Field-crop-sprayer potential drift measured using test bench: Effects of boom height and nozzle type

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Abstract

Because of variations in environmental conditions, spray-drift field measurements following ISO 22866:2005 involve complicated and time-consuming experiments often with low repeatability. Therefore, simple, repeatable, and precise alternative drift assessment methods that are complementary to the official standards are required. One of the alternatives is the use of a drift test bench for field crop sprayers. Previous studies have demonstrated that the drift test bench can be considered an adequate complement to existing standard protocols for field drift measurements. In this study, in order to further improve the methodology and to evaluate the possibility of classifying different field-crop-sprayer settings according to drift risk using a test bench, a series of tests were performed in a test hall. A conventional mounted Delvano HD3 crop sprayer (Delvano, Kuurne, Belgium) equipped with an 800-l spray tank and a 15-m-wide stainless steel spray boom was used. Eight different sprayer setups were tested, involving three nozzle types (TeeJet XR 110 04, Agrotop TDXL 110 04 and Micron Micromax 3) and three boom heights (0.30, 0.50, and 0.70 m). For the drift classification, the reference sprayer drift behaviour was defined as that obtained using conventional flat fan TeeJet XR 110 04 nozzles operated at 0.30 MPa and at a boom height of

0.50 m. The different sprayer setups were successfully assigned to different drift reduction classes, and the results underlined the effects of nozzle type and boom height on the potential drift. The feasibility of the test-bench methodology for classifying field-crop-sprayer drift according to ISO 22369-1:2006 was demonstrated.

Keywords: sprayer setting, spray drift, droplet size, drift reduction, classification.

Nomenclature:

D	spray deposit measured on Petri dish (μl cm^{-2})
As	absorbance (ABS, dimensionless) of Petri dish sample washing
A_0	absorbance (ABS, dimensionless) of blank Petri dish sample washing
At	absorbance (ABS, dimensionless) of tank solution
V	volume of deionised water (μl) used to elute sample
S	area of Petri dish collection surface (165 cm^2)
DPV	drift potential value (dimensionless)
Di	spray deposit on single deposit collector placed in covered bench slots (μl cm^{-2})
D[v,0.1]	Droplet size parameter. 10^{th} percentile
D[v,0.5]	Droplet size parameter. 50^{th} percentile
D[v,0.9]	Droplet size parameter. 90^{th} percentile
RSD	reference spray deposit under boom (μl cm^{-2})
SE	standard error of the mean
VMD	Volume Median Diameter

1. Introduction

The requirements of the European Directive 128/2009/EC on the sustainable use of pesticides include the objective to reduce spray drift during application of agrochemicals to crops, especially in the proximity of sensitive areas (e.g., water bodies, natural reserves, and urban areas). To achieve this goal, various spray-drift mitigation measures can be adopted, which either affect the sprayer components directly (e.g., the mounting of air-induction nozzles) or require sprayer adjustment. Alternatively, indirect mitigation measures such as the construction of buffer zones and physical barriers (e.g., hedges) along the borders of sprayed fields can be adopted. A combination of direct and indirect spray-drift mitigation measures may facilitate minimisation of the widths of the buffer zones established between the application areas and the sensitive zones, thereby increasing the land surface available for cultivation.

In order to define buffer-zone widths, it is necessary to consider certain parameters, such as the features of the sensitive area in question (e.g., the size of a water course), the toxicity of the applied agrochemicals and, most importantly, the spray application parameters adopted for the agrochemical distribution (Gilbert, 2000; Nilsson and Svensson, 2004). As regards the latter, it is necessary to consider the sprayer type, nozzles, and operative parameters of the sprayer (Herbst and Ganzelmeier, 2000; van de Zande et al., 2000; Nuyttens et al., 2007). In 2006, criteria to classify spraying equipment according to drift risk were established (ISO 22369-1:2006). These criteria are based on a relative comparison between the drift generated by the candidate spraying equipment and a reference apparatus, which is selected as being representative of the most common spraying technique adopted for a certain scenario (e.g., for application to field crops, vineyards or orchards). To date, this relative comparison has been performed using drift measurement data that can be obtained in the field, applying the ISO 22866:2005 test methodology (ISO 22866:2005), or in a laboratory wind tunnel, following the ISO standard 22856:2008 (Nuyttens et al., 2011).

Both standardised test methodologies, however, have certain limitations. ISO 22866:2005 methodologies are designed for tests to measure the amount of drift outside the applied field for defined wind-speed and -direction conditions. However, it is difficult to perform relative comparisons between spraying results, as operation under the same wind conditions is required for a successful comparison. Moreover, the test procedure itself is complex and time consuming and, as regards spray application to arboreal crops, the results are affected by the morphological and vegetative features of the orchard/vineyard in which the tests are performed. On the other hand, the ISO 22856:2008 methodology facilitates the performance of relative comparisons more rapidly. However, this comparison is primarily between nozzles rather than the full spraying system, as the test procedure involves drift measurement in a wind tunnel with dimensions sufficient to contain small boom sprayers only. Therefore, using ISO 22856:2008, it is difficult to compare the spray drift generated by complete sprayers, since drift not only depends on the spray quality, but also on the sprayer configuration and adjustment.

To overcome these limitations, researchers at the Dipartimento di Scienze Agrarie, Forestali e Alimentari (DiSAFA) at the University of Torino (Turin, Italy), in collaboration with the Advanced Agricultural Measurement Systems (AAMS)-Salvarani company (Maldegerm, Belgium), researched and developed an *ad hoc* test bench for the measurement of potential spray drift (Balsari et al., 2007). Potential spray drift is defined as the percentage of initial spray volume that remains suspended in the air after the sprayer passage and which represents the fraction of spray liquid more susceptible to drift out of the treated area by the action of air currents during the application process. It differs from the absolute spray drift because it consists only of a plume of droplets which remain suspended in the air after the passage of the sprayer along the swath and these droplets deposit sometime after the boom has moved over a given point. As potential drift has to be measured in the absence of wind, its amount is not affected by wind velocity and direction, but it depends only on the turbulence generated by the sprayer moving forward and is influenced by boom height and size of the sprayed droplets. On the other hand absolute spray drift, according to the definition given in ISO 22866 (2005) is represented by the “quantity of plant protection product that is carried out of the sprayed (treated) area by the action of air currents during the application process”. Its amount is therefore represented by all the spray that is applied within the field but is blown out of target area by wind. Wind velocity and direction therefore strongly affect absolute drift values, making it difficult to determine the influence of individual sprayer parameters on the results obtained, particularly if the wind conditions vary. This is the reason why, in order to make relative comparisons between spraying equipment in terms of drift risk, measurement of potential drift was considered here to be a more suitable parameter for providing objective and reproducible data since the influence of environmental conditions on the results obtained is much less.

Researchers have promoted the establishment of an ISO standardised test methodology (ISO 22401:2015) for measuring the potential spray drift generated by field crop sprayers. During the process of establishing the test method, the members of ISO TC23/SC6/WG 16 performed indoor tests on field crop sprayers at the Praktijkcentrum voor Land- en Tuinbouw (PCLT) testing hall in Roeselare (Belgium), which were primarily intended to assess the robustness of the proposed methodology. During these tests, among other investigations, an evaluation of the potential spray drift generated by different combinations of boom heights and nozzle types on a Delvano HD3 mounted field crop sprayer was conducted, using the test bench.

This paper reports on these tests and their findings, thereby clarifying the influence of boom height and nozzle type on potential spray drift. Hence, the efficacy of the ISO 22401:2015 methodology for classifying different field-crop-sprayer settings according to drift risk is evaluated, and discusses the reproducibility of the test-bench-based results and its functionality.

2. Materials and methods

2.1 Measuring set

Tests were conducted at PCLT Roeselare in Belgium, in a test hall of approximately 60 m in length, 30 m in width, and 8 m in height, with a completely level earth floor (Fig. 1).

[Insert Fig. 1]

The environmental conditions (air temperature and relative humidity, wind speed and direction) were measured and registered during the tests using an Allemano Testo 400 thermo-hygrometer (Nuova Allemano, Collegno, Italy) and a Gill Windsonic sonic anemometer (Gill Instruments, Hampshire, UK) at 1-Hz frequency. Instruments were positioned on one side of the test hall at 2 m height from the ground.

All the tests were conducted at an average air temperature of 10°C (minimum and maximum: 8.7°C and 11.3°C, respectively), an average relative humidity of 81% (minimum and maximum: 78% and 84%, respectively) and a very low average wind speed of 0.07 m s^{-1} (minimum and maximum: 0.04 and 0.14 m s^{-1}, respectively). Thus, the environmental conditions for all of the performed tests were stable and uniform. The tests were performed in accordance with the ISO 22401:2015 methodology (ISO 22401:2015). The drift test bench consisted of an aluminium frame of 10.5-m length and 0.5-m width, which contained slots for artificial collectors (plastic Petri dishes, 150-mm diameter; Kartell, Milano). These artificial collector slots were positioned at intervals of 0.5 m and equipped with sliding lids to ensure that the collectors could be completely covered. The test bench was positioned such that the line of collectors was parallel to the driving direction and aligned with the centre of the right-hand side of the spray boom (Fig. 1). Two slots at both extremities of the bench were left permanently uncovered so that the effective overall spray deposition under the boom could be measured. Deposit collectors were located at a height of approximately 0.25 m from the ground. During each run, the boom sprayer moved at a set forward speed along a path of approximately 50 m in length, spraying over the covered test bench, which was positioned halfway along the spray track. When the boom made contact with the actuator rod, the slots were automatically uncovered by a pneumatic system. The actuator rod was always positioned 2.0 m behind the centre of the last collector on the test bench, independent of the nozzle type used, in order to prevent the nozzles from spraying directly onto the collectors.

To allow all the droplets suspended in the air to be deposited, but prevent accidental contamination, the exposed Petri dishes were manually covered, but not until 60 s after the sprayer had passed. After collecting the Petri dishes, all sliding covers were cleaned to prevent dripping liquid contaminating the dishes.

2.2 Spray application techniques

The tests were executed using a conventional mounted Delvano HD3 field crop sprayer (Delvano, Kuurne, Belgium) equipped with an 800-l spray tank and a 15-m wide stainless spray boom with 0.50 m nozzle spacing. The boom was mounted on a trapezoidal suspension, which ensured its stability and horizontality. The sprayer was coupled to a New Holland 8260 tractor with 75-kW power. All tests were performed at 6 km h^{-1} forward speed.

Eight different spray application techniques were tested, with three repetitions for each setup (Table 1). Three different nozzle types (a TeeJet XR 11004 conventional flat-fan at 0.30-MPa pressure, an Agrotop TDXL 11004 air-induction flat fan at 0.30 MPa, and Micron Micromax 3 rotary atomisers operated at 0.28 MPa pressure and 2000 or 3200 rpm rotation speed) and three boom heights (0.30, 0.50, and 0.70 m) were considered. In accordance with previous studies (van de Zande et al., 2008), the reference spraying technique was defined as operation of the TeeJet XR 11004 nozzles at 0.30 MPa with a 0.50-m boom height, at a constant forward speed of 6 km h^{-1}. This corresponded to an application volume of 316 l ha^{-1}. The boom height was measured from the nozzle tip to the deposit collectors. The effective forward speed was manually checked by measuring the time required by the sprayer to cover a distance of 40 m along the spray track.

[Insert Table 1]

2.3 Spray quality assessment

The spray quality obtained for the various examined setups was evaluated through measurements of the droplet size yielded by the three different nozzle types and the corresponding operative parameters (Table 1). The droplet size measurements were performed at the DiSAFA Crop Protection Technology laboratory of Turin University using a Malvern Spraytec laser diffraction system (Malvern Instruments Ltd., Malvern, UK) equipped with a 750 mm lens and with dedicated software. For each nozzle type, measurements were carried out on a single nozzle in fix position, 0.30 m above the laser beam, which targeted the spray jet in accordance with the nozzle axis. For each of the four examined setups, the Malvern systems acquired data for at least 60 s for each measurement, and the tests were repeated three times. The D[v,0.1], D[v,0.5], D[v,0.9], and V_{100} droplet parameters were calculated.

[Insert Table 2]

2.4 Deposition measurements

The spray solution consisted of a water solution with a tracer of Tartrazine E102 yellow dye (at a targeted concentration of 10 g l^{-1}). This was prepared by pouring a weighed amount of the tracer powder into the main spray tank, which contained a measured amount of clear water. Using the sprayer agitation system, the solution was thoroughly mixed for at least 10 min to obtain a uniform tracer concentration. Before each test, the boom was activated for approximately 60 s in order to ensure all hoses and nozzles were primed with the spray solution. For each test, one 150-mm Petri dish collector was placed in each test bench slot, resulting in a total of 22 collectors. As noted above, two of these collectors were permanently uncovered.

Before each test run, two tank samples were taken from the nozzles in order to measure the actual tracer concentration, while the sprayer was activated at the set operating pressure in a static position. These samples were collected and then stored for laboratory analysis in order to obtain the reference absorbance value.

The permanently uncovered collectors were manually washed in the laboratory using 100 ± 1 ml of deionised water, and the other collectors (which were only exposed after the sprayer pass) were washed with 10 ± 1 ml of deionised water. The washings were analysed using a WDR PC 1600 spectrophotometer set at an excitation wavelength of 434 nm (corresponding to the absorption peak of the Tartrazine tracer). The spray depositions in the Petri dishes (*D*) were calculated according to Eq. (1) and expressed in µl cm^{-2}, such that

$$D = \frac{(As - A0)}{Ar} \times \frac{V}{S}, \qquad (1)$$

where *As* is the absorbance (ABS, dimensionless) of the Petri dish sample washing, A_0 is the absorbance (ABS, dimensionless) of the washing from a blank Petri dish collected during the indoor tests, *Ar* is the absorbance (ABS, dimensionless) of the tank solution, *V* is the volume of deionised water (µl) used to wash the sample, and *S* is the area of the Petri dish collection surface (165 cm^2). The variation in the D_i obtained in the collectors positioned within the test bench and along the spray boom travel direction were plotted, in order to obtain the shape of the trailing plume generated during the spray process.

2.5 Drift Potential Value Calculation

The drift potential value (*DPV*) was calculated for each examined setup, following ISO 22401:2015, on the basis of the sum of the spray deposits registered along the test bench. This calculation considered data from the collectors placed in the slots that were uncovered after the sprayer pass only (see Eq. (2)). The sum of these deposits was then divided by the reference spray deposit under the boom (*RSD*; µl cm^{-2}), which was calculated for each individual test iteration based on the measured average nozzle flow rate and the effective forward speed. Thus,

$$DPV = \sum Di / RSD \times 100, \quad (2)$$

where *Di* is the spray deposit on a single deposit collector positioned in the covered slots (µl cm^{-2}).The *RSD* value has a direct influence on the *DPV* calculation, but this parameter is calculated using the intended volume rate (l ha^{-1}) for which the sprayer is calibrated. In order to verify the accuracy of the sprayer calibration and, therefore, the reliability of the *RSD* for the *DPV* calculation, two uncovered Petri dishes were placed at the extremities of the test bench for each spray run. These Petri dishes were used to determine the actual amount of spray deposit recovered under the boom.

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2.6 Statistical analysis

The effects of the boom height and nozzle type on the *DPV* values were evaluated using one-way analysis of variance (ANOVA) testing, followed by a *post hoc* comparison using a Tukey test ($P <$ 0.05). The R statistical software package was used in all cases (R Development Core Team, 2012). The data were transformed (ln [*DPV*/100]) to yield residual normality and homoscedasticity prior to the statistical analysis. Moreover, residual analyses were also conducted. In addition, the relationship between the *RSD* and *Di* of the uncovered collectors (µl cm^{-2}), which were positioned at distances 0 and 10.5 m along the test bench, were assessed.

3. Results

3.1 Spray quality assessment

The droplet-size measurements indicated that the TeeJet XR 11004 conventional flat-fan nozzle at 0.30 MPa produced medium droplets, according to the American Society of Agricultural Engineers (ASAE) classification (Fig. 2a), with a non-negligible volume of fine droplets present in its spectrum. Specifically, the D[v,10] result was 70 µm (Table 2). Further, the Agrotop TDXL 11004 air-induction flat fan nozzle at 0.30 MPa produced very coarse droplets (Fig. 2b), with a D[v,50] of 467 µm (Table 2), and a reduced amount of very fine droplets in the spray jet (the D[v,10] result was 186 µm). The Micron Micromax 3 rotary atomisers generated a more uniform spectrum of droplets for both tested rotation speeds, as their sizes ranged between 150 and 500 µm. Further, there was a complete cut-off of fine droplets of fewer than 100 µm in size (Table 2). In addition, the D[v,10], D[v,50], and D[v,90] values were more similar to one another than in the case of the flat fan hydraulic nozzles. Therefore, the cumulative volume trend in relation to the droplet size for the rotary atomiser was very different to the trends observed for the hydraulic nozzles (Fig. 2c and 2d).

[Insert Fig. 2 and Table 2]

3.2. Indoor trials

3.2.1 Effect of boom height

For both of the examined flat-fan nozzle types, it was found that the boom height has a significant effect on the *DPV* values (Table 3). For a boom height of 70 cm, the drift was significantly higher than that for 50 cm, followed again by that for 30 cm (Fig. 4). For conventional hydraulic nozzles, it is worth noting that the *DPV* value registered at 70-cm boom height was double (55 ± 3) the *DPV* obtained for the 50-cm boom height (25 ± 0.4). Furthermore, the latter value was twice the *DPV* measured at the 30-cm boom height (12 ± 1). A similar trend was observed for the air-induction nozzles.

In absolute terms, the *DPV* values obtained using the conventional flat-fan nozzles at 30-cm boom height (*DPV* = 12 ± 1) were very close to those obtained using the air-induction flat fan nozzles at 70-cm boom height (*DPV* = 11 ± 1). Considering the obtained *DPV* value trend, it is also clear that the effect of boom height is independent of nozzle type (Table 3). These results are in accordance with the recommendations concerning optimal boom height made by various researchers in the ambit of the Train Operators to Promote Best Management Practices and Sustainability (TOPPS) project (see the "Best Management Practices to reduce spray drift" document on the TOPPS website (TOPPS, 2015)).

The boom height also affected the variability of the results obtained for the various test iterations. Higher standard errors of the mean (SE) values (Fig. 3) were obtained when the boom height was increased; this was particularly evident in the case of the conventional flat-fan nozzles.

[Insert Fig. 3, Table 3]

3.2.2 Effect of nozzle type

Significant differences among nozzle types were also found (Table 3). For 50-cm boom height, the largest (25.2) and smallest (1.9) *DPV* values were obtained for the conventional nozzles and the Micron Micromax 3 rotary atomisers at 2000 min^{-1} rotation speed, respectively (Fig. 4). Significant differences in terms of *DPV* were also found between the two rotation speed settings of the atomisers (Fig. 4).

A detailed analysis of the combined effects of nozzle type and boom height indicates that conventional flat-fan nozzles are much more strongly affected by boom height than air-injection nozzles. This behaviour can be also linked to the droplet sizes and spectral distributions (D50 values of 193 and 497 µm for conventional and air-injection flat fan nozzles, respectively, and D10 values of 70 and 186 µm values for the same nozzles, respectively). Note that these results also demonstrate the efficacy of the test bench for drift evaluation purposes and for discrimination between the factors affecting drift. Further, these findings are in line with those obtained by Balsari et al. (2007).

As regards the comparison of the effect of nozzle type at the standard recommended boom height for flat fan nozzles (50 cm), it is interesting to note (Fig. 4) the large and statistically significant difference between conventional and air-injection flat-fan nozzles, with the air-injection nozzles generating a drift potential less than three times that of the conventional nozzles. In these tests, rotary atomisers were also included, and two different droplet size spectra were obtained by modifying the rotation speed (2000 and 3200 rpm). Despite the different nozzle designs, the results indicate that the rotary atomisers have similar tendencies to flat-fan nozzles, with a significantly lower drift potential that corresponds to a coarser spray quality.

[Insert Fig. 4 and Table 5]

3.2.3 Deposition curves

Figure 5 shows the curves obtained for the conventional and air-injection nozzles at the three examined boom heights. A detailed analysis of these curves indicates that the majority of the spray deposits were located within the first 4 and 2 m of the test bench when conventional and air-induction nozzles were employed, respectively. However, the trailing plume shape was very similar for each nozzle type, and the different boom heights affected the magnitude of the spray deposits only; therefore, the *DPV* values were affected, but the spray deposition along the test bench was not.

To consider the complete curve for the DPV calculation requires taking into account the whole of the plume of droplets that remains suspended in the air after the boom sprayer passed, especially the finer droplets which are more susceptible to drift. The spray deposit collected on the first dish of the test bench, uncovered just after the sprayer pass, often represents the highest drift deposit on the test bench, but this is not always true. The trend of the deposits on the test bench, does generally decrease but not always in a systematically, showing some “waves” (see Fig. 5). These irregular trends of spray deposits along the test bench are more evident when finer spray (i.e. produced by conventional nozzles) and boom heights over 50 cm are used. The analysis of the whole plume of droplets therefore provides more complete information about the potential drift risk.

Figure 6 shows the deposition curves obtained for the two examined rotary atomisers. As expected, higher D_i spray deposition values were found towards the upper end of the test bench when the Micromax 3 nozzles were operated at a rotation speed of 3200 rpm, which generated finer droplets. However, when the rotation speed was reduced to 2000 rpm, yielding a coarser spray quality, very low spray deposits were observed on the test bench collectors.

If nozzle type is the only variable considered in the deposition curve evaluation (Fig. 6), then the influence of droplet size and droplet spectrum uniformity are clear. The conventional flat-fan nozzles generated droplets with a D[v,0.1] of 70 μm and a V_{100} of 24.2% (see Table 2), whereas the rotary atomisers yielded a D[v,0.1] value of 206 μm with 0% for V_{100}. These factors, combined with the significant differences in terms of the volume application rates between the hydraulic and centrifugal nozzles, seem to have an important effect on the drift potential.

[Insert Fig. 5 and 6]

3.2.4 Relationship between RSD and uncovered Petri dishes

In all tests the recovery rate on the permanently exposed collectors was always >70% of RSD, as recommended by ISO 22401, proving that the test procedure was followed appropriately. Figure 7 shows the relationship between the theoretical *RSD* values (based on the intended spray volume expressed in μl cm^{-2}) and the actual spray deposits recovered under the boom in all of the tests. In general, the relationship between the *RSD* and the spray deposit detected on the uncovered collectors resulted similar for both test-bench extremities and results were more strictly correlated when the centrifugal nozzles were employed, with respect to the conventional and air-induction flat-fan nozzles. In all the tests examined the variability of deposits on the permanently uncovered collectors, assessed by the three replicates, resulted in similar values at the beginning (0 m) and at the end of the test bench (10.5 m), with CV values generally around 10%. In the eight tests examined the average ratio between the deposit under the boom and the corresponding RSD ranged between 86% and 104%. Considering all the tests examined, however, any relationship ($P<0.05$) was found between the ratio of the deposit under the boom vs. the corresponding RSD and the DPV obtained.

[Insert Fig. 7]

3.2.5 Relationship between DPV and spray quality

The *DPV* values were also compared in relation to the droplet size spectrum generated by each evaluated nozzle. Figure 8 shows the relationship between the *DPV* values and the four most widely used droplet-spectrum indicators: D[v,0.1], D[v,0.5], D [v,0.9], and V_{100} (ASABE, 2009; ISO, 2011). Some trends between these parameters and the *DPV* results were found, especially in the case of D[v,0.1]. These results are clearly in accordance with those obtained in previous studies, where the correlation between V_{100} and the total spray drift was very strongly demonstrated (Legg, 1983; Bode, 1984; Miller, 1988; Western et al., 1989; Bouse et al., 1990; Combellack et al., 1996; Baetens et al., 2008; Arvidsson et al., 2011; Gil et al., 2014). **[Insert Fig. 8]**

3.2.6. Drift reduction

By comparing the average *DPV* values obtained for the eight examined sprayer settings, it was observed that, in the majority of the cases, the potential drift was lower than that of the reference value (TeeJet XR 11004 conventional flat-fan nozzles operated at 50-cm boom height). Only when the boom height was increased to 70 cm for the conventional nozzles was a *DPV* value higher than the reference obtained (Table 4). A very high reduction (> 90%) in the potential drift with respect to the reference sprayer setting was obtained when the air-induction nozzles were operated at 30-cm boom height, and also when the rotary atomisers were operated at 2000-rpm rotation speed and at 50-cm boom height.

[Insert Table 6 and Table 7]

4. Discussion

The experimental results confirmed the conclusions of previous studies (Gil et al., 2014; Gil et al., 2015), i.e., that the test methodology used to assess the potential drift of field crop sprayers described in ISO Standard 22401:2015 is appropriate, and that it facilitates successful discrimination between the *DPV* values obtained for a single sprayer with different test settings (e.g., different nozzle-type and boom-height combinations). Applying the drift reduction classes established in ISO 22369-1:2006 to the experimental *DPV* results, it was, in fact, possible to assign six sprayer setups to particular drift reduction classes (Table 5). The reference *DPV* value obtained using conventional flat-fan nozzles at a boom height of 50 cm was retained throughout the tests. This classification yielded reliable results, indicating that the coarser the sprayed droplets and the lower the boom height, the smaller the drift. (This confirms the results obtained by Balsari et al. (2007)). Further tests are currently being conducted in order to verify whether the classifications obtained for the examined sprayer settings using the test bench to evaluate the potential drift are consistent with those obtained for the same sprayer settings under application of the ISO 22866:2005 test methodology (spray drift measurement in the field) or the ISO 22856:2008 test methodology (spray drift measurement in a wind tunnel).

The obtained results also demonstrate that the indoor use of the test bench facilitates reduced the variance of the results since the coefficient of variation between the three *DPV* values obtained for each examined setup was always found to be within 15%.

5. Conclusions

This study presented an evaluation of the potential spray drift generated by different combinations of boom heights and nozzle types for a Delvano HD3 mounted field crop sprayer, using a previously designed test bench. The experimental results confirmed the robustness of the ISO 22401:2015 test methodology for the measurement of the potential spray drift generated by field crop sprayers, with the aim of classifying different sprayer settings according to drift risk. Concerning boom height and nozzle type boom sprayer setting parameters, test results showed the capability of the test bench and relative ISO standard methodology (ISO 22401) to recognise their significant effect on DPV. The use of air-induction nozzles compared to standard nozzles at the same working height, enabled to reduce potential drift between 56% and 91% (see Table 4). Lowering of boom height from 70 to 50 cm allowed to reduce DPV by 55% and 36% using the standard and the air induction nozzles respectively (see Table 4). Further, as the use of test bench facilitates indoor operation, it allows effective results to be obtained within a short period of time, because the reproducibility of the results is very high. Moreover, the ISO 22401:2015 test methodology facilitates comparison of sprayer settings according to drift risk using the full field-crop-sprayer apparatus, similar to field-operation conditions, and not just with a sprayer component (e.g., a nozzle). Because of the simplicity of this method and the reproducibility of the results, it is expected that very similar results could be obtained in different laboratories around the world for the same sprayer settings. The use of an indoor test bench can therefore be considered to be an effective approach to performing a rapid and reliable drift classification of field crop sprayer settings. On one hand, the indoor test bench allows the complete sprayer to be employed, as in field treatments, and on the other hand, the results are not affected by the variable and unpredictable outdoor environmental conditions. Further refinements of the *DPV* calculation method are envisaged in order to facilitate comparison between the potential drifts obtained for sprayer trial setups involving different forward speeds (Nuyttens, 2016).

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Figure Captions

Fig. 1: PCLT test hall in Roeselare (Belgium), where the experimental trials were conducted.

Fig. 2: Cumulate volume curves as functions of droplet size measured by Malvern Spraytec system for spray jet generated by: (a) TeeJet XR 11004, (b) Agrotop TDXL 11004, (c) Micron Micromax 3 (2000 rpm), and (d) Micron Micromax (3200 rpm) nozzles, and comparison with ASAE classification. VF = very fine; F = fine; M = medium; C = coarse; VC = very coarse; XC = extremely coarse; UC = unclassified.

Fig. 3: *DPV* values according to nozzle type and boom height. The different letters for each nozzle type indicate significant differences in response to boom height variations (post hoc Tukey test, $P < 0.05$). The bars indicate the mean + SE.

Fig. 4: *DPV* values according to nozzle type for 50-cm boom height. The different letters indicate significant differences among the nozzle type results (post hoc Tukey test, $P < 0.05$). The bars indicate the mean + SE.

Fig. 5: Spray-deposit profiles for two different nozzle types (TeeJet XR 11004 and Agrotop TDXL 11004) and three boom heights (30, 50, and 70 cm). The mean ± SE ($\mu l\ cm^{-2}$) of the spray deposit on the collectors at each interval along the test bench is shown.

Fig. 6: Spray-deposit profiles for different nozzle types (TeeJet XR 11004, Agrotop TDXL 11004, Micron coarse drops, Micron fine drops) at 50-cm boom height. The mean ± SE ($\mu l\ cm^{-2}$) of the spray deposit on the collectors at each interval along the test bench is shown.

Fig. 7: Relationship between *RSD* (µL cm^{-2}) and *Di* on uncovered collectors (µl cm^{-2}) located at 0 (left) and 10.5 m (right) along the test bench.

Fig. 8: *DPV* values according to droplet size expressed in terms of D[v,0.1] (upper left), D[v,0.5] (upper right), D[v,0.9] (bottom left), and V_{100} (bottom right).

Tables

Table 1: Setups examined in experiments.

Setup	Nozzle type	Operating pressure (MPa)	Boom height (cm)	Volume application rate (l ha^{-1})
1	TeeJet XR 11004	0.30	30	316
2	TeeJet XR 11004	0.30	50	316
3	TeeJet XR 11004	0.30	50	316
4	Agrotop TDXL 11004	0.30	30	316
5	Agrotop TDXL 11004	0.30	50	316
6	Agrotop TDXL 11004	0.30	70	316
7	Micron Micromax 3 (2000 rpm)	0.28	50	110
8	Micron Micromax 3 (3200 rpm)	0.28	50	110

Table 2: Droplet size parameters measured for tested nozzles using Malvern Spraytec instrument.

Nozzle type	Pressure (MPa)	D[v,0.1] (μm)	D[v,0.5] (μm)	D[v,0.9] (μm)	V_{100} (%)
TeeJet XR 11004	0.30	70	193	429	24.2
Agrotop TDXL 11004	0.30	186	467	764	4.4
Micron Micromax 3, 2000 rpm	0.28	286	344	415	0.0
Micron Micromax 3, 3200 rpm	0.28	206	241	282	0.0

Table 3. Results of two-way analysis of variance considering nozzle type (XR and TDXL and height (30, 50 and 70 cm) as a source of variation

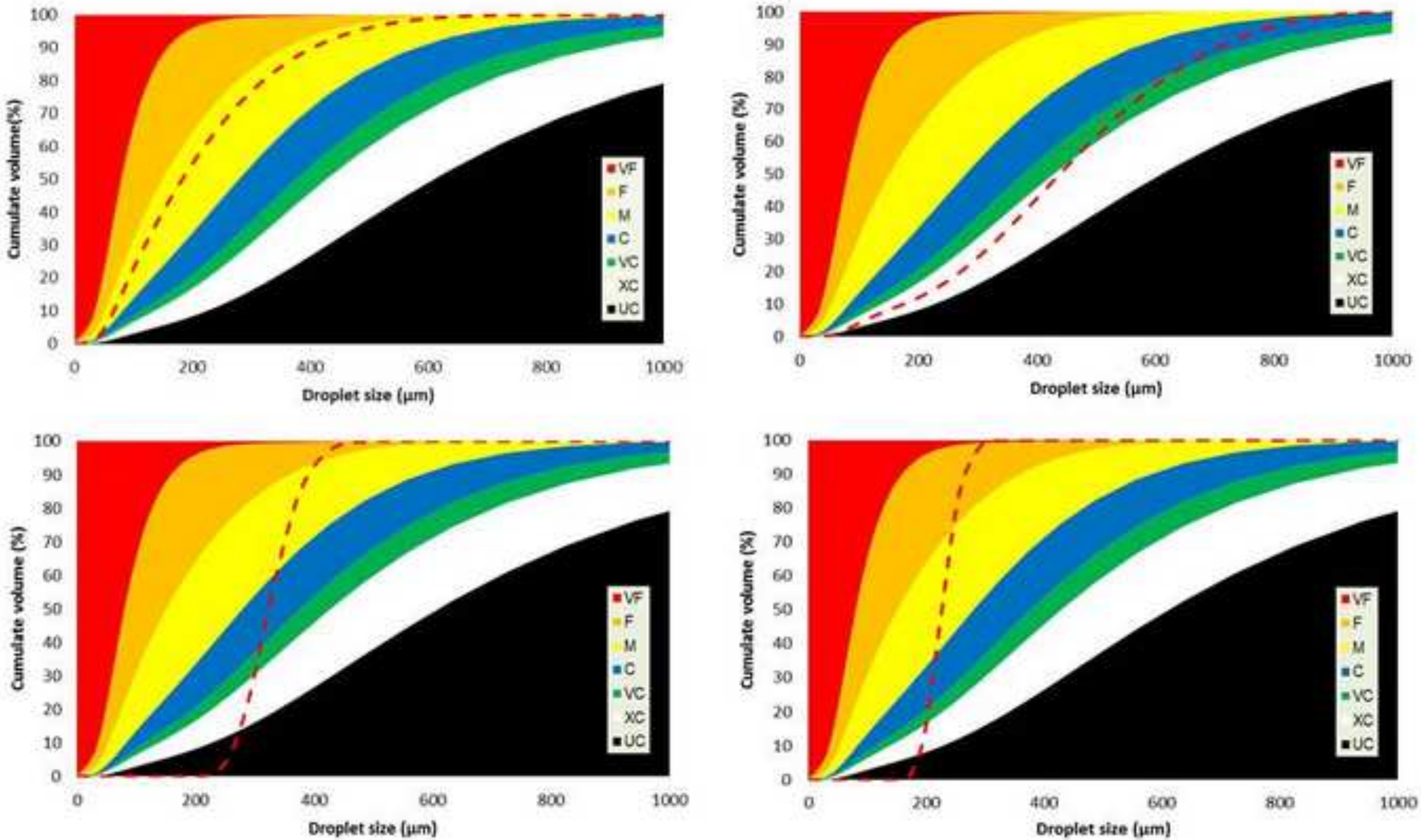
Source of variation	Df	Sum Sq	Mean Sq	F value	Pr(>F)
nozzle type (N)	1	10.578	10.578	194.885	1.31e-09
height (H)	2	7.531	7.531	138.746	1.19e-08
N x H	2	0.011	0.011	0.195	0.666
Residuals	14	0.760	0.054		

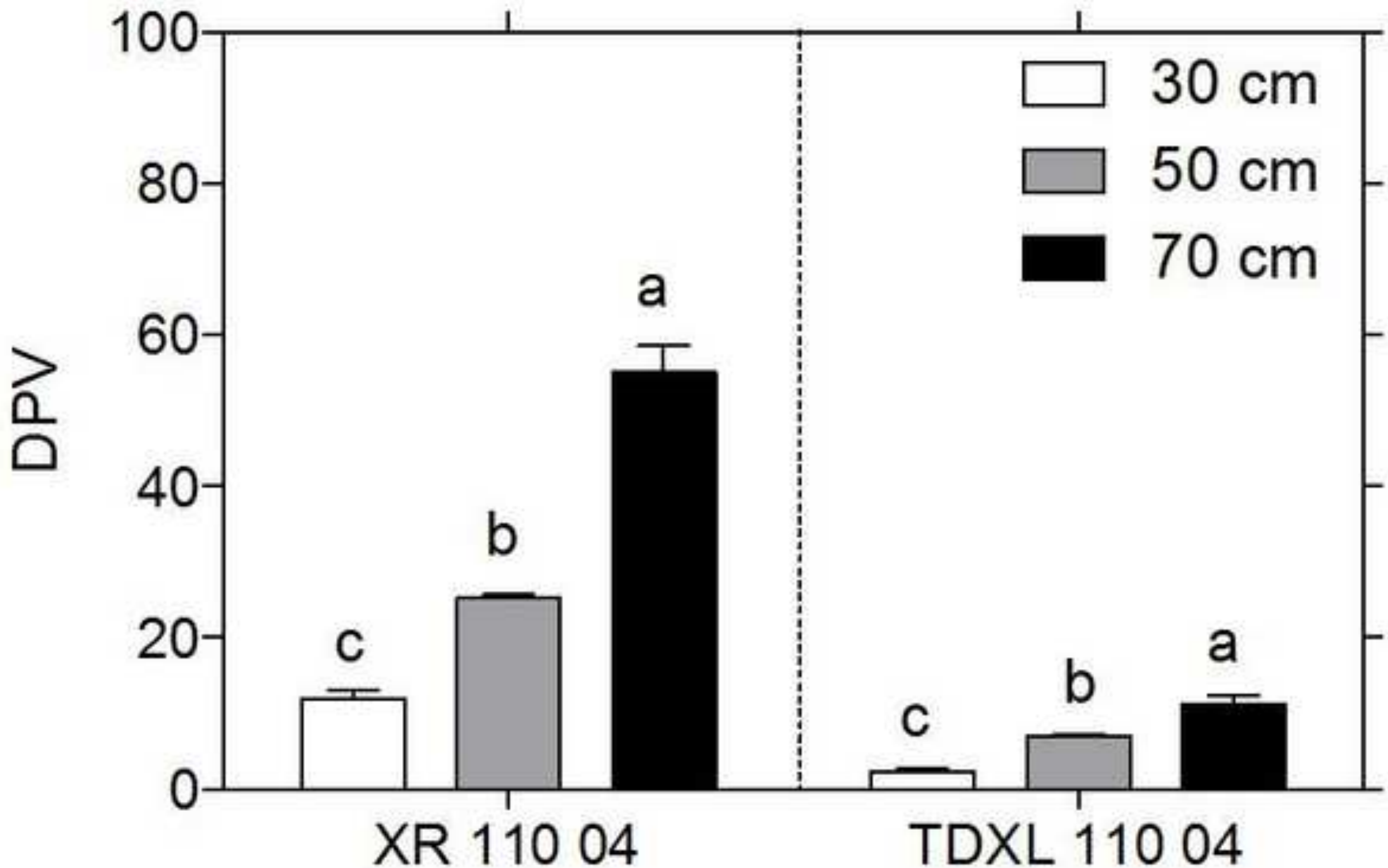
Table 4: Summary of average *DPV* values obtained for eight different examined sprayer setups and differences with respect to reference *DPV* value. The reference *DPV* value is that achieved using conventional flat-fan nozzles at 50-cm boom height.

Nozzle type	Boom height (cm)	Average DPV	Relative difference vs. reference DPV
TeeJet XR 11004	30	12	-52%
	50	25	0
	70	55	+ 119%
Agrotop TDXL 11004	30	2	- 91%
	50	7	- 72%
	70	11	- 56%
Micron Micromax 3, 2000 rpm	50	2	- 92%
Micron Micromax 3, 3200 rpm	50	11	- 55%

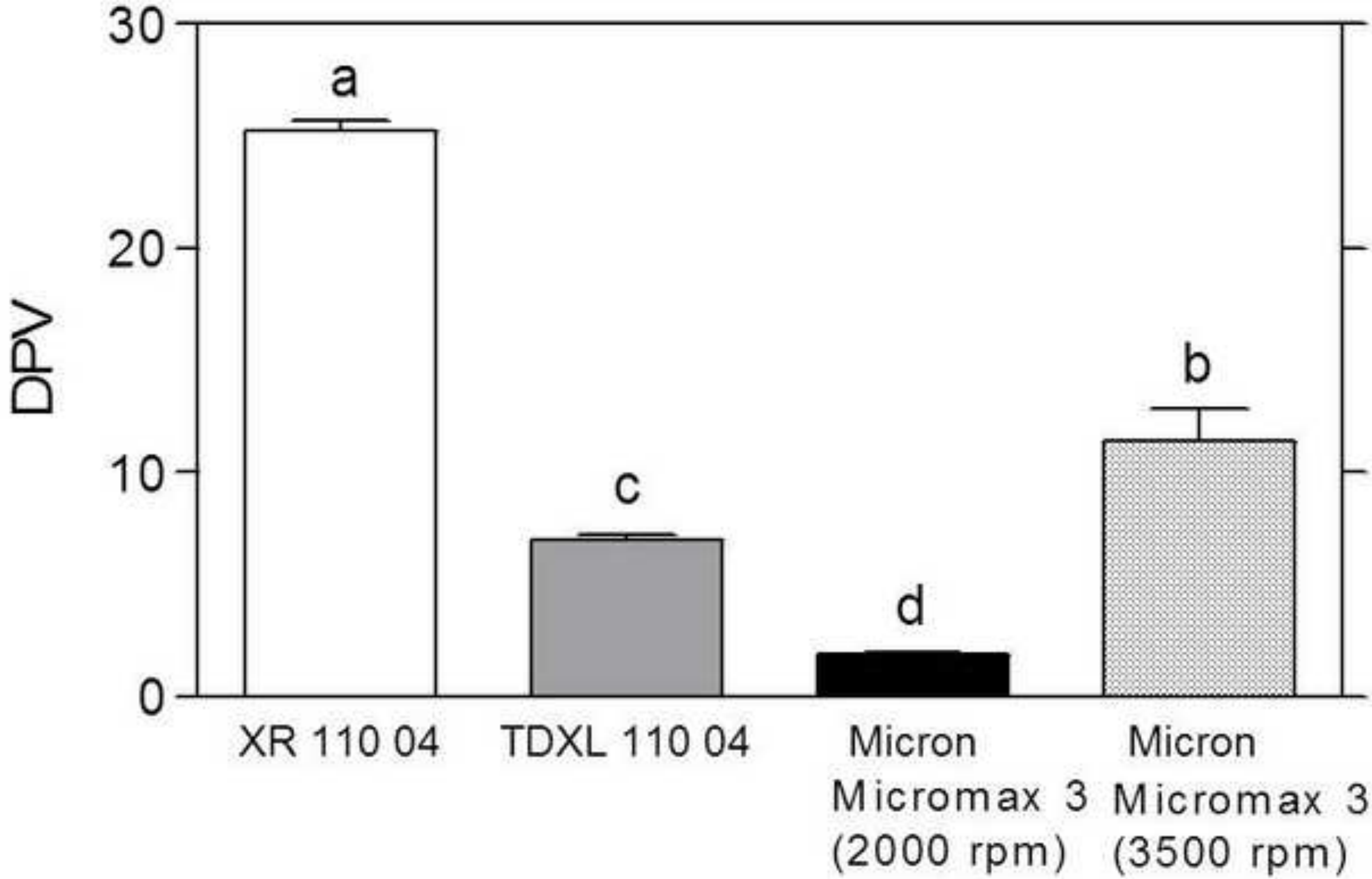
Table 5: Summary of average *DPV* values obtained for 8 different examined sprayer setups and corresponding drift reduction classes vs. reference setting, assigned in accordance with ISO 22369-1:2006.

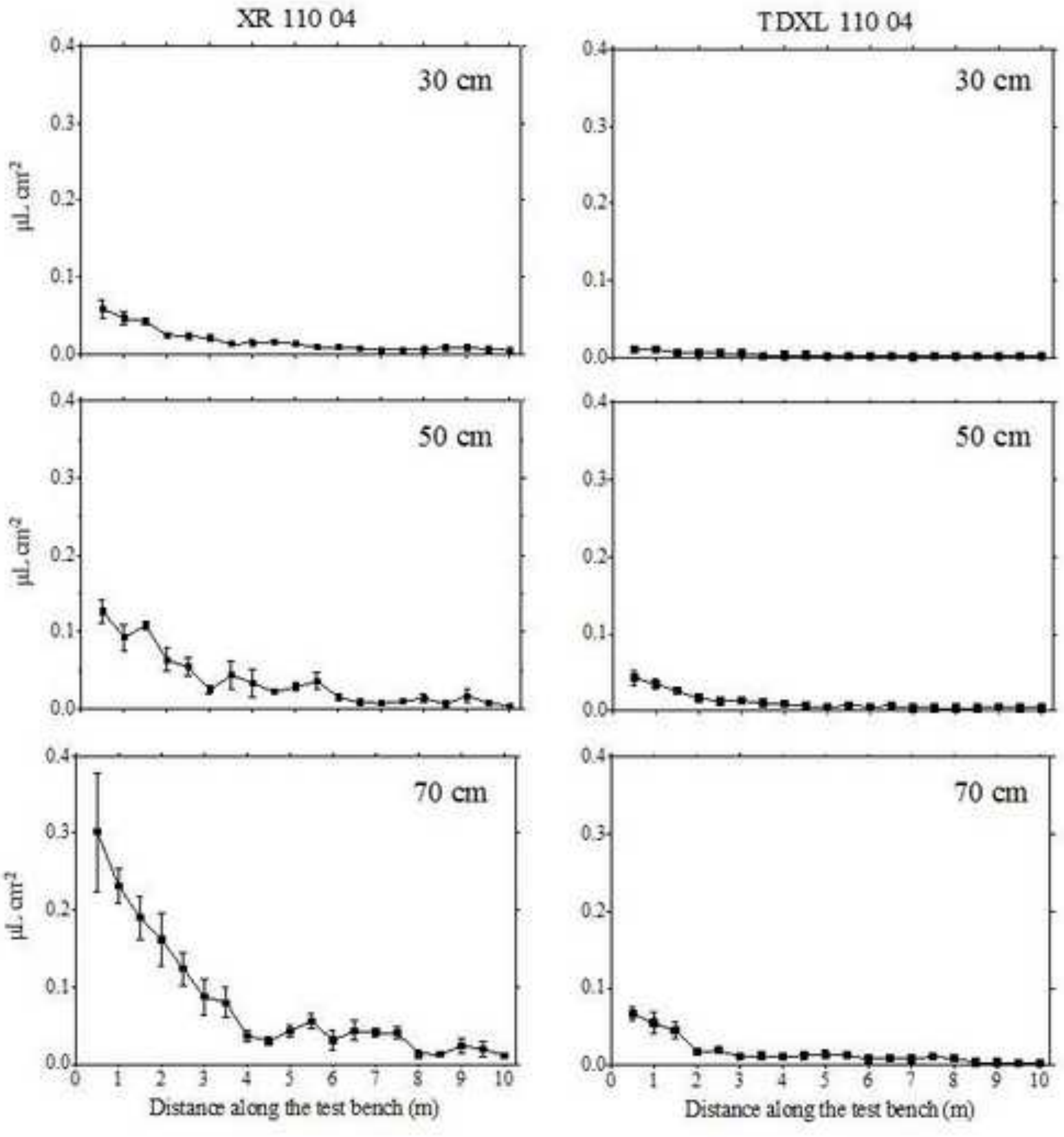
Nozzle type	Boom height (cm)	Average *DPV*	Drift reduction class (ISO 22369-1)
TeeJet XR 11004	50	25	Reference
	30	12	E
	70	55	No drift reduction
Agrotop TDXL 11004	30	2	C
	50	7	E
	70	11	E
Micron Micromax 3, 2000 rpm	50	2	C
Micron Micromax 3, 3200 rpm	50	11	E

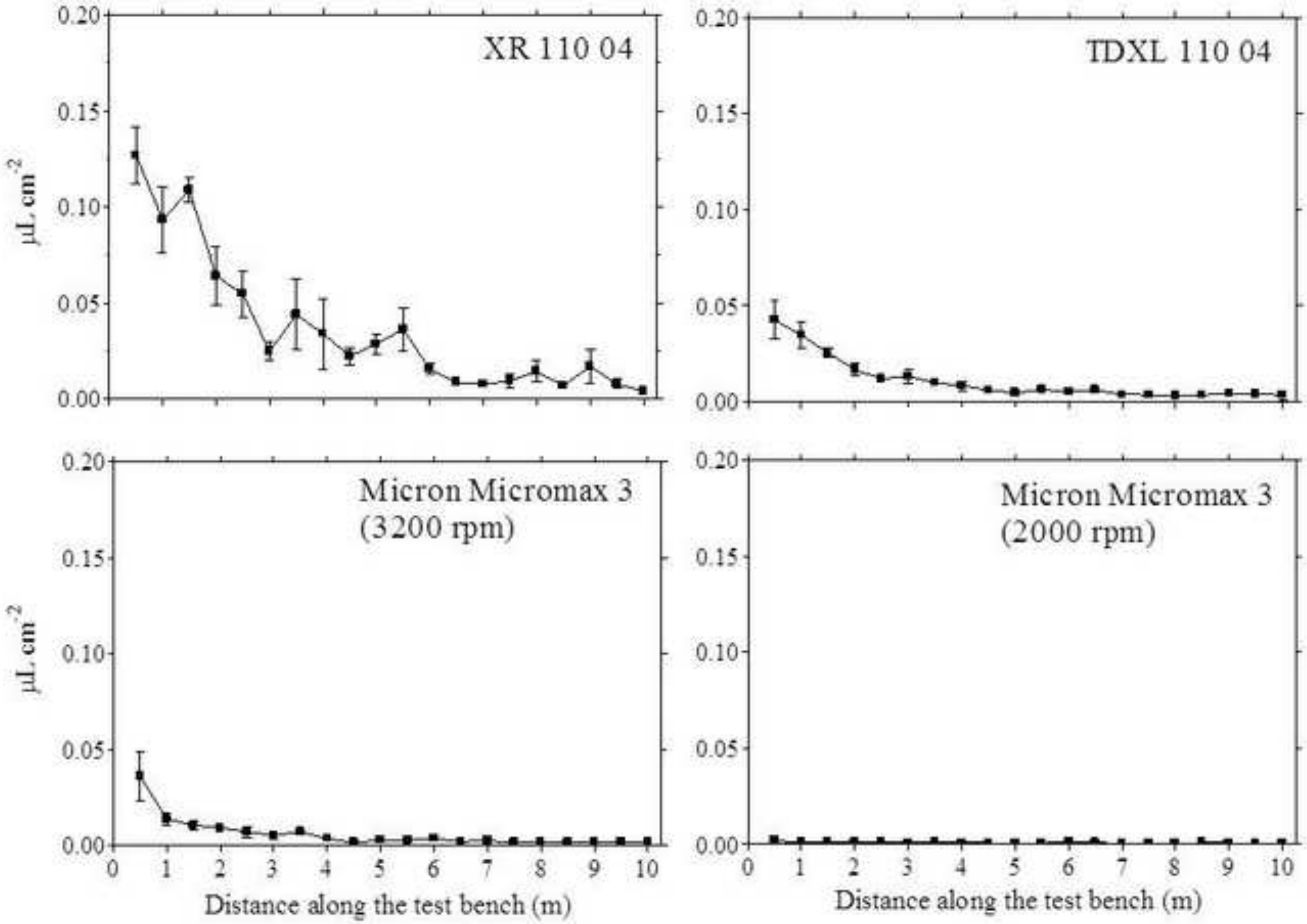

Cumulate volume(%)
Droplet size (µm)
VF
F
M
C
VC
XC
UC
Cumulate volume (%)
Droplet size (µm)
VF
F
M
C
VC
XC
UC
Cumulate volume (%)
Droplet size (µm)
VF
F
M
C
VC
XC
UC
Cumulate volume (%)
Droplet size (µm)
VF
F
M
C
VC
XC
UC

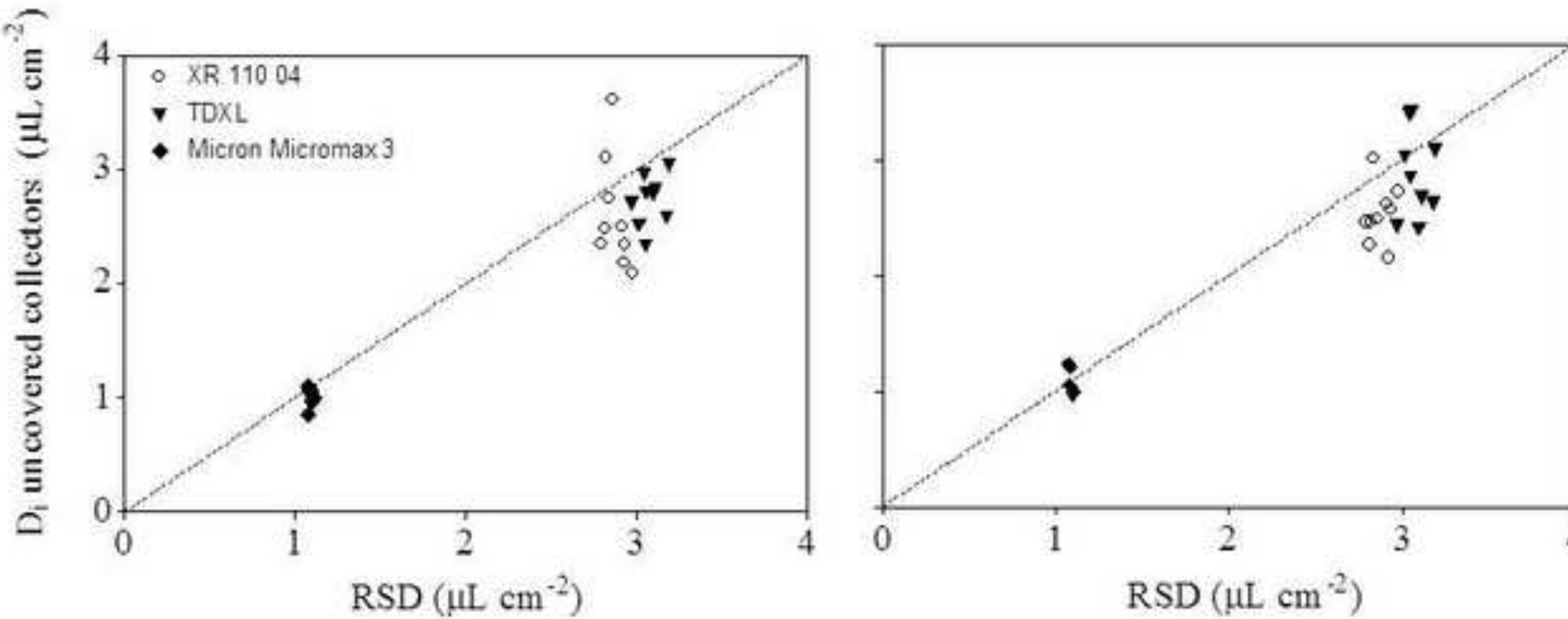


100
80
60
40
20
0
DPV
30 cm
50 cm
70 cm
a
b
c
c
b
a
XR 110 04
TDXL 110 04

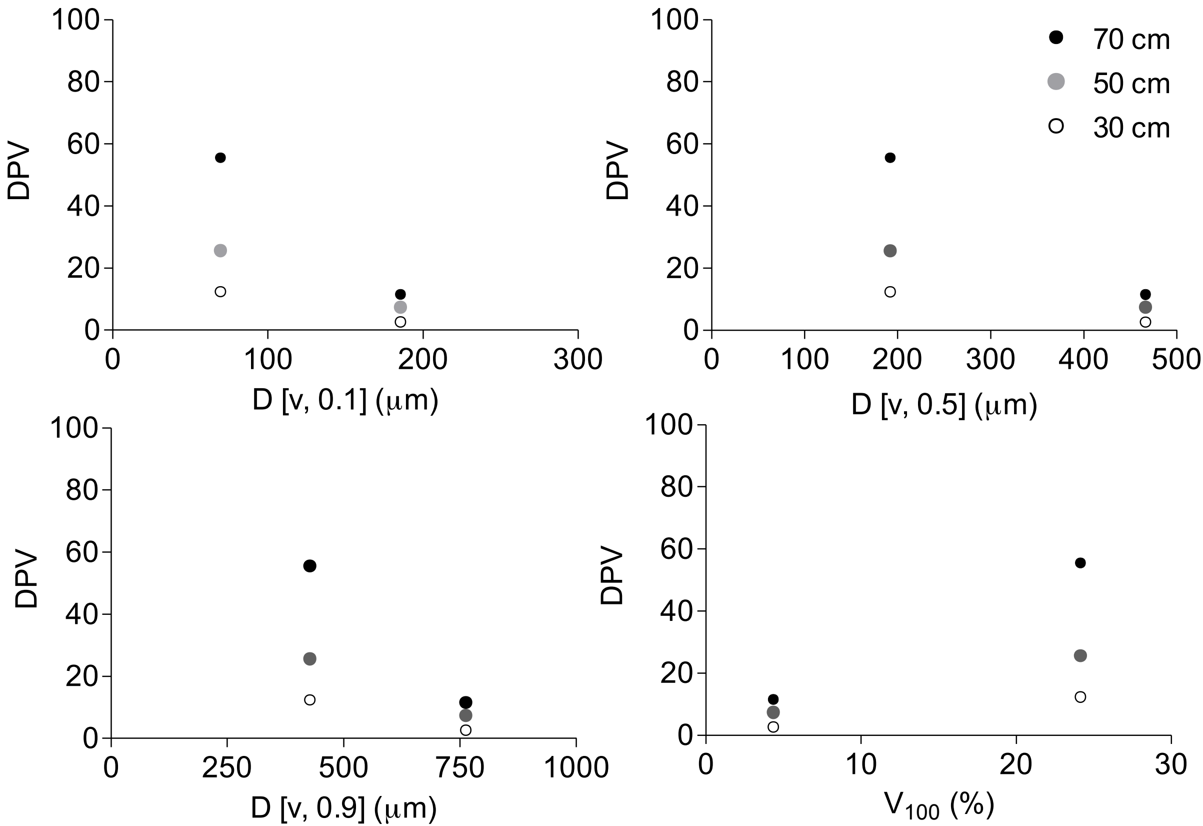

30
20
10
0
DPV
a
c
d
b
XR 110 04
TDXL 110 04
Micron Micromax 3 (2000 rpm)
Micron Micromax 3 (3500 rpm)


XR 110 04
TDXL 110 04
30 cm
50 cm
70 cm
µL cm²
0.0
0.1
0.2
0.3
0.4
0
1
2
3
4
5
6
7
8
9
10
Distance along the test bench (m)


XR 110 04
TDXL 110 04
Micron Micromax 3
(3200 rpm)
Micron Micromax 3
(2000 rpm)
μL cm-2
Distance along the test bench (m)
0.00
0.05
0.10
0.15
0.20
0
1
2
3
4
5
6
7
8
9
10



Di uncovered collectors (µL cm-2)
XR 110 04
TDXL
Micron Micromax 3
0
1
2
3
4
RSD (µL cm-2)
RSD (µL cm-2)



70 cm
50 cm
30 cm
DPV
D [v, 0.1] (μm)
D [v, 0.5] (μm)
D [v, 0.9] (μm)
V100 (%)