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Published version:

DOI:10.1016/j.agrformet.2014.12.002

Influence of wind velocity and wind direction on measurements of spray drift potential of boom sprayers using drift test bench

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Abstract

In 2009, the European Directive for a Sustainable Use of Pesticides (128/2009/CE) established important mandatory actions to be accomplished by all Member States (MS) in the European Union. The main objective is to achieve the sustainable use of pesticides by reducing their risks and impacts on human health and the environment. Among other important actions, drift reduction measures are essential to avoid the entry of plant protection products (PPP) in water or other undesirable areas. As the risk of environmental contamination is directly related to the spray application technology, there is a strong need for objective methods for drift evaluation as well as robust procedures for the classification of sprayers according to their risk of contamination.

For this purpose, and as a complementary tool to actual drift measurement methodologies in the field or in laboratory conditions, a new method has been proposed for the quantification of the potential drift generated by horizontal boom sprayer systems using an ad hoc test bench.

This study aims to evaluate the influence of wind velocity and wind direction on the drift potential value (DPV) using the proposed methodology and test bench. The results indicated that wind velocities below 1.0 m s^{-1} have a negligible influence on the DPV. Front wind led to higher DPVs than lateral wind. A global analysis of data indicates that the proposed methodology and test bench are interesting tools for the quick and objective evaluation of the potential drift if used in appropriate environmental conditions.

Keywords: drift potential value (DPV), drift test bench, wind velocity, wind direction, spray deposition, spray drift.

Highlights

A drift test bench is promising for assessing the drift potential of boom sprayers

Wind velocity <1 m s^{-1} does not impact drift potential value of medium spray nozzles

Wind direction relative to bench position affects DPV more than does wind velocity

1. Introduction

The European Directive for a Sustainable Use of Pesticides (128/2009/EC) (EP, 2009), officially published in October 2009, established a point of no return in Europe for the improvement of all aspects pertaining to crop protection. Improved crop protection processes with higher efficacy and efficiency could increase the benefits of plant protection products (PPP) while reducing the risk of environmental contamination and realizing better and high-quality food production and more sustainable agriculture. Currently, agriculture is considered a major contributor to water pollution owing to the use of nitrates, phosphates, and pesticides (Doruchowski et al., 2014).

This directive required all EU Member States (MS) to establish dedicated buffer zones, defined as permanently vegetated areas of land that are managed separately from the remainder of a field or catchment for the runoff of various agricultural pollutants (Muscutt et al., 1993). The specific characteristics of these zones are defined in each MS's National Action Plan (NAP). Among other technical information and specifications, the NAP must include the minimum requirements for buffer zone widths and its relation with different spray application techniques, mainly in terms of its capacity to reduce/avoid drift, and therefore, the risk of environmental damage. It is therefore clear that drift measurement methodologies along with an accurate classification scheme for every single sprayer/technology based on the potential contamination risk are essential tools.

Spray drift, defined as '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' (ISO, 2005) can be one of the most important (or main) factors affecting the risk of environmental pollution with pesticides, and therefore, there is a strong need for drift measurement methods. Moreover, according to the measured values, standardized protocols for the classification/evaluation of different spray technologies based on their risk of contamination are also required. These two steps will allow the MS to proceed with a proportional definition and sizing of buffer zones that are more adapted to particular situations.

In the last few years, several studies aimed at evaluating and quantify the effect of the different parameters involved in spray drift. Nevertheless, considerable effort is required to classify different crop protection techniques in spray drift reduction classes (ISO, 2006). This is further complicated by the fact that these classes frequently vary greatly because of the influence of weather conditions (Zande et al., 2000; Balsari et al., 2007; Zande et al., 2010) and by differences in the measurement protocols and techniques (Arvidsson et al., 2011).

In most cases, the spray drift measurements in the field follow the standardized protocol established by ISO 22866:2005, resulting in very complicated and time-consuming experiments (Phillips and Miller, 1999; Ravier et al., 2005; Carlsen et al., 2006; Schampheleire et al., 2008; Rimmer et al., 2009) and even a high dependence on external factors. Moreover, field experiments with different spraying systems cannot be performed under directly comparable and exactly repeatable conditions. Information about the driftability of an intended sprayer configuration can typically be obtained; however, these results are unsuitable for establishing any type of ranking or classification because of their great variability. The difference in drift reduction capabilities can therefore generally be determined only through sufficient repetitions under similar conditions and pair- wise comparison. The fall-out drift measurements presented in literature (Arvidsson et al., 2011) can, in some cases, differ by as much as a factor of 10 for the same nozzle size and working pressure, which can be attributed to different factors such as the weather conditions and spray application technology (Nuyttens et al., 2006). Arvidsson et al (2011) found 0.20% and 0.94% variations in drift per degree temperature and per m s^{-1} wind velocity, respectively.

Therefore, various studies have proposed alternatives for drift measurements in an attempt to develop easy, repeatable, and precise methods as complementary procedures to actual standards. One of the proposed alternatives, related to field crop sprayers, is Balsari et al.'s (2007) use of an *ad hoc* drift test bench. This method allows the drift potential value (DPV) to be quantified during a simulated application process with selected working parameters. Gil et al. (2014) used this method for measuring the DPV of a range of conventional and air injection flat fan nozzles. Their results demonstrated that the drift test bench can be considered an adequate complement to actual standard protocols for field measurements of drift (ISO, 2005). Zande et al. (2014) found similar results for field measurements (ISO 22866) using a test bench, and they ranked the nozzles that were similar in terms of drift reduction classes. Other indoor tests reported good correlation between the drift reduction potentials from the test bench and the wind tunnel measurements (Nuyttens et al., 2014).

ISO's ad hoc working group for drift measurements (ISO TC 23/SC 6/WG 16) officially adopted the test bench as a new method for measuring the drift potential of horizontal boom sprayer systems (ISO, 2014). However, further investigations are required to clarify the effect of environmental conditions (mainly wind velocity and its relative direction to the bench) to define the maximum limits for these wind factors so as to avoid a negative influence on the results. Vanella et al. (2011) concluded that this method needs relatively stable atmospheric conditions, as the combined effects of wind velocity and direction significantly affected the drift potential of the sprayer.

In the context of improving the present ISO draft standard concerning drift potential measurements by the use of test bench, the aim of the present study was to evaluate the effect of wind velocity and wind direction on the DPV in order to define a wind velocity threshold value to indicate in that ISO methodology. Repetitive field trials were made keeping all the other sprayer working parameters (forward velocity, nozzle characteristics, working pressure, and boom height) constant. For this purpose a reference spraying system defined according to ISO 22369-2 was tested through 20 repetitions..

2. Materials and methods

2.1 Experimental design

The bench consists of a 12 m × 0.5 m steel frame with slots for collectors (Petri dishes) situated at 0.5-m intervals (Figure 1). Each slot is equipped with a sliding cover that makes it possible to cover/uncover the collector as needed. Once the boom sprayer passes by the entire bench, a pneumatic system automatically uncovers the collectors to capture the spray fraction that remains suspended in the atmosphere behind the boom before settling after some time. The purpose of the bench is to collect and quantify, in the absence of wind, the potential drift fraction, defined as the spray fraction that remains suspended over the bench immediately after the sprayer pass and that can be carried out of the target zone by weather air currents (Balsari et al., 2007).

A 12-m-long stainless steel bench was placed at the centre of the right-hand-side spray boom of the sprayer at 3.0 m from the centre axis of the tractor in coincidence with the middle point of the right-hand side of the boom (Gil et al., 2014), maintaining a NW-SE position relative to the wind direction. Artificial collectors with a capture area of 153.94 cm^2 (Petri dishes with 14-cm diameter) were placed at 0.5-m intervals along the bench slots. The sample position was 0.30 m above the ground, as recommended by ISO (2014). The first two collectors remained permanently uncovered whereas the others on the bench (length: 10 m) were initially covered using the sliding plates of the test bench. The sprayer started application using only the right-hand side of the boom half over the bench, spraying a 2 mg/L solution of water and tracer (yellow Tartrazine E 102). The spray track started 20 m before the bench and then moved over the bench with the covered collectors. Spraying was continued for a further 20 m after the end of the test bench, for a total spray length of 52 m. After the sprayer passed over the end of the bench and reached a point exactly 2 m beyond the last covered collector, an automatic pneumatic system activated the sliding covers initiated by the passing spray boom, which revealed the Petri dishes so as to capture the droplets still airborne over the bench. Droplets were collected for 60 s after the opening of the system. Every single Petri dish was then covered, adequately labelled, and placed in dry and dark conditions until the laboratory determination of the tracer concentration. To determine the presence of tracer as background in the environment before each trial, two open petri dishes were placed on the bench and picked up before the next spray test. The tracer concentration at the artificial collectors was quantified using a spectrophotometer (Thermo Scientific Genesys 20).

Field trials were conducted 20 times using a conventional mounted 12-m boom sprayer (Ilemo Hardi, S.A.U., Lleida, Spain). The working pressure (3.0 bar), sprayer forward speed (6 km h^{-1}), boom height above the test bench surface (0.5 m), and nozzle type and size (XR 110 03 flat fan nozzle 110° Teejet®, Spraying Systems Co., Wheaton, Illinois, USA) were selected according to the reference spraying system (ISO, 2010) and maintained constant during all the tests (Fig. 2). The resulting spray volume rate was 236 L ha^{-1}.

During the tests, weather conditions such as the wind velocity, wind direction, air temperature and relative humidity were recorded continuously every second s at 2.0 m height from the ground. For this purpose, a Campbell weather station with a Datalogger CR800, a sonic anemometer (wind sonic 232), and two temperature and humidity sensors (HC2S3) were placed laterally 5 m from the test bench position and 5 m from the end of the bench, avoiding any interference at the measurement area.

2.2 Quantification of DPV

After the sprayer passed over the bench, the deposit on each artificial collector (*Di*) (unit: µL cm^{-2}), was calculated as follows:

$$D_i = \frac{\left(\rho_{smpl} - \rho_{blk}\right) \times V_{dil}}{\rho_{spray} \times A_{col}}$$

where D_i is the spray deposit on a single deposit collector (unit: µL cm^{-2}); ρ_{smpl}, the absorbance value of the sample (adim.); ρ_{blk}, the absorbance value of the blanks (adim.); V_{dil}, the volume of the dilution liquid (deionised water) used to dissolve the tracer deposit from the collector (unit: µL); ρ_{spray}, the absorbance value of the spray mix concentration applied during the tests and sampled at the nozzle (adim.); and A_{col}, the projected area of the collector for capturing the spray drift (unit: cm^2).

Once the amount of tracer on every single collector was measured, the DPV was calculated as follows:

$$DPV = \sum_{i=1}^{n} D_i / RSD \times 100$$

where *DPV* is the drift potential value (dimensionless); D_i, the spray deposit on a single deposit collector (unit: µL cm^{-2}); *n*, the number of collectors (20); and *RSD*, the reference spray deposit under the boom as calculated using the intended volume rate (unit: µL cm^{-2}).

RSD represents the intended (theoretical) amount of spray deposit in the treated area, assuming a perfectly even distribution under the boom. For the first set of trials, the RSD values ranged from 1.5 μL cm^{-2} (150 L ha^{-1}) to 3.25 μL cm^{-2} (325 L ha^{-1}). The RSD values were compared with the actually measured deposition values in the uncovered collectors to obtain an understanding of the spray deposition under the boom and to verify the eventual main deviations from the expected value.

2.3 Statistical analysis

The data analysis consisted of evaluating the correlation between the wind characteristics (velocity and direction) and DPV; also was analysed the relationship between wind velocity and the recovery values (%) on the uncovered Petri dishes. This analysis was performed using R software (R Development Core Team, 2011).

3. Results

3.1 Wind characteristics during field trials

The average wind velocity was 0.4–2.4 m s^{-1}, which allowed the correlation between the wind characteristics and the DPV to be measured in each case. The wind direction in relation to bench placement and tractor driving line was also recorded. During the field trials, the most frequent wind directions were SE-NW (front wind relative to spray track) and SW-NE (lateral wind). Figure 3 shows the distribution of all wind directions during the trials and their relation with the bench position.. The average temperature during the trials was 17 °C, with a maximum of 18.9 °C and minimum of 16.1 °C. The relative humidity was 66.3%–91.4%. Table 1 shows the mean values of all the parameters recorded during the field trials.

During each trial, values of wind velocity and wind direction were recorded every second.. A further analysis of these parameters (Fig. 4) indicates that wind velocities corresponding to a lateral wind direction showed less variation during the trials than that observed for frontal winds. Interestingly, the wind direction was generally more uniform than wind velocity during each trial.

The correlation between the wind velocity and the wind direction is mostly important. Figure 5 shows the correlation of the average values of wind velocity and wind direction and its relation with the bench position. Interestingly, the wind velocities were generally higher for front wind even with highly dispersed values. However, at these high wind velocities corresponded the highest spray deposits registered in the Petri dishes, resulting in the highest DPV values (Fig. 6).

3.2 Correlation between DPV and wind characteristics

Fig. 6 shows the DPV obtained in each spray test and its relation with the wind velocity. DPVs obtained for an average wind velocity lower than 1 m s^{-1} showed great uniformity, and no significant relationship was found between the DPV and the wind velocity (Table 2). The coefficient of variation of all DPVs obtained in the trials under wind velocity lower than 1 m s^{-1} was 5.29%, with an average DPV of 23.7. These results are consistent with those of previous studies (Gil et al., 2014). Fig. 6 shows that the DPV values obtained with wind velocity over 1 m s^{-1} (average: 65.26) presented a higher variability (CV: 29.03%). According to the obtained results, a safety threshold of wind velocity can be established at a maximum environmental average wind velocity of 1 m s^{-1}. A deeper analysis of the relation between DPV and wind characteristics indicates that more erratic values were obtained with SE wind direction (front wind related to test bench position), whereas S-SW wind direction (lateral wind related to bench placement) had much less effect on the DPV (Fig. 6).

A detailed analysis of the relationship between DPV and wind direction indicates that front wind has much more effect on DPV than lateral wind. Considering the tests results (Table 3), with the front wind the highest values of DPV (65.26) and coefficient of variation (47.78%) were obtained. When tests were operated with front wind, DPV ranged from 110.42 (max) to 16.04 (min). On the opposite, when tests were made with lateral wind more uniform data, with a narrower range of variability, were obtained. It is also interesting to remark the important differences on the values of Parson's coefficient of correlation when comparing DPV with wind direction. While for the front wind the Pearson's coefficient was 0.3417, for the lateral wind it was -0.489. All those figures allow considering the front wind as with more influence on DPV, if compared with lateral wind.

The effect of wind direction can also be observed in Fig. 7, which separately plots the deposition curves along the test bench obtained from all the trials with S-SW wind direction, corresponding to lateral wind, and the deposition curves obtained for the case of front wind (SE wind). Important differences among the deposition on the collectors, mainly in the last part of the test bench, were observed as a consequence of the wind direction. In general, front wind blows spray droplets towards the last part of the bench, generating a soft and homogeneous slope on the deposition curves, with relatively high deposition on the rear part of the bench.

Another important effect of wind direction can be explained by the analysis of the cumulative deposition along the test bench. Fig. 8 shows the cumulative deposition curves obtained separated by the two different wind directions, front and lateral wind. In this case, too, the effect of wind direction on the DPV is clear. The spray plume seems to be displaced to the rear in the case of front wind, being collected 50% of the total deposit in the first three meters of the bench, while the same percentage with lateral wind was collected at the first one and a half meter of the bench (Fig. 8).

3.3 Effect of wind on recovery deposit on uncovered collectors

The recovery efficiency of the two uncovered petri dishes placed at the beginning of the test bench during each trial was evaluated by calculating the percentage of liquid collected from the total expected according to the spray volume applied as follows:

$$R\ (\%) = \frac{C_s\ x\ V_s}{S\ x\ C_d\ x\ D}\ x\ 10^7$$

where R is the recovery value on uncovered collectors (%); C_s, the tracer concentration measured on the collector (µg L^{-1}); V_s, the amount of water added for tracer extraction (mL); S, the collector surface (cm^2); C_d, the tracer concentration in the tank (µg L^{-1}); and D, the intended applied volume rate (L ha^{-1}).

Fig. 9 shows the influence of the wind velocity on the recovery capacity of the uncovered samples. The ANOVA test conducted to evaluate the recovery values obtained on the uncovered collectors indicates no significant relationship between the percentage recovery and the wind velocity ($P < 0.05$), particularly for wind velocities below 1.5 m s^{-1} (Table 4). The average recovery value was 87% for all the tests with a wind velocity below 1.5 m s^{-1}, indicating the good functioning of the spray boom distribution.

3.4 Spatial effect of wind direction on DPV

The deposition curves of all trials were grouped according to the wind direction in relation with the bench position. Fig. 10 shows the averaged deposition curves obtained during all trials with lateral and front winds. The figure also shows the tendency curves for the two cases and a plot of their corresponding mathematical expressions. In this sense, the differences in deposition values along the test bench are noteworthy for the two wind directions, being constants for every sampling point.

4. Conclusions

As specified in ISO 22369-2, 2010, weather conditions, especially those affecting wind velocity and wind direction, have a variable influence on the final evaluation of the drift potential obtained using a test bench. The results obtained from 20 tests operated at different wind velocities and wind directions indicated that DPVs were not statistically influenced when trials were conducted with average wind velocities below 1 m s^{-1}. This value is higher than that recommended as maximum limit for wind velocity during trials in the new proposed standard (ISO DIS 22401), which was initially 0.5 m s^{-1}.

The wind direction relative to the test bench and tractor forward direction clearly influenced the spatial distribution of the spray deposition recovered along the whole bench and affected the DPV values themselves. Front winds tended to provide higher deposits on the rear part of the test bench. Therefore, field tests for drift measurements using a test bench should be arranged carefully considering the wind direction relative to the bench.

No significant effect was detected on recovery values on uncovered Petri dishes in trials conducted with wind velocities below 1.5 m s^{-1}, resulting in an average value of 87%. The recovery value on uncovered Petri dishes is a remarkable indicator of the actual applied volume, avoiding undesirable mistakes during trials, and of the fact that no deviations in spray distribution occurred during the tests.

Acknowledgements

This work was funded by the Spanish Ministry of Economy and Competitiveness (SAFESPRAY project AGL2010-22304-C04-04) and the European Regional Development Fund (ERDF). The authors would like to thank AgriArgo Ibérica and Ilemo-Hardi, S.A.U., for their collaboration in this research project.

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Table 1 Wind velocity (m s^{-1}), wind direction, and DPVs recorded during field trials.

Test	Wind velocity (m s^{-1})			Wind direction		DPV
	Minima	Maxima	Average	Compass Rose	(º)	
1	0.8	2.4	1.6	S-SW	169.0	28.09
2	0.8	1.9	1.3	S-SW	171.4	25.39
3	0.8	2.1	1.4	S-SW	173.8	90.85
4	0.9	1.9	1.5	S-SW	173.8	86.04
5	1.0	2.4	1.6	S-SW	170.2	110.43
6	0.9	2.3	1.6	S-SW	160.9	65.86
7	0.8	2.5	1.4	S-SW	171.4	75.02
8	0.4	1.7	1.0	SE	217.8	31.22
9	0.4	1.4	0.9	SE	228.4	28.76
10	0.5	1.2	0.9	SE	227.0	13.11
11	0.3	1.0	0.7	SE	229.6	20.45
12	0.2	0.5	0.4	SE	264.5	18.41
13	0.3	0.9	0.5	SE	218.3	16.62
14	0.2	0.6	0.4	SE	201.2	19.29
15	0.5	1.2	0.8	SE	187.1	36.51
16	0.7	2.5	1.5	S-SW	139.5	25.26
17	0.5	2.4	1.6	S-SW	118.3	16.04
18	1.2	2.9	1.9	S-SW	131.6	80.47
19	1.2	3.2	2.2	S-SW	150.4	87.00
20	1.2	3.5	2.4	S-SW	147.3	92.67

Table 2 ANOVA test for statistical analysis of relationship between DPV (dependent variable) and predictors (constant): wind velocity. Evaluated range: wind velocity < 1.0 m s^{-1}

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	0.014	1	0.014	2.695	**0.152**
Residual	0.32	6	0.005		
Total	0.046	7			

Table 3 Statistical analysis of DPV values and its relationship with wind direction. Average from all DPV values depending on wind direction

Wind direction	Average	CV	σ	Max	Min	Range	ρ^1
Front	65.26	47.78	31.18	110.42	16.04	94.38	0.3417
Lateral	23.04	33.01	7.6	36.50	13.11	23.39	-0.489

ρ^1 Pearson's coefficient of correlation between DPV and wind direction

Table 4 ANOVA test for statistical analysis of relationship between percentage of recovery on uncovered collectors, %R (dependent variable) and predictors (constant): wind velocity. Evaluated range: wind velocity <1.5 m s^{-1}

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	0.005	1	0.005	1.114	**0.308**
Residual	0.073	12	0.005		
Total	0.079	13			

FIGURE CAPTIONS

Figure 1 Scheme of relative position of tractor and drift test bench during trials. Detail of collectors over the bench.

Figure 2 General overview of field trials.

Figure 3 Compass rose representing all wind directions during trials and relative position of bench.

Figure 4 Boxplot of all wind velocity (upper) and wind direction (lower) measurements for 20 trials.

Figure 5 Relationship between wind velocity and wind direction for 20 trials. Relation between average values of wind velocity and wind direction .

Figure 6 Relationship between wind velocity and DPVs for 20 trials.

Figure 7 Deposition curves along test bench classified according to wind direction. Curves obtained during tests with front wind (upper). Curves obtained during tests with lateral wind (lower).

Figure 8 Cumulative DPV averaged curves obtained with lateral wind and front wind. Values of 50% and 75% cumulative DPV are shown.

Figure 9 Effect of wind velocity on recovery values measured on uncovered collectors. Values of wind velocity below 1.5 m s^{-1} did not cause significant variations in recovery efficiency.

Figure 10 Average deposition curves along bench obtained after individual curves, classified according to wind direction. Theoretical deposition tendency observed for lateral and front winds is also shown.

Figure 1

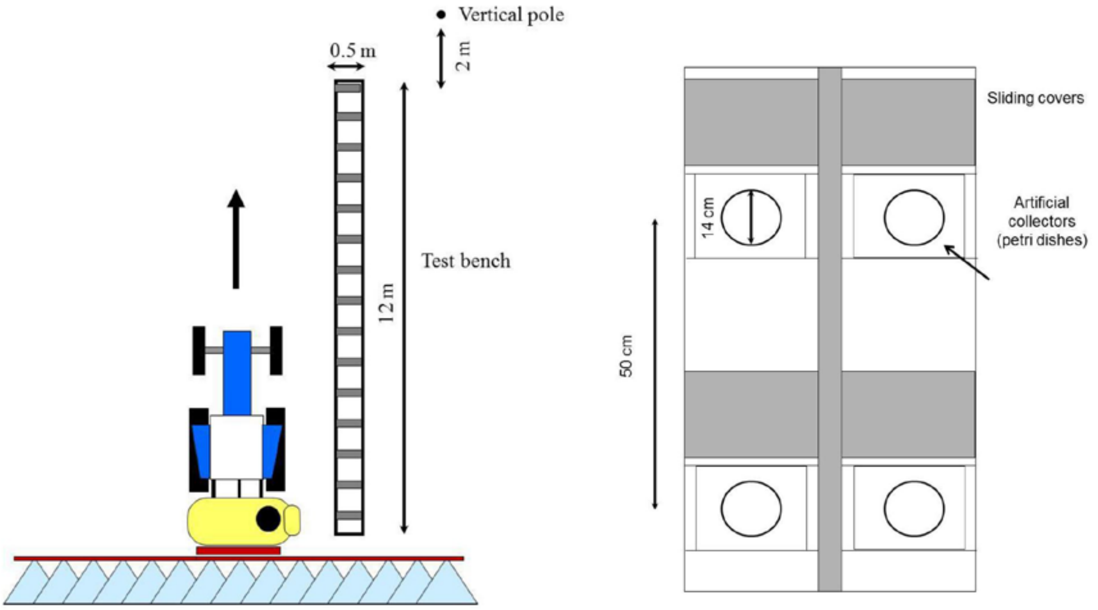


Figure 2

Figure 3

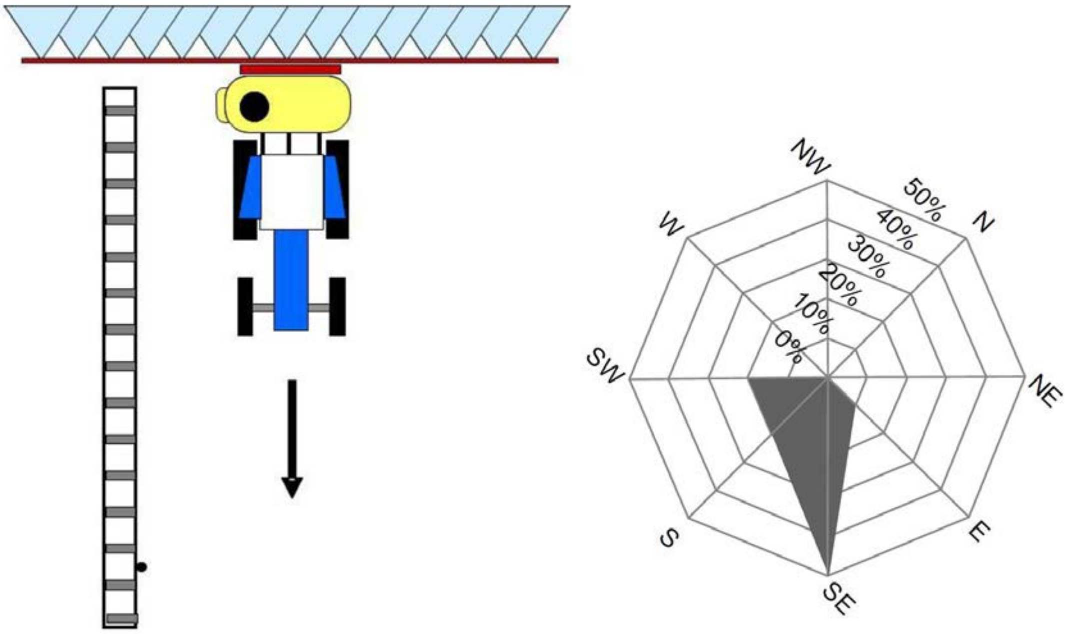


Figure 4

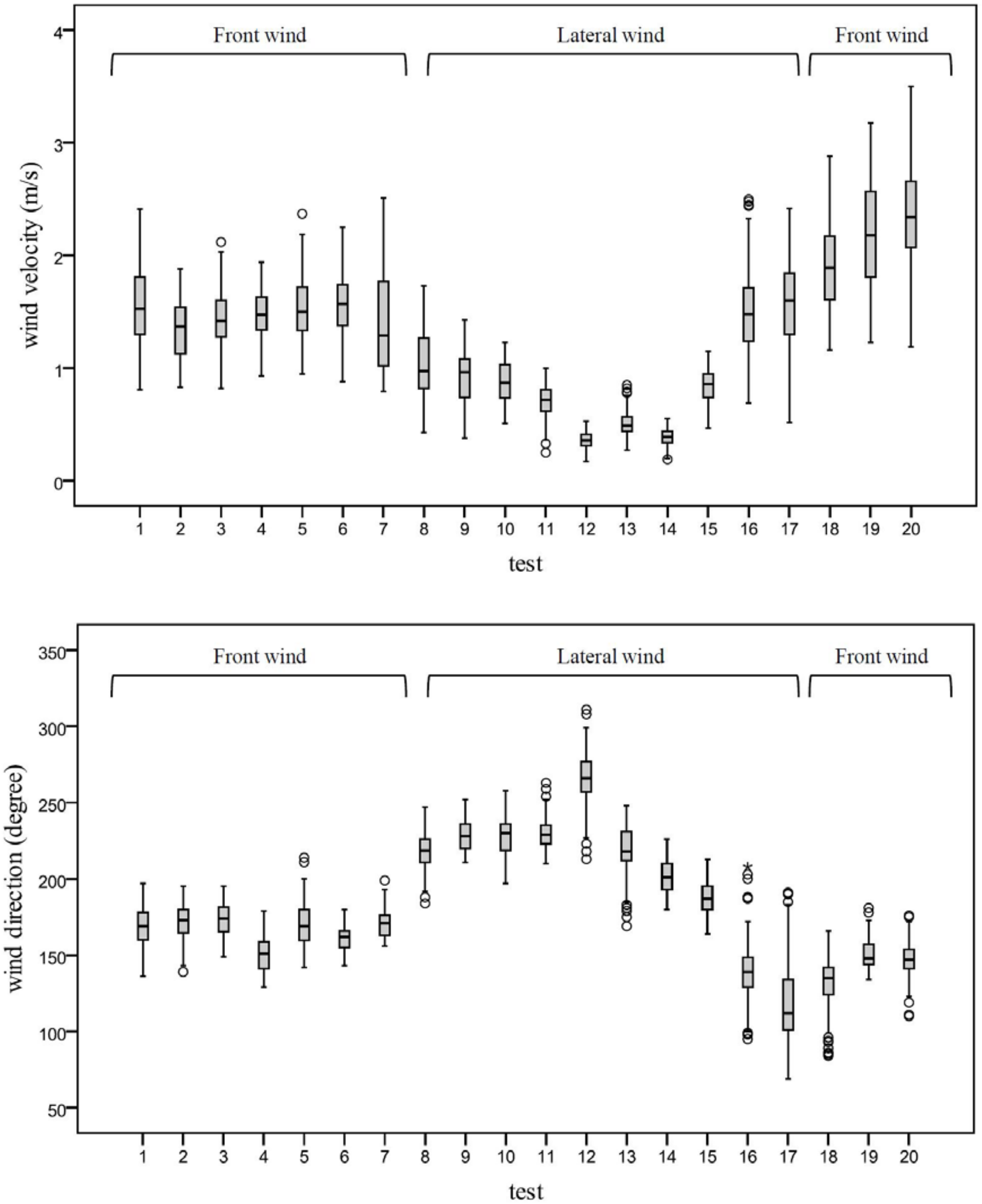

Front wind
Lateral wind
Front wind
wind velocity (m/s)
0
1
2
3
4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
test
Front wind
Lateral wind
Front wind
wind direction (degree)
50
100
150
200
250
300
350
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
test

Figure 5

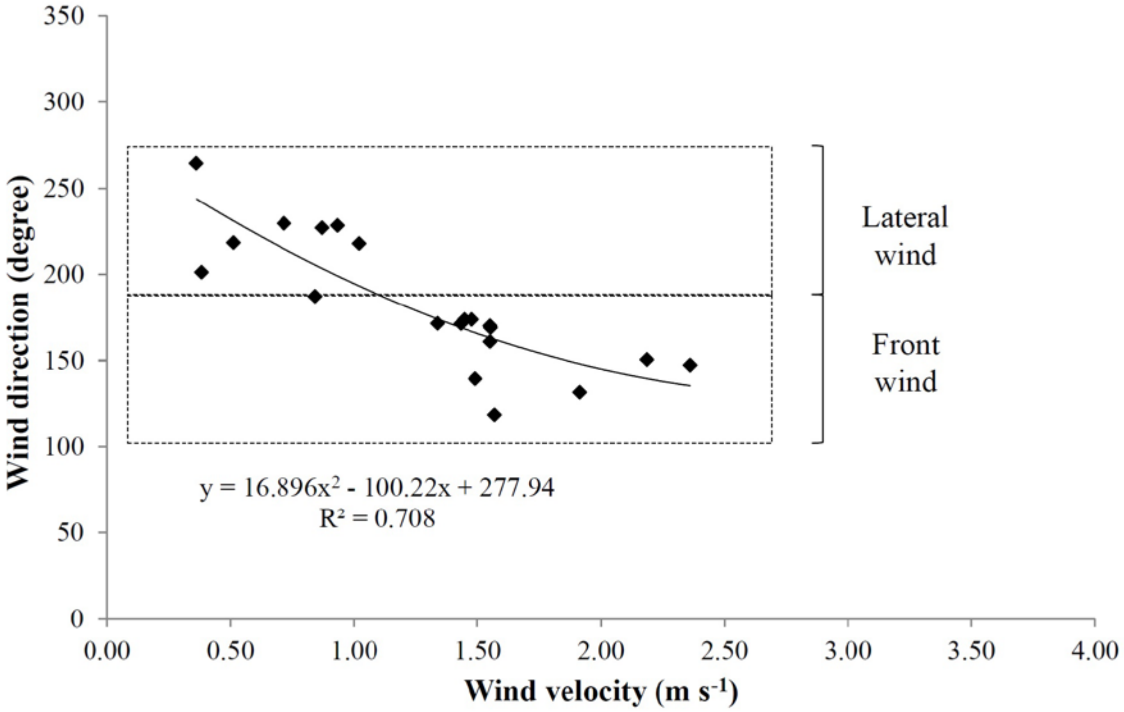


Figure 6

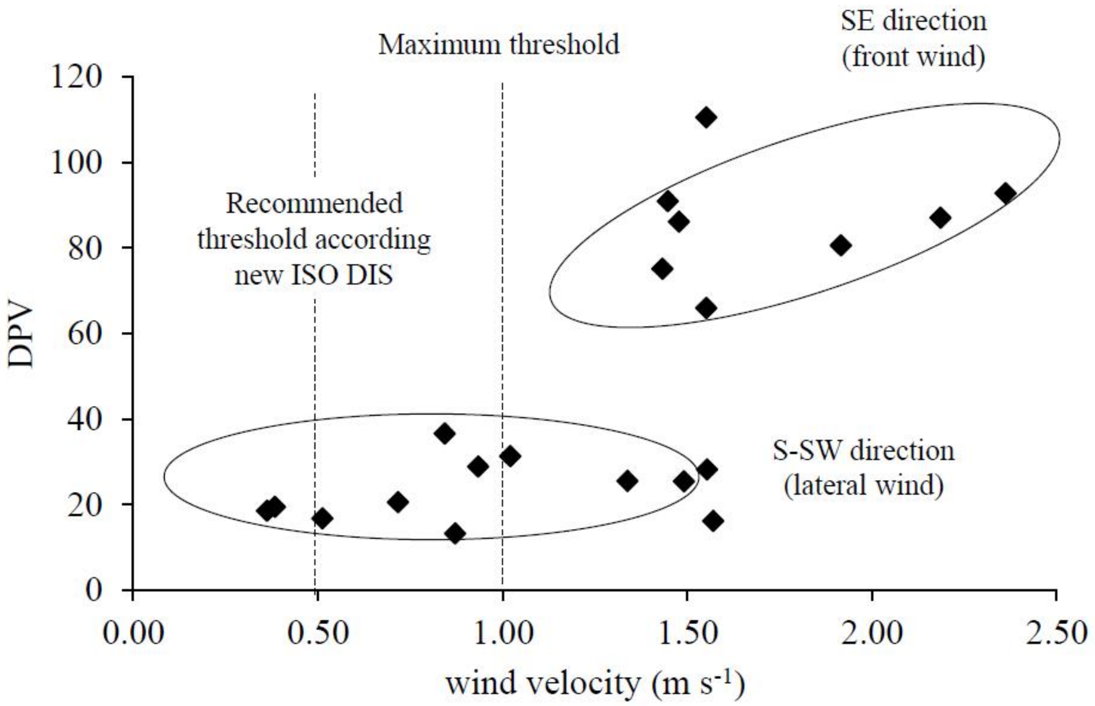


Figure 7

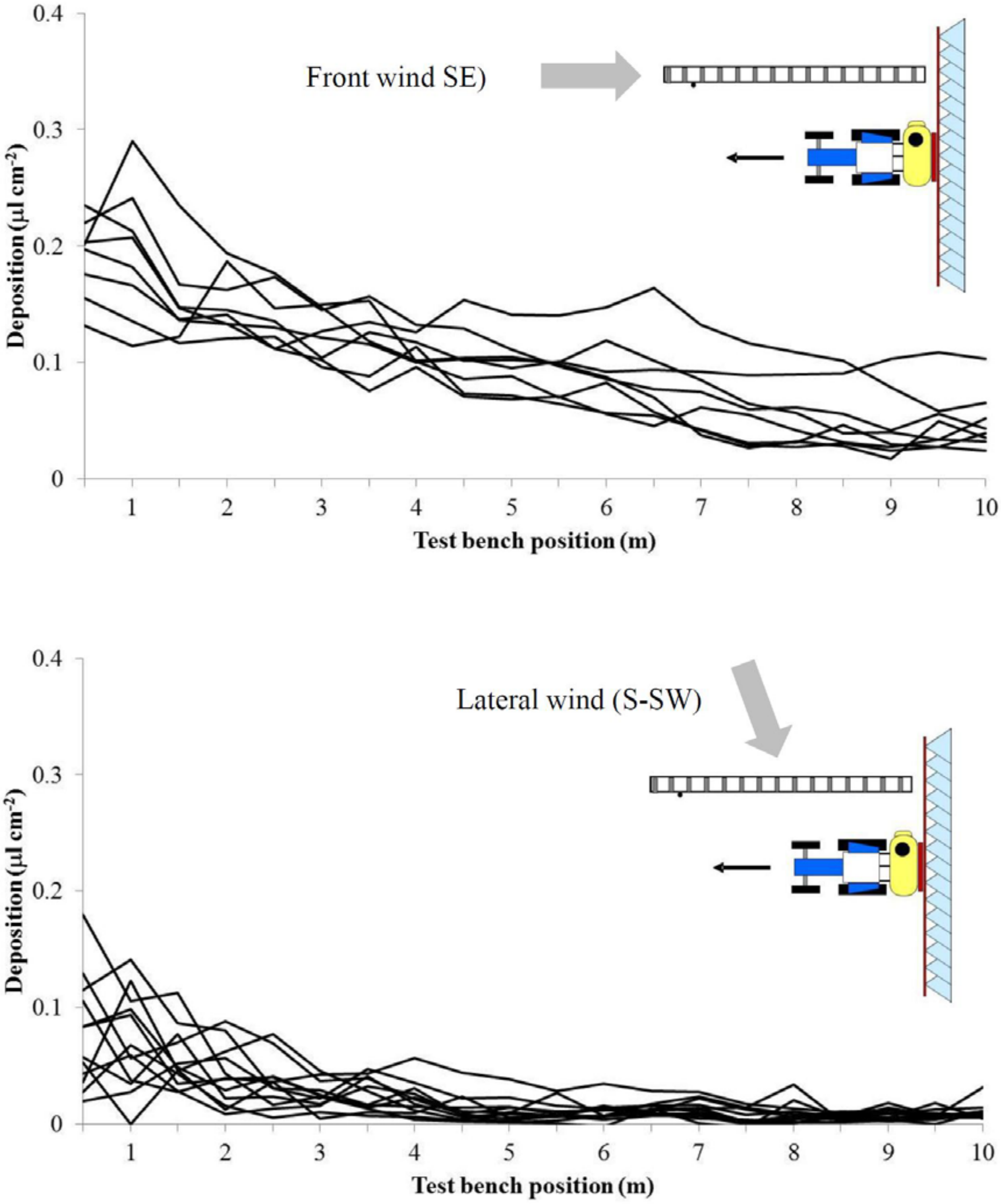

Front wind SE)
Deposition (µl cm^{-2})
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10
Test bench position (m)
Lateral wind (S-SW)
Deposition (µl cm^{-2})
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10
Test bench position (m)

Figure 8

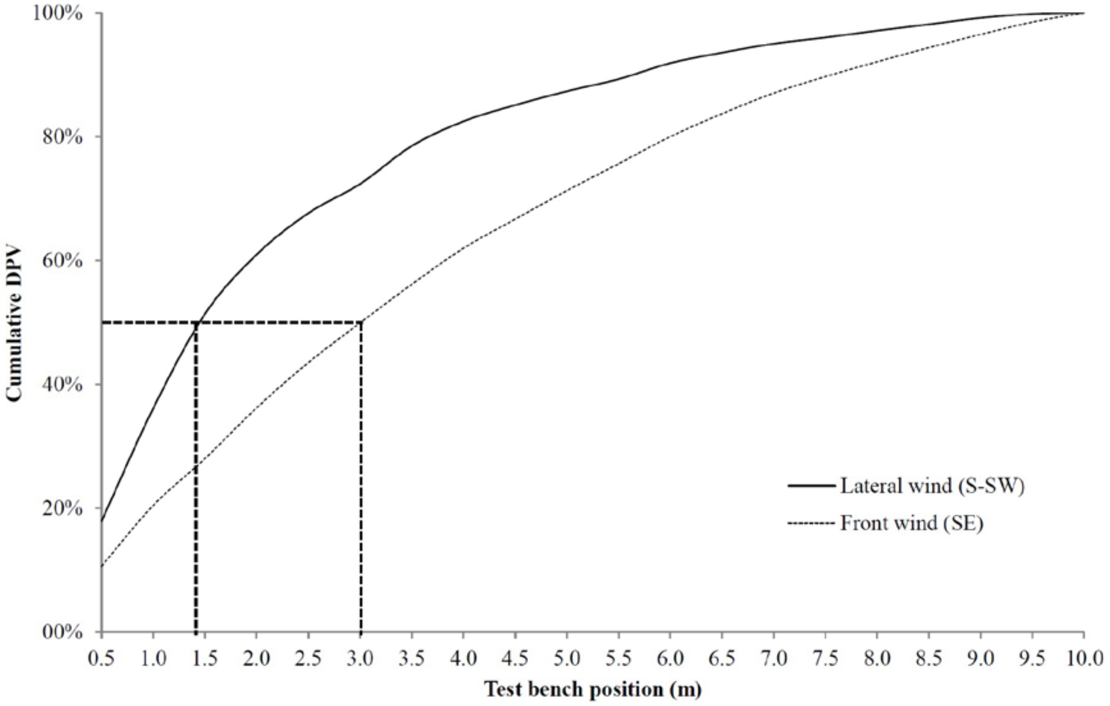


Figure 9

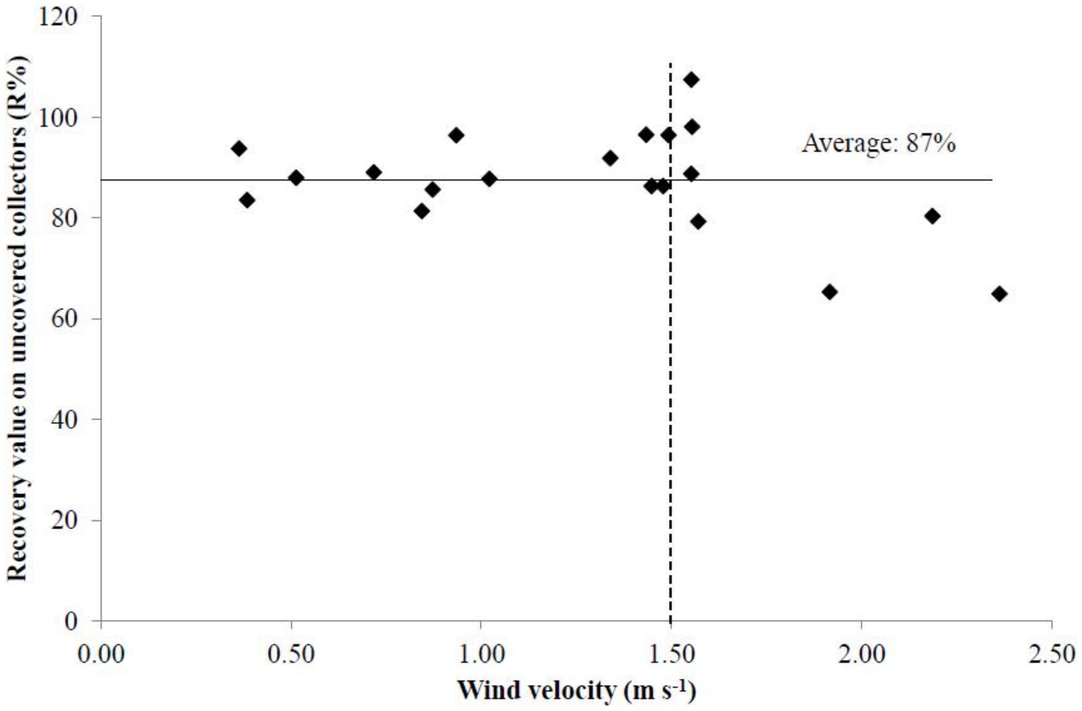
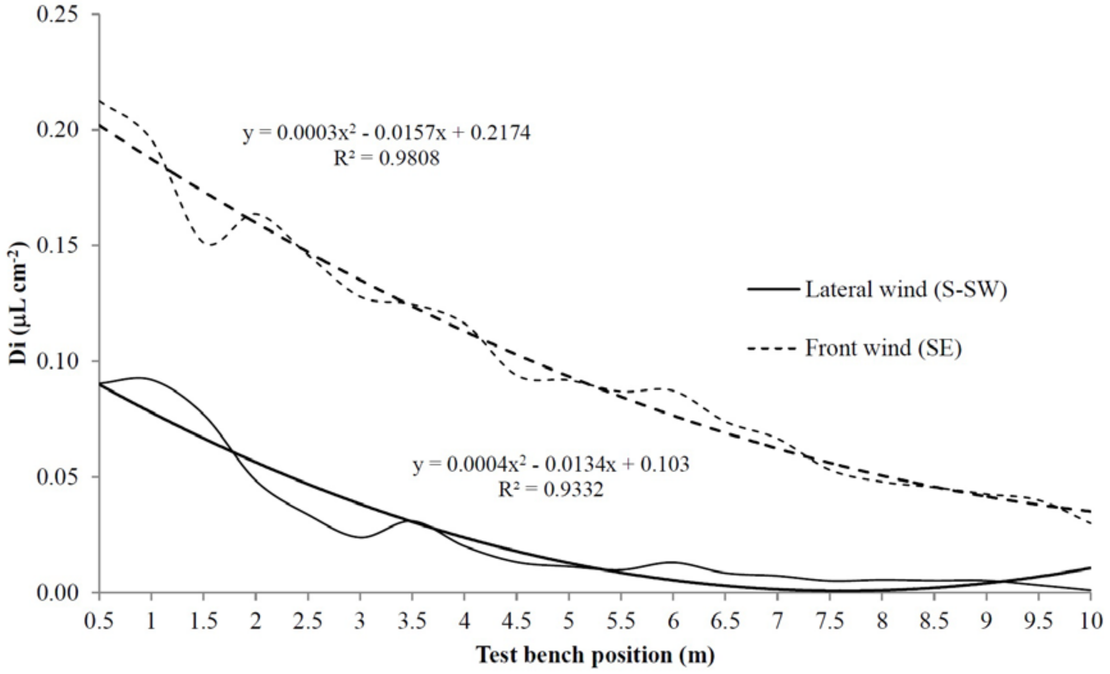


Figure 10


0.25
0.20
0.15
0.10
0.05
0.00
Di (µL cm⁻²)
y = 0.0003x² - 0.0157x + 0.2174
R² = 0.9808
y = 0.0004x² - 0.0134x + 0.103
R² = 0.9332
Lateral wind (S-SW)
Front wind (SE)
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
Test bench position (m)