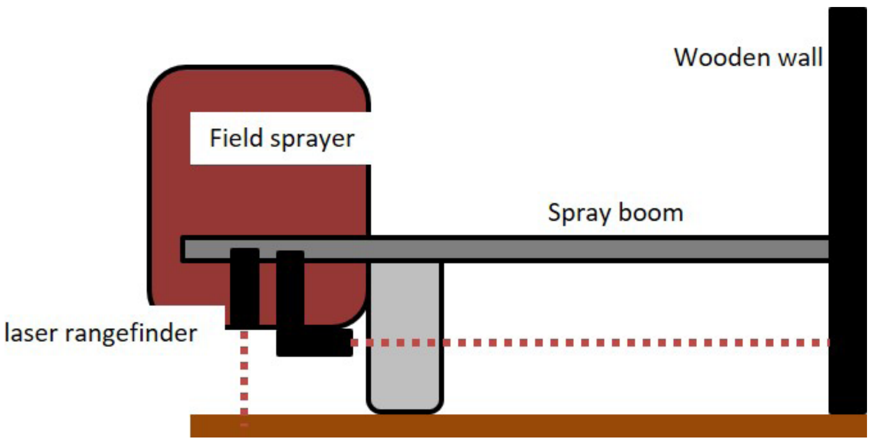


Figure 3: Layout of the recording of the boom movement with laser rangefinder

In order to identify possible influences of the filling level of the field sprayer on the boom movement, the measurements are carried out at three filling levels (100 % filling, 50 % filling, 5 % filling). This happens while driving at a speed of 7.5 km $h^{-1}$ over a measuring distance of 20 m. In order to create conditions as practical as possible, the measurements are carried out on a tramline in the field. Each run of a level repeats five times.

## Qualitative distribution measurements

### Droplet size measurement

The effects of a changing nozzle constellation on the droplet spectrum are recorded by measuring the droplet sizes of used nozzles. The „Particle Droplet Image Analyser“ (PDIA) with the „VisiSize 6“ software (Oxford Lasers Ltd., United Kingdom) measures the droplet size. This laser works with a wavelength of λ = 532 nm. The light from the laser is scattered by a diffuser and serves as an exposure source for the droplet imaging camera. The value D10 indicates that 10 % of the liquid volume is smaller. At D50, also known as the volume median diameter, 50 % is larger and 50 % smaller than the value. The value D90 indicates that 90 % of the liquid volume is smaller. The PDIA has a dimension of approx. 11.5 × 8.5 mm. The Volume Diameter D10, D50 and D90 were determined as test characteristics. The nozzles ID 120 03, ID 120 02, IS 80 03 and IS 80 02 are tested at 5 bar operating pressure in seven repetitions in the laboratory.

### Crop covering

Using water-sensitive paper (WSP, size: 76 x 26 mm) and the image analysis programme „Image J“ ( ImageJ bundled with 64-bit Java 1.8.0_172, https://imagej.net/ij/index.html) the crop liquid coverage was measured. The WSP is yellow in an unused dry state and turns bluish to purple in contact with moisture. The following image adjustments were set in “Image J”:

- Bits per pixel: 8 (grayscale LUT)
- Lower threshold level 62 / Upper threshold level 129
- image resolution: width 894 pixels / heigth 300 pixels
- Size 262 k

A wheat field with an advanced growth stage (BBCH stage of 55 – 59) was selected for the trial in order to obtain the best possible results on distribution in the crop. Two WSP were placed at four measuring points (Figure 4: A, B, C, D) along the boom direction, each at three different heights. The position of the WSP was set at ground level (below = b), in the middle of the crop (35 cm above the ground, middle = m) and 10 cm below the top of the crop (65 cm above the ground, above = a). Three of the four measuring points were set up in the area of the tramline affected by the application with the modified nozzles. The other measuring point was set up outside this area. The WSP at the three heights were vertically offset to avoid a possible splash shadow from the higher WSP. Shading by the wheat leaves was not prevented, as this was also intentional. For each crossing of a variant, three of these measurement series were repeated at a distance of 2.5 m. After each pass, the three-measurement series were shifted by 7.5 m in the direction of travel in order to avoid a possible influence of covering leaves from the previous pass.

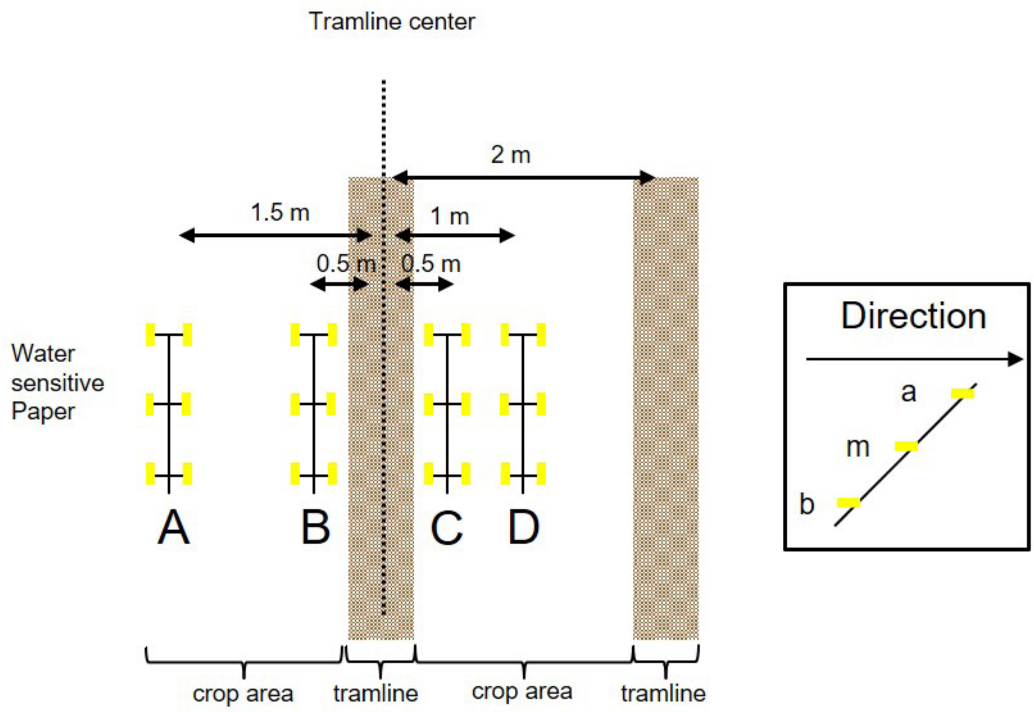


Figure 4: Positioning of the water-sensitive papers (WSP); A, B, C, D = measuring points parallel to the boom; measuring points at the heights: a = above, m = middle of the stand, b = below at the ground level; two WSP were attached to each height measurement point, tramline width 0.5 m

After application, the water-sensitive paper was placed individually in labelled roll rim jars with snap-on lids to prevent further discolouration due to high humidity or splash water. Afterwards, all the WSP were laminated so that no external influences could no longer affect the discolouration. Then the laminated WSP are scanned and saved as a file in JPEG format. The "Image J" analyses these files and calculates the area of the discoloured part of the WSP.

## Statistical Evaluation

The coefficient of variation and the mean value were used as statistical parameters in this work in order to describe the results of all measurements and to show possible differences in the quantitative and qualitative spray liquid distribution between the variants. When analysing the results, the distribution range of 16 nozzles was considered for the calculation of the coefficient of variation. The excluded area of the tramline was also omitted from the calculation. The determined coefficients of variation of the spray liquid distribution were then compared between the variants. Formula coefficient of variation according to equation 1:

$$V_k = \frac{\sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}}{\bar{x}} \cdot 100\ \% \quad \text{mit} \quad \bar{x} = \frac{\sum x_i}{n} \qquad \text{(Eq. 1)}$$

The Student-Newman-Keuls test was used to test the significance of the difference between the variants. The software environment SPSS handles the statistical evaluations. With regard to the number of replicates, an attempt was always made to realise the maximum number of replicates in the field trials and laboratory tests available within the framework of the time and material resources available.

## Results

### Quantitative distribution measurements

#### Lateral distribution

Static measurements in the laboratory and dynamic measurements in the field show the quantitative distribution of the spray liquid. The coefficients of variation were calculated without the area of the tramline (Table 1). The distribution measurements under static conditions were repeated six times per variant and the dynamic ones three times each. The calculated coefficients of variation of the measured spray liquid distributions range from 2.09 to 8.12 % for all variants. In all types of distribution measurements, the whole-area application (W-A) had the lowest coefficient of variation. The coefficient of variation in the first variant of tramline deactivation (T-L 1) was the highest at 8.12 %.

Table 1: Coefficients of variation of the static (n = 6) and dynamic (n = 3) distribution measurements; W-A = whole area application; T-L 1 = tramline deactivation variant one; T-L 2 = tramline deactivation variant two

| **Distribution measurement type** | **Coefficients of variation in %** | | |
|---|---|---|---|
| | **T-L 1** | **T-L 2** | **W-A** |
| Static distribution measurement | 5.58 | 5.03 | 2.09 |
| Dynamic distribution measurement with filter paper | 8.12 | 6.69 | 5.83 |
| Dynamic distribution measurement with Petri dishes | 6.90 | 6.33 | 4.23 |

#### Spray boom movement

Table 2 shows the results of the spray liquid distribution accuracy of the three variants T-L 1, T-L 2 and W-A with the aid of the coefficient of variation. Shifting the position of the boom in the vertical direction led to an increase in the coefficient of variation for all variants. Variant T-L 1 and T-L 2 had the highest value when the position of the boom in the vertical direction changed by 10 cm (9.69 % and 7.01 %). Variant W-A had the highest coefficient of variation (3.96 %) with a shift of -10 cm. A shift in the horizontal direction only affected the coefficient of variation in the variant T-L 1 and T-L 2. The coefficient of variation increased as well. With a coefficient of variation of 12.85 % in T-L 1 and 11.95 % in T-L 2, it records the highest values for a shift of 10 cm. There were no effects in the W-A variant.

Table 2: Coefficients of variation of static distribution measurements at different positions in vertical and horizontal direction (n = 6) of the boom to the tramline; W-A = whole area application; T-L 1 = Tramline deactivation variant one; T-L 2 = Tramline deactivation variant two

| Position change to the starting point in cm | | | coefficients of variation in % | | |
|---|---|---|---|---|---|
| | | | T-L 1 | T-L 2 | W-A |
| No change | | | 5.58 | 5.03 | 2.09 |
| Vertical | Up | + 10 | 9.69 | 7.01 | 2.84 |
| | | + 5 | 7.65 | 5.96 | 3.59 |
| | Down | -5 | 4.86 | 4.74 | 3.08 |
| | | -10 | 7.28 | 6.07 | 3.96 |
| Horizontal | Right | + 10 | 12.85 | 11.95 | 2.05 |
| | | + 5 | 7.23 | 6.68 | 2.13 |
| | Left | - 5 | 7.13 | 7.27 | 2.11 |
| | | - 10 | 12.42 | 11.37 | 2.07 |

By using a laser rangefinder, the lateral and vertical movements of the boom can be recorded. It creates a movement profile as well. It shows how much a boom generally moves during driving. Figure 5 shows the movement profiles of the boom in the horizontal direction during a crossing with a spray tank in three filling levels. The value Y = 0 represented the starting point of the spray boom. An oscillation of the boom around the value Y = 0 was measured in all movement profiles of the horizontal boom movement of all three filling levels. The extent of the oscillations is quantified in Figure 5 in the form of a positive and negative deviation based on the value Y = 0. The movement profiles of the boom of the different filling levels were similar. The highest deviation 63 mm of the boom occurred 5 % filling level. The mean deviation for the full spray tank was 24 mm, for the half-full spray tank 22 mm and for the sprayer with a 5 % filling level 24 mm. In all filling levels, more than 95 % of the deviations were equal to or greater 50 mm.

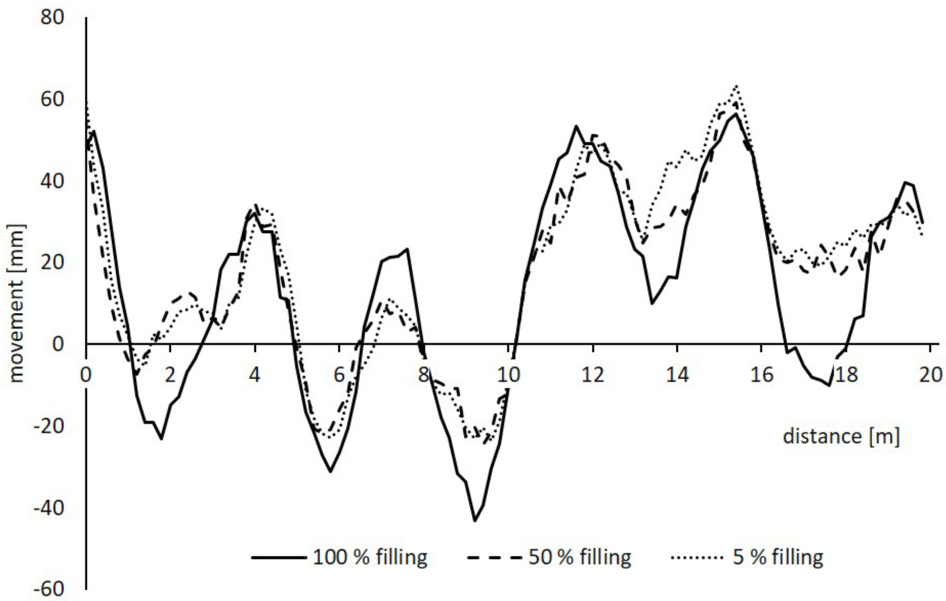


Figure 5: Horizontal movements (in mm) of the boom to the middle of the tramline at three different filling conditions of the field sprayer

Figure 6 shows the movement profiles of the boom movements in the vertical direction during one crossing. The value Y = 0 represents the previously defined target area distance. An oscillation of the boom around the value Y = 0 was measured in all movement profiles of the horizontal boom movement of all three filling levels. The extent of the oscillations was also quantified in the form of a positive and negative deviation starting from the value Y = 0. The movement profiles of the boom of the different filling levels were similar. It mostly deviated 66 mm at the boom with a 5 % filling level. The average deviation for the full spray tank was 12 mm, for the half-full spray tank 17 mm and the sprayer with a 5 % filling level 19 mm. For all filling levels, the deviation was less than 50 mm in more than 95 % of cases.

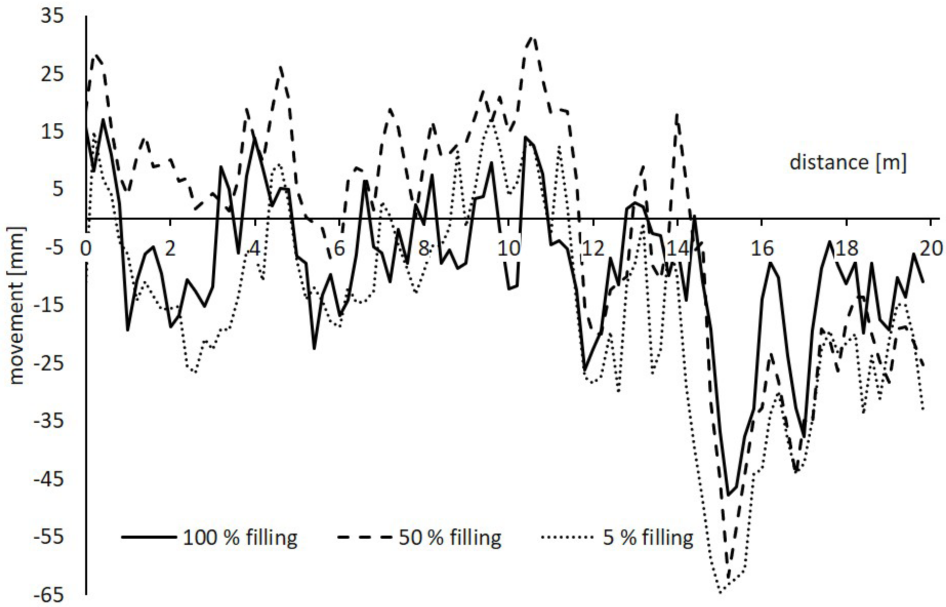

Figure 6: Vertical movements (in mm) of the boom to the exit point measured at three different filling conditions of the field sprayer

## Droplet size measurement

Table 3 shows the mean values of D10, D50 and D90 of the nozzles ID 120 03, ID 120 02, IS 80 03 and IS 80 02. The statistical differences between the variants were considered separately according to the mean values of the droplet diameters of the respective nozzle sizes. The D10 of the ID 120 03 and ID 120 02 with 140 µm and 141 µm was significantly smaller than the IS 80 03 and IS 80 02 with 149 µm and 148 µm. The absolute differences of these mean values were remarkably slight.

Table 3: Mean values of droplet diameter of four different nozzles types. Different lower-case letters indicate significant differences ($p \leq 0.05$).

| Classification according to mean values of droplet diameter | Nozzle calibre droplet sizes in µm [1)] | | | |
|---|---|---|---|---|
| | ID 120 03 | ID 120 02 | IS 80 03 | IS 80 02 |
| D10 | $140^{b}$ | $141^{b}$ | $149^{a}$ | $148^{a}$ |
| D50 | $333^{b}$ | $310^{c}$ | $428^{a}$ | $338^{b}$ |
| D90 | $645^{b}$ | $577^{c}$ | $884^{a}$ | $640^{b}$ |

[1)] Lower case letters a, b, and c indicate significant differences ($p \leq 0.05$).

The mean value of D50 of ID120 02 was 310 µm and significantly smaller than the other nozzles. The IS 80 03 has significantly the highest D50 with 428 µm. The ID 120 03 (333 µm) and the IS 80 02 (338 µm) did not differ significantly from each other. In the area of the D90 of the ID 120 02 was with 577 µm the significantly lowest. The IS 80 03 had significantly the highest D90 with 884 µm. The ID 120 03 (645 µm) and the IS 80 02 (640 µm) did not differ significantly from each other.

## Crop covering

To determine the covering of the crop, 24 strips of water-sensitive paper were used for each repetition and variant and thus a total of 216 strips were evaluated with the programme „Image J". Figure 7 shows the percentage covering of the water-sensitive paper in the respective positions and altitudes. The coverage at the top of the crop (a) ranged between 12 - 30 %, with the lowest values determined at position C. The middle area of the crop and the ground area is covered by 10 - 20 %, whereby again the lowest coverage tended to be determined in position C. The statistical differences between the variants were considered separately in the respective positions and heights. In positions A, B and C, there were no significant differences between the variants at all heights. The coverage of variant T-L 1 was significantly higher in position D above in crop (a) and in the middle (m) than in variant W-A. Variant T-L 2 did not differ significantly from the other variants. At the ground position (b), variant T-L 2 had significantly lower values than variant T-L 1 and W-A.

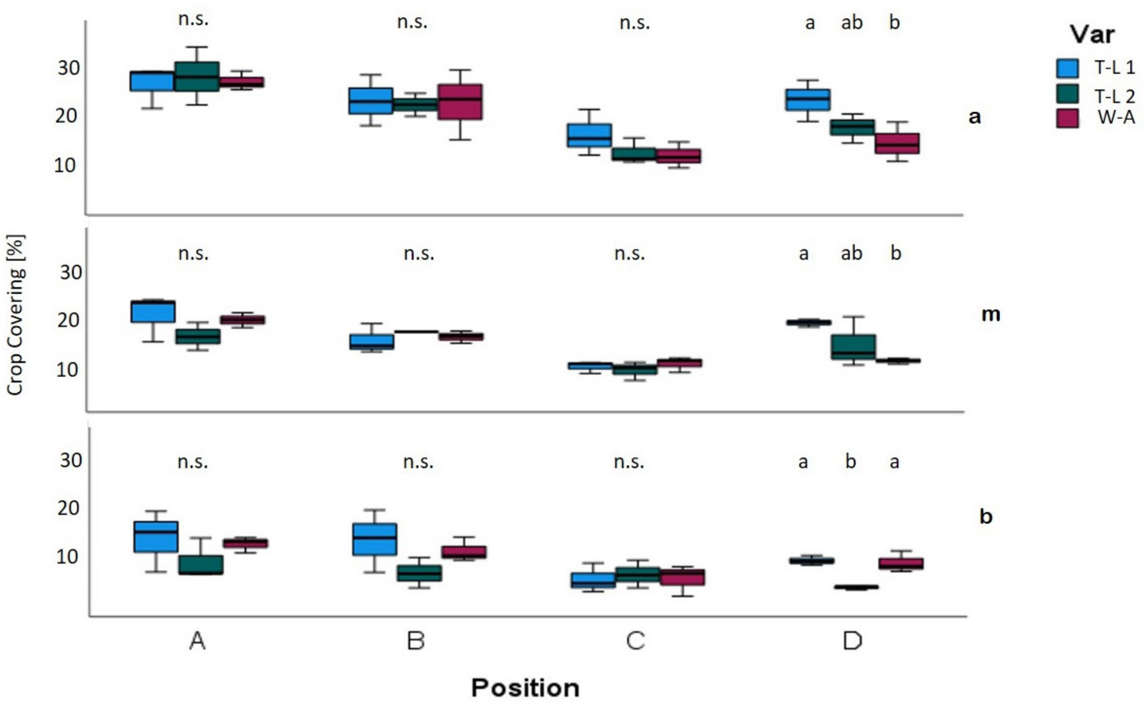


Figure 7: Box-Whisker-Plots of the percentage of covered surface of water-sensitive paper (n = 6) at different heights a (above), m (middle), b (below) at the ground level and positions to the tramline (A, D) within the crop (B, C) in the tramline; lower case letters a, b above the box-whisker plots of D indicate significant differences ($p \leq 0.05$)

## Discussion

The tramline deactivation during application is a technical possibility to exclude pesticides from the tramline. However, the results of the study showed that a change in the nozzle constellation on field sprayers to recess the tramline had a marginal influence on the distribution quantity and quality of the spray liquid.

### Quantitative distribution measurements

In the different approaches of lateral distribution measurements (static in the lab and, dynamic with filter paper and Petri dishes in the field), the lowest coefficients of variation always occurred in the whole-area treatment. According to guidelines for the testing of field sprayers (JKI 2013a, JKI 2019), the coefficients of variation of the spray liquid must not exceed a value of 7 % for new sprayers and for field sprayers in use 10 % in static measurement. These guidelines mainly apply only to a standardised nozzle configuration of the boom. However, mixed nozzles on the boom can be specially authorised and registered by the JKI, so that they are also covered by the guidelines (JKI 2022, JKI 2013b). The value of 7 % was only exceeded in variant T-L 1 in the dynamic measurement using filter paper (8.12 %) but was still below the limit value of 10 % for field sprayers in use. However, the guidelines only apply to static measurements with nozzle constellations registered and approved by the JKI. Therefore, it should be noted that these guidelines were only used here as orientation values for a better assessment of the results from the static distribution measurements in the laboratory and dynamic distribution measurements in the field for the variants T-L 1 and T-L 2.

Possible effects on the quantity or coefficient of variation of the spray liquid distribution due to the movement of the spray boom during application were explored as well. Among other things, it should be determined how great the differences were compared to standard practice and whether the legal guidelines are complied with. The boom movement in horizontal and vertical direction affected the spray liquid distribution more in the variants with a recessed tramline (T-L 1 and T-L 2) than in the variant with the whole area standard application (W-A). Movements of the spray boom in a vertical direction directly affected the size and shape of the spray flat that hits the crop. Especially in the area of the tramline, where asymmetric nozzles were used, the change of the spray flat had the greatest effect. A horizontal movement of the boom also led to an effect on the variation coefficient of the spray liquid distribution with the variants T-L 1 and T-L 2. This could be due to the fact that the recessed area of the tramline, in which no spray liquid should arrive, moves into the crop area in which the spray liquid should arrive.

With the W-A variant, this type of position change did not affect the distribution of the spray liquid, because the whole areas were applied with the spray liquid. The coefficient of variation of the spray liquid distribution was still below 10 % for all variants with a spray boom movement up to 5 cm and still complied with the guidelines for testing sprayers in use (JKI 2019). The rather smaller effects of the change in position of the boom up to 5 cm are presumably due to the fact that the variants T-L 1 and T-L 2 did not leave out the tramline with a sharp edge and thus a part of the spray liquid still applied there (Bröring and von Hörsten 2019). The extent to which the boom moved and deviated from the tramline was established by recording the boom movement during the crossing. 95 % of the deviations in vertical and horizontal direction were less than or equal to 5 cm. The maximum deviations were less than 7 cm. Based on the guidelines for field sprayers, the coefficient of variation of the spray liquid distribution during application would fulfil the requirements.

### Qualitative distribution measurements

The nozzle constellation in the area of the tramline was varied in the T-L 1 and T-L 2 variants in order to leave out the tramline during application. Therefore, effects on the distribution quality of the spray liquid are considered in order to be able to conclude on possible differences in the active ingredient attachment of plant protection products to the crop as well. Important properties of the spray liquids are the mean values of droplet diameter D10, D50 and D90 (Kifferle and Stahli 2001). Variant T-L 1 is equipped with ID 120 02 and IS 80 03 in the area of the tramline and thus had the biggest differences in droplet sizes compared to the nozzle size ID 120 03. This may result in possible differences with regard to the deposition of the active ingredient compared to the variant W-A in the area of the tramline. In contrast, the IS 80 02 nozzle, used in the T-L 2 variant, showed hardly any differences in droplet sizes to the nozzle size ID 120 03. Therefore, a similar deposit of pesticides as with nozzles IS 80 02 and ID 120 03 can be expected. The different droplet sizes of the nozzles can be attributed to the size of the openings in the mouthpieces.

Good distribution in the crop is an essential prerequisite for the successful effect of plant protection products (Böckmann et al. 2021). When recording the cover of the crop, the results showed that the variants T-L 1, T-L 2 and W-A do not differ significantly within positions A, B and C. Only in position D (in the crop between the tramline) significant differences between the variants occurred. In the case of variant T-L 1, one of the highest plant coverings was determined at all heights. This was related to the modified nozzle constellation in the tramline area. Due to the edge nozzles (IS 80 03) being inclined by 20° from the tramline, more spray liquid was sprayed into the area between the tramline at a modified spray angle. In addition, smaller nozzle calibres (ID 120 02) were used in the two nozzle positions between the edge nozzles. Due to the smaller nozzle calibres, the droplet spectrum shifted more towards smaller droplets. Small droplets have higher mobility in the crop so that they can penetrate the stand better and accumulate more at deeper levels (Moser and Cong 1979, Knott and Göhlich 1974). As a result, many drops reached the middle and ground level of the crop as well.

Variant T-L 2 had the lowest coverings of the crop near the ground. It can be assumed, that the cause is the modified nozzle constellation. In contrast to variant T-L 1, only the nozzles directly above the tramline were replaced by edge nozzles (IS 80 02). However, not only has the target area distance been reduced to 40 cm, but the nozzles have also been rotated by 50° to the boom axis so that the spray area is smaller. This could lead to such a change in the spray behaviour of the nozzles that the overlapping and distribution in the nozzle assembly is affected (Lardoux et al. 2007). In addition, the area of the wetted surface can decrease due to the reduction in the expansion of the spray fan (Wolf 2002). This could be a reason for the low number of droplets in the lower level.

The results of the qualitative and quantitative distribution measurements of the spray liquid conclude that in the crop area the active ingredient accumulation of the variants with tramline deactivation (T-L 1 and T-L 2) is similar to the active ingredient accumulation of the whole-area treatment (W-A). With this knowledge, it would be conceivable to leave out the tramline during application with the variants T-L 1 and T-L 2, which, in contrast to the variant W-A, would save plant protection products and reduce the burden on the environment (Bröring and von Hörsten 2019). However, in order to make more concrete statements about the effectiveness of a plant protection treatment, further field trials and practical applications with corresponding effectiveness tests of plant protection products would need to be carried out.

## Conclusions

A tramline deactivation in field sprayers makes it possible to leave out this crop-free area during the application of plant protection products. The technical implementation requires a modification of the nozzle constellation in the area of the tramline, which in turn can cause a change in the spraying behaviour and pattern.

However, these changes only have a minor effect on the quantitative and qualitative distribution of the spray liquid. The test methods used in this study and the legal guidelines taken into account, have so far only been applied to field sprayers with uniform-surface spray liquid distribution. In order to establish systems with tramline deactivation for field sprayers in agricultural practice, the test methods and legal guidelines must be modified. Provided, of course, that the following field trials are successful with regard to the effectiveness of plant protection products in the crop.

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## Conflicts of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

### Acknowledgements

The project was supported by funds of the Federal Ministry of Food and Agriculture (BMEL) based on a decision of the Parliament of the Federal Republic of Germany via the Federal Office for Agriculture and Food (BLE).