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

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1 **Influence of wind velocity and wind direction on measurements of**

2 **spray drift potential of boom sprayers using drift test bench**

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11

12 **Abstract**

13 In 2009, the European Directive for a Sustainable Use of Pesticides (128/2009/CE)

14 established important mandatory actions to be accomplished by all Member States (MS)

15 in the European Union. The main objective is to achieve the sustainable use of

16 pesticides by reducing their risks and impacts on human health and the environment.

17 Among other important actions, drift reduction measures are essential to avoid the entry

18 of plant protection products (PPP) in water or other undesirable areas. As the risk of

19 environmental contamination is directly related to the spray application technology,

20 there is a strong need for objective methods for drift evaluation as well as robust

21 procedures for the classification of sprayers according to their risk of contamination.

22 For this purpose, and as a complementary tool to actual drift measurement

23 methodologies in the field or in laboratory conditions, a new method has been proposed

24 for the quantification of the potential drift generated by horizontal boom sprayer

25 systems using an ad hoc test bench.

26 This study aims to evaluate the influence of wind velocity and wind direction on the

27 drift potential value (DPV) using the proposed methodology and test bench. The results

28 indicated that wind velocities below 1.0 m s^{-1} have a negligible influence on the DPV.

29 Front wind led to higher DPVs than lateral wind. A global analysis of data indicates that

30 the proposed methodology and test bench are interesting tools for the quick and

31 objective evaluation of the potential drift if used in appropriate environmental

32 conditions.

33 **Keywords:** drift potential value (DPV), drift test bench, wind velocity, wind direction,

34 spray deposition, spray drift.

35 **Highlights**

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

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

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

39

40 **1. Introduction**

41 The European Directive for a Sustainable Use of Pesticides (128/2009/EC) (EP, 2009),

42 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

67 with a proportional definition and sizing of buffer zones that are more adapted to

68 particular situations.

69 In the last few years, several studies aimed at evaluating and quantify the effect of the

70 different parameters involved in spray drift. Nevertheless, considerable effort is required

71 to classify different crop protection techniques in spray drift reduction classes (ISO,

72 2006). This is further complicated by the fact that these classes frequently vary greatly

73 because of the influence of weather conditions (Zande et al., 2000; Balsari et al., 2007;

74 Zande et al., 2010) and by differences in the measurement protocols and techniques

75 (Arvidsson et al., 2011).

76 In most cases, the spray drift measurements in the field follow the standardized protocol

77 established by ISO 22866:2005, resulting in very complicated and time-consuming

78 experiments (Phillips and Miller, 1999; Ravier et al., 2005; Carlsen et al., 2006;

79 Schampheleire et al., 2008; Rimmer et al., 2009) and even a high dependence on

80 external factors. Moreover, field experiments with different spraying systems cannot be

81 performed under directly comparable and exactly repeatable conditions. Information

82 about the driftability of an intended sprayer configuration can typically be obtained;

83 however, these results are unsuitable for establishing any type of ranking or

84 classification because of their great variability. The difference in drift reduction

85 capabilities can therefore generally be determined only through sufficient repetitions

86 under similar conditions and pair- wise comparison. The fall-out drift measurements

87 presented in literature (Arvidsson et al., 2011) can, in some cases, differ by as much as a

88 factor of 10 for the same nozzle size and working pressure, which can be attributed to

89 different factors such as the weather conditions and spray application technology

90 (Nuyttens et al., 2006). Arvidsson et al (2011) found 0.20% and 0.94% variations in

91 drift per degree temperature and per m s^{-1} wind velocity, respectively.

92 Therefore, various studies have proposed alternatives for drift measurements in an

93 attempt to develop easy, repeatable, and precise methods as complementary procedures

94 to actual standards. One of the proposed alternatives, related to field crop sprayers, is

95 Balsari et al.'s (2007) use of an *ad hoc* drift test bench. This method allows the drift

96 potential value (DPV) to be quantified during a simulated application process with

97 selected working parameters. Gil et al. (2014) used this method for measuring the DPV

98 of a range of conventional and air injection flat fan nozzles. Their results demonstrated

99 that the drift test bench can be considered an adequate complement to actual standard

100 protocols for field measurements of drift (ISO, 2005). Zande et al. (2014) found similar

101 results for field measurements (ISO 22866) using a test bench, and they ranked the

102 nozzles that were similar in terms of drift reduction classes. Other indoor tests reported

103 good correlation between the drift reduction potentials from the test bench and the wind

104 tunnel measurements (Nuyttens et al., 2014).

105 ISO's ad hoc working group for drift measurements (ISO TC 23/SC 6/WG 16) officially

106 adopted the test bench as a new method for measuring the drift potential of horizontal

107 boom sprayer systems (ISO, 2014). However, further investigations are required to

108 clarify the effect of environmental conditions (mainly wind velocity and its relative

109 direction to the bench) to define the maximum limits for these wind factors so as to

110 avoid a negative influence on the results. Vanella et al. (2011) concluded that this

111 method needs relatively stable atmospheric conditions, as the combined effects of wind

112 velocity and direction significantly affected the drift potential of the sprayer.

113 In the context of improving the present ISO draft standard concerning drift potential

114 measurements by the use of test bench, the aim of the present study was to evaluate the

115 effect of wind velocity and wind direction on the DPV in order to define a wind

116 velocity threshold value to indicate in that ISO methodology. Repetitive field trials were

117   made keeping all the other sprayer working parameters (forward velocity, nozzle

118   characteristics, working pressure, and boom height) constant. For this purpose a

119   reference spraying system defined according to ISO 22369-2 was tested through 20

120   repetitions..

121   **2. Materials and methods**

122   *2.1 Experimental design*

123   The bench consists of a 12 m × 0.5 m steel frame with slots for collectors (Petri dishes)

124   situated at 0.5-m intervals (Figure 1). Each slot is equipped with a sliding cover that

125   makes it possible to cover/uncover the collector as needed. Once the boom sprayer

126   passes by the entire bench, a pneumatic system automatically uncovers the collectors to

127   capture the spray fraction that remains suspended in the atmosphere behind the boom

128   before settling after some time. The purpose of the bench is to collect and quantify, in

129   the absence of wind, the potential drift fraction, defined as the spray fraction that

130   remains suspended over the bench immediately after the sprayer pass and that can be

131   carried out of the target zone by weather air currents (Balsari et al., 2007).

132   A 12-m-long stainless steel bench was placed at the centre of the right-hand-side spray

133   boom of the sprayer at 3.0 m from the centre axis of the tractor in coincidence with the

134   middle point of the right-hand side of the boom (Gil et al., 2014), maintaining a NW-SE

135   position relative to the wind direction. Artificial collectors with a capture area of 153.94

136   cm^2 (Petri dishes with 14-cm diameter) were placed at 0.5-m intervals along the bench

137   slots. The sample position was 0.30 m above the ground, as recommended by ISO

138   (2014). The first two collectors remained permanently uncovered whereas the others on

139   the bench (length: 10 m) were initially covered using the sliding plates of the test bench.

140   The sprayer started application using only the right-hand side of the boom half over the

141 bench, spraying a 2 mg/L solution of water and tracer (yellow Tartrazine E 102). The

142 spray track started 20 m before the bench and then moved over the bench with the

143 covered collectors. Spraying was continued for a further 20 m after the end of the test

144 bench, for a total spray length of 52 m. After the sprayer passed over the end of the

145 bench and reached a point exactly 2 m beyond the last covered collector, an automatic

146 pneumatic system activated the sliding covers initiated by the passing spray boom,

147 which revealed the Petri dishes so as to capture the droplets still airborne over the

148 bench. Droplets were collected for 60 s after the opening of the system. Every single

149 Petri dish was then covered, adequately labelled, and placed in dry and dark conditions

150 until the laboratory determination of the tracer concentration. To determine the presence

151 of tracer as background in the environment before each trial, two open petri dishes were

152 placed on the bench and picked up before the next spray test. The tracer concentration at

153 the artificial collectors was quantified using a spectrophotometer (Thermo Scientific

154 Genesys 20).

155 Field trials were conducted 20 times using a conventional mounted 12-m boom sprayer

156 (Ilemo Hardi, S.A.U., Lleida, Spain). The working pressure (3.0 bar), sprayer forward

157 speed (6 km h^{-1}), boom height above the test bench surface (0.5 m), and nozzle type and

158 size (XR 110 03 flat fan nozzle 110° Teejet®, Spraying Systems Co., Wheaton, Illinois,

159 USA) were selected according to the reference spraying system (ISO, 2010) and

160 maintained constant during all the tests (Fig. 2). The resulting spray volume rate was

161 236 L ha^{-1}.

162 During the tests, weather conditions such as the wind velocity, wind direction, air

163 temperature and relative humidity were recorded continuously every second s at 2.0 m

164 height from the ground. For this purpose, a Campbell weather station with a Datalogger

165 CR800, a sonic anemometer (wind sonic 232), and two temperature and humidity

166   sensors (HC2S3) were placed laterally 5 m from the test bench position and 5 m from

167   the end of the bench, avoiding any interference at the measurement area.

168   *2.2 Quantification of DPV*

169   After the sprayer passed over the bench, the deposit on each artificial collector (Di)

170   (unit: µL cm^{-2}), was calculated as follows:

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

171

172   where D_i is the spray deposit on a single deposit collector (unit: µL cm^{-2}); ρ_{smpl}, the

173   absorbance value of the sample (adim.); ρ_{blk}, the absorbance value of the blanks (adim.);

174   V_{dil}, the volume of the dilution liquid (deionised water) used to dissolve the tracer

175   deposit from the collector (unit: µL); ρ_{spray}, the absorbance value of the spray mix

176   concentration applied during the tests and sampled at the nozzle (adim.); and A_{col}, the

177   projected area of the collector for capturing the spray drift (unit: cm^{2}).

178   Once the amount of tracer on every single collector was measured, the DPV was

179   calculated as follows:

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

180

181   where DPV is the drift potential value (dimensionless); D_i, the spray deposit on a single

182   deposit collector (unit: µL cm^{-2}); n, the number of collectors (20); and RSD, the

183   reference spray deposit under the boom as calculated using the intended volume rate

184   (unit: µL cm^{-2}).

185   RSD represents the intended (theoretical) amount of spray deposit in the treated area,

186   assuming a perfectly even distribution under the boom. For the first set of trials, the

187   RSD values ranged from 1.5 µL cm^{-2} (150 L ha^{-1}) to 3.25 µL cm^{-2} (325 L ha^{-1}). The

188   RSD values were compared with the actually measured deposition values in the

189   uncovered collectors to obtain an understanding of the spray deposition under the boom

190   and to verify the eventual main deviations from the expected value.

191   *2.3 Statistical analysis*

192   The data analysis consisted of evaluating the correlation between the wind

193   characteristics (velocity and direction) and DPV; also was analysed the relationship

194   between wind velocity and the recovery values (%) on the uncovered Petri dishes. This

195   analysis was performed using R software (R Development Core Team, 2011).

196   **3. Results**

197   *3.1 Wind characteristics during field trials*

198   The average wind velocity was 0.4–2.4 m s^{-1}, which allowed the correlation between the

199   wind characteristics and the DPV to be measured in each case. The wind direction in

200   relation to bench placement and tractor driving line was also recorded. During the field

201   trials, the most frequent wind directions were SE-NW (front wind relative to spray

202   track) and SW-NE (lateral wind). Figure 3 shows the distribution of all wind directions

203   during the trials and their relation with the bench position.. The average temperature

204   during the trials was 17 °C, with a maximum of 18.9 °C and minimum of 16.1 °C. The

205   relative humidity was 66.3%–91.4%. Table 1 shows the mean values of all the

206   parameters recorded during the field trials.

207 During each trial, values of wind velocity and wind direction were recorded every

208 second.. A further analysis of these parameters (Fig. 4) indicates that wind velocities

209 corresponding to a lateral wind direction showed less variation during the trials than that

210 observed for frontal winds. Interestingly, the wind direction was generally more

211 uniform than wind velocity during each trial.

212 The correlation between the wind velocity and the wind direction is mostly important.

213 Figure 5 shows the correlation of the average values of wind velocity and wind

214 direction and its relation with the bench position. Interestingly, the wind velocities were

215 generally higher for front wind even with highly dispersed values. However, at these

216 high wind velocities corresponded the highest spray deposits registered in the Petri

217 dishes, resulting in the highest DPV values (Fig. 6).

218 *3.2 Correlation between DPV and wind characteristics*

219 Fig. 6 shows the DPV obtained in each spray test and its relation with the wind velocity.

220 DPVs obtained for an average wind velocity lower than 1 m s^{-1} showed great

221 uniformity, and no significant relationship was found between the DPV and the wind

222 velocity (Table 2). The coefficient of variation of all DPVs obtained in the trials under

223 wind velocity lower than 1 m s^{-1} was 5.29%, with an average DPV of 23.7. These

224 results are consistent with those of previous studies (Gil et al., 2014). Fig. 6 shows that

225 the DPV values obtained with wind velocity over 1 m s^{-1} (average: 65.26) presented a

226 higher variability (CV: 29.03%). According to the obtained results, a safety threshold of

227 wind velocity can be established at a maximum environmental average wind velocity of

228 1 m s^{-1}. A deeper analysis of the relation between DPV and wind characteristics

229 indicates that more erratic values were obtained with SE wind direction (front wind

230 related to test bench position), whereas S-SW wind direction (lateral wind related to

231 bench placement) had much less effect on the DPV (Fig. 6).

232 A detailed analysis of the relationship between DPV and wind direction indicates that

233 front wind has much more effect on DPV than lateral wind. Considering the tests results

234 (Table 3), with the front wind the highest values of DPV (65.26) and coefficient of

235 variation (47.78%) were obtained. When tests were operated with front wind, DPV

236 ranged from 110.42 (max) to 16.04 (min). On the opposite, when tests were made with

237 lateral wind more uniform data, with a narrower range of variability, were obtained. It is

238 also interesting to remark the important differences on the values of Parson's coefficient

239 of correlation when comparing DPV with wind direction. While for the front wind the

240 Pearson's coefficient was 0.3417, for the lateral wind it was -0.489. All those figures

241 allow considering the front wind as with more influence on DPV, if compared with

242 lateral wind.

243 The effect of wind direction can also be observed in Fig. 7, which separately plots the

244 deposition curves along the test bench obtained from all the trials with S-SW wind

245 direction, corresponding to lateral wind, and the deposition curves obtained for the case

246 of front wind (SE wind). Important differences among the deposition on the collectors,

247 mainly in the last part of the test bench, were observed as a consequence of the wind

248 direction. In general, front wind blows spray droplets towards the last part of the bench,

249 generating a soft and homogeneous slope on the deposition curves, with relatively high

250 deposition on the rear part of the bench.

251 Another important effect of wind direction can be explained by the analysis of the

252 cumulative deposition along the test bench. Fig. 8 shows the cumulative deposition

253 curves obtained separated by the two different wind directions, front and lateral wind. In

254   this case, too, the effect of wind direction on the DPV is clear. The spray plume seems

255   to be displaced to the rear in the case of front wind, being collected 50% of the total

256   deposit in the first three meters of the bench, while the same percentage with lateral

257   wind was collected at the first one and a half meter of the bench (Fig. 8).

258   *3.3 Effect of wind on recovery deposit on uncovered collectors*

259   The recovery efficiency of the two uncovered petri dishes placed at the beginning of the

260   test bench during each trial was evaluated by calculating the percentage of liquid

261   collected from the total expected according to the spray volume applied as follows:

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

262   where R is the recovery value on uncovered collectors (%); C_s, the tracer concentration

263   measured on the collector (μg L^{-1}); V_s, the amount of water added for tracer extraction

264   (mL); S, the collector surface (cm^2); C_d, the tracer concentration in the tank (μg L^{-1});

265   and D, the intended applied volume rate (L ha^{-1}).

266   Fig. 9 shows the influence of the wind velocity on the recovery capacity of the

267   uncovered samples. The ANOVA test conducted to evaluate the recovery values

268   obtained on the uncovered collectors indicates no significant relationship between the

269   percentage recovery and the wind velocity ($P < 0.05$), particularly for wind velocities

270   below 1.5 m s^{-1} (Table 4). The average recovery value was 87% for all the tests with a

271   wind velocity below 1.5 m s^{-1}, indicating the good functioning of the spray boom

272   distribution.

273   *3.4 Spatial effect of wind direction on DPV*

274   The deposition curves of all trials were grouped according to the wind direction in

275   relation with the bench position. Fig. 10 shows the averaged deposition curves obtained

276   during all trials with lateral and front winds. The figure also shows the tendency curves

277   for the two cases and a plot of their corresponding mathematical expressions. In this

278   sense, the differences in deposition values along the test bench are noteworthy for the

279   two wind directions, being constants for every sampling point.

280   **4. Conclusions**

281   As specified in ISO 22369-2, 2010, weather conditions, especially those affecting wind

282   velocity and wind direction, have a variable influence on the final evaluation of the drift

283   potential obtained using a test bench. The results obtained from 20 tests operated at

284   different wind velocities and wind directions indicated that DPVs were not statistically

285   influenced when trials were conducted with average wind velocities below 1 m s^{-1}. This

286   value is higher than that recommended as maximum limit for wind velocity during

287   trials in the new proposed standard (ISO DIS 22401), which was initially 0.5 m s^{-1}.

288   The wind direction relative to the test bench and tractor forward direction clearly

289   influenced the spatial distribution of the spray deposition recovered along the whole

290   bench and affected the DPV values themselves. Front winds tended to provide higher

291   deposits on the rear part of the test bench. Therefore, field tests for drift measurements

292   using a test bench should be arranged carefully considering the wind direction relative

293   to the bench.

294   No significant effect was detected on recovery values on uncovered Petri dishes in trials

295   conducted with wind velocities below 1.5 m s^{-1}, resulting in an average value of 87%.

296   The recovery value on uncovered Petri dishes is a remarkable indicator of the actual

297 applied volume, avoiding undesirable mistakes during trials, and of the fact that no

298 deviations in spray distribution occurred during the tests.

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366   **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	($^{\circ}$)	
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

367

368   **Table 2** ANOVA test for statistical analysis of relationship between DPV (dependent

369   variable) and predictors (constant): wind velocity. Evaluated range: wind velocity < 1.0

370   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			

371

372

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

375

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

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

377

378 **Table 4** ANOVA test for statistical analysis of relationship between percentage of

379 recovery on uncovered collectors, %R (dependent variable) and predictors (constant):

380 wind velocity. Evaluated range: wind velocity <1.5 m s^{-1}

381

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			

382

383

384   FIGURE CAPTIONS

385   **Figure 1** Scheme of relative position of tractor and drift test bench during trials. Detail

386   of collectors over the bench.

387   **Figure 2** General overview of field trials.

388   **Figure 3** Compass rose representing all wind directions during trials and relative

389   position of bench.

390   **Figure 4** Boxplot of all wind velocity (upper) and wind direction (lower) measurements

391   for 20 trials.

392   **Figure 5** Relationship between wind velocity and wind direction for 20 trials. Relation

393   between average values of wind velocity and wind direction .

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

395   **Figure 7** Deposition curves along test bench classified according to wind direction.

396   Curves obtained during tests with front wind (upper). Curves obtained during tests with

397   lateral wind (lower).

398   **Figure 8** Cumulative DPV averaged curves obtained with lateral wind and front wind.

399   Values of 50% and 75% cumulative DPV are shown.

400   **Figure 9** Effect of wind velocity on recovery values measured on uncovered collectors.

401   Values of wind velocity below 1.5 m s^{-1} did not cause significant variations in recovery

402   efficiency.

403   **Figure 10** Average deposition curves along bench obtained after individual curves,

404   classified according to wind direction. Theoretical deposition tendency observed for

405   lateral and front winds is also shown.
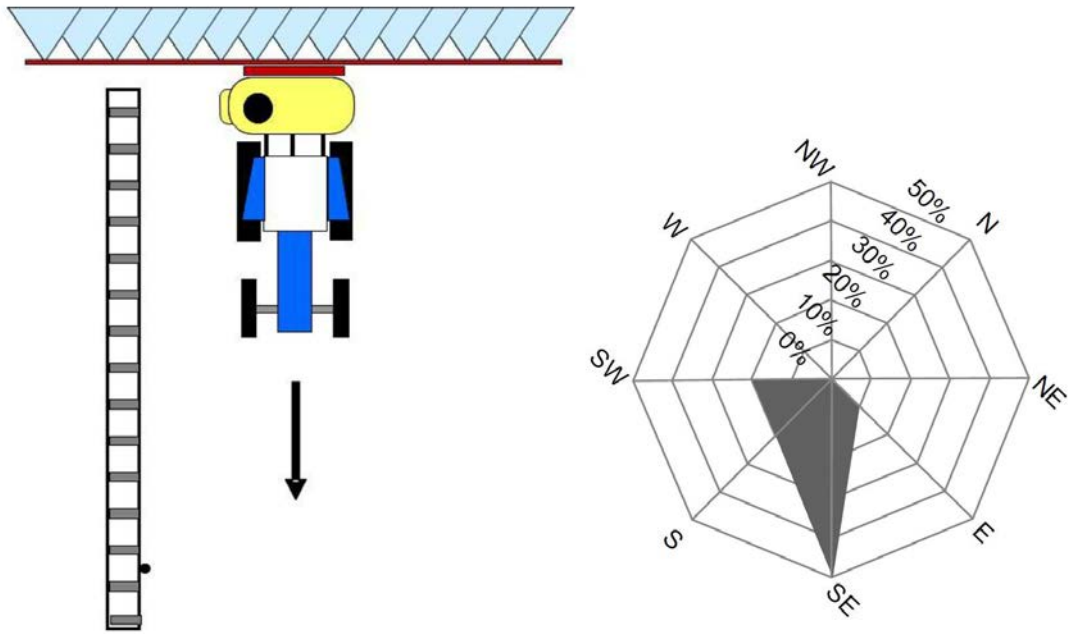
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407   Figure 1
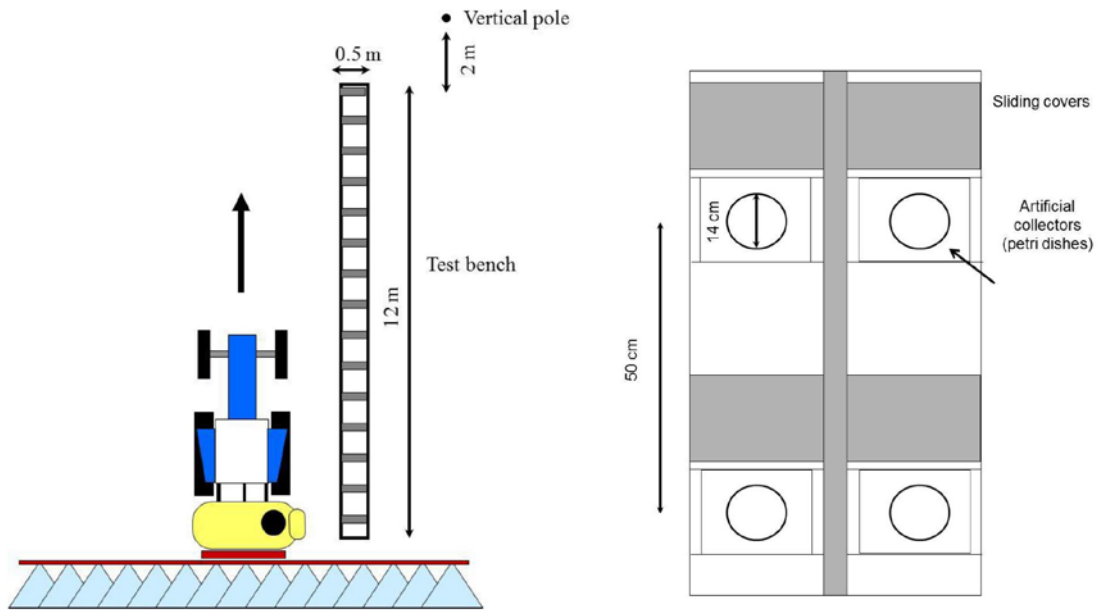
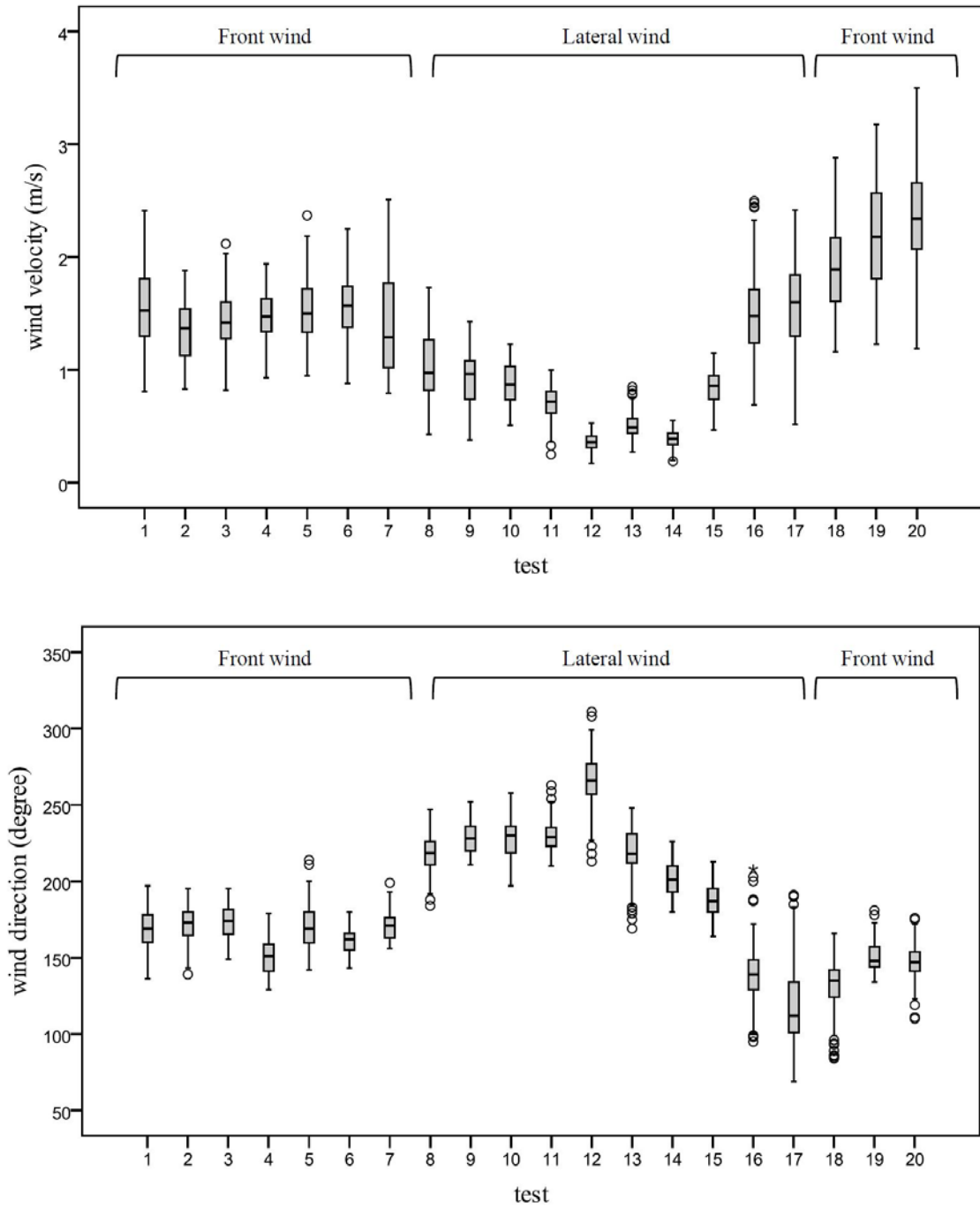

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409   Figure 2

410
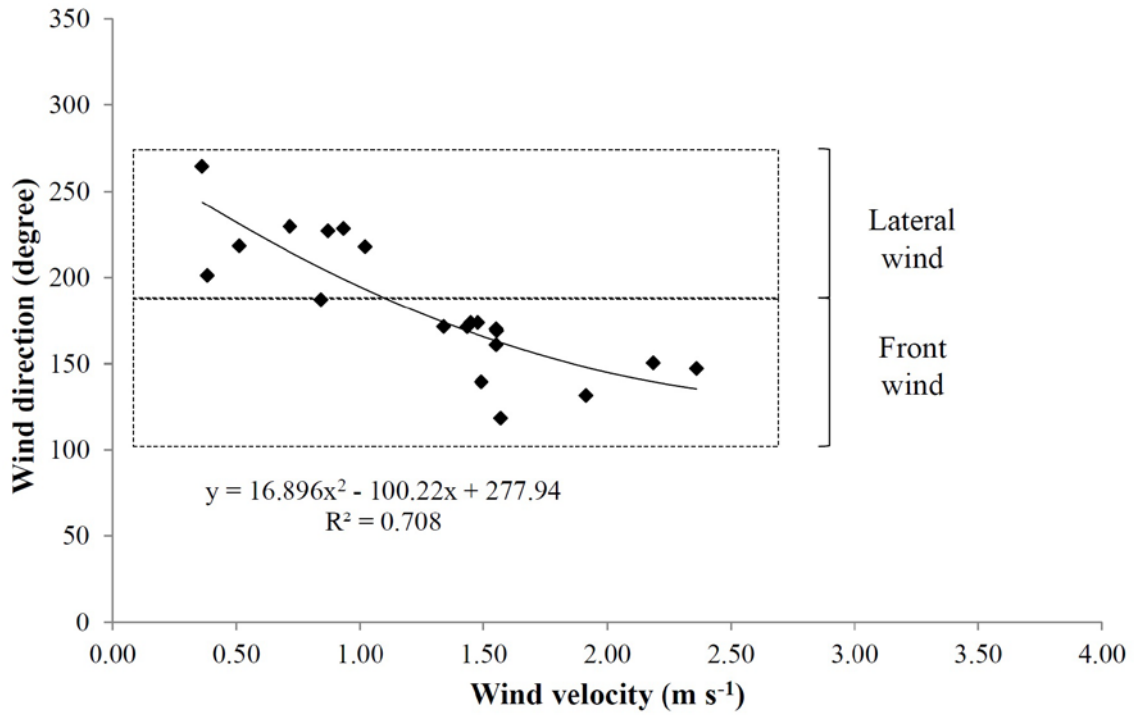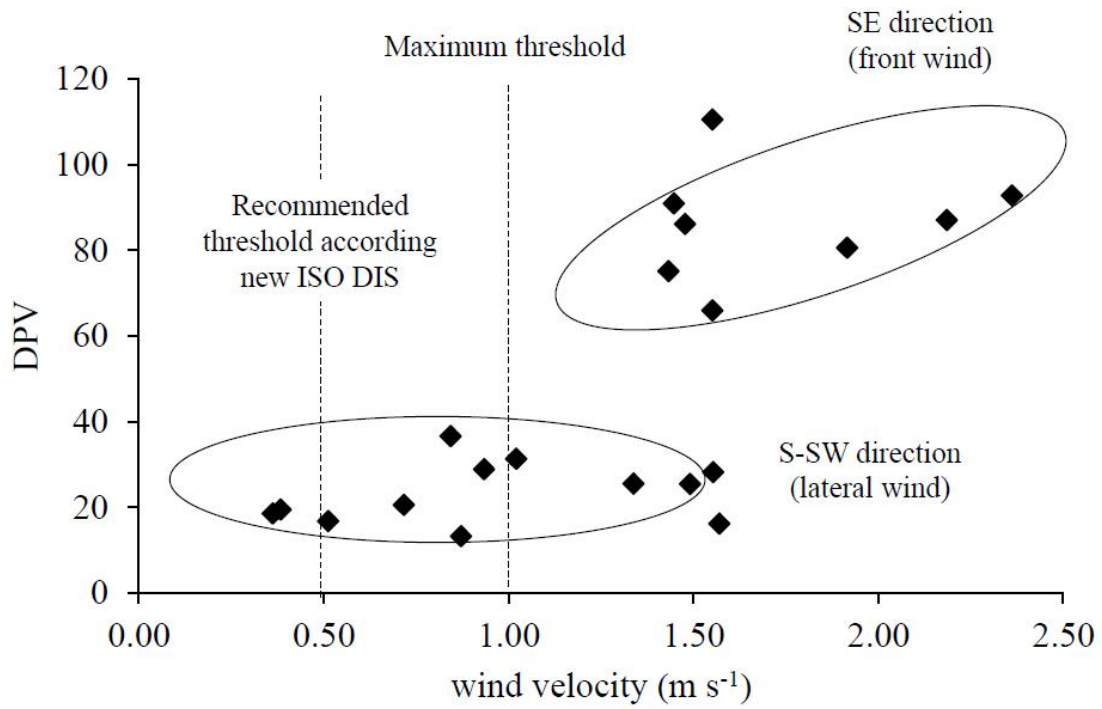
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412   Figure 3

413
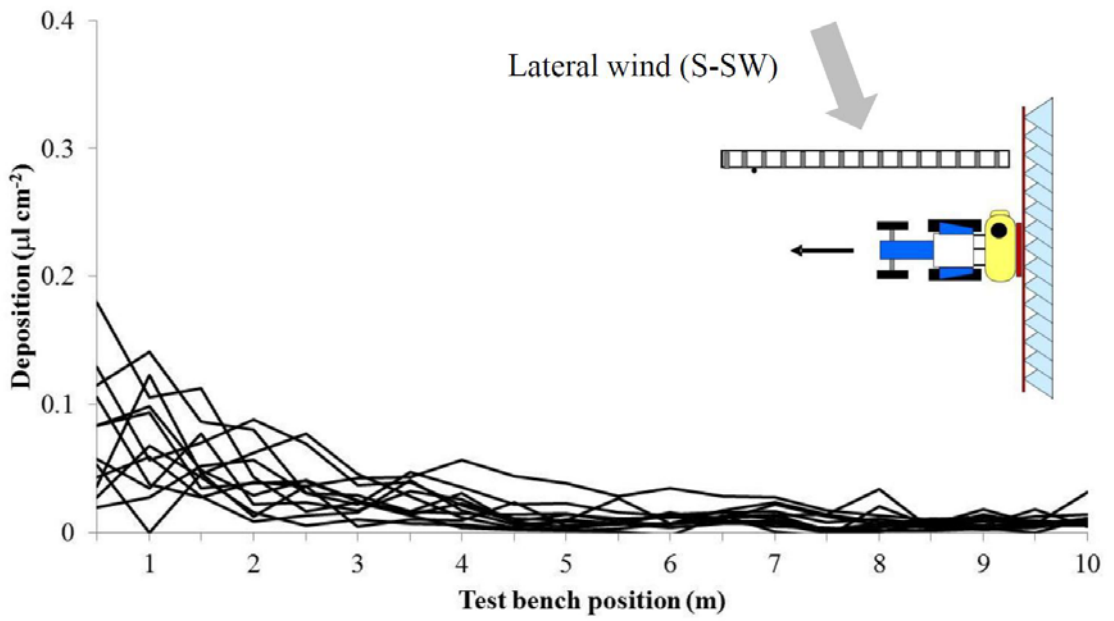
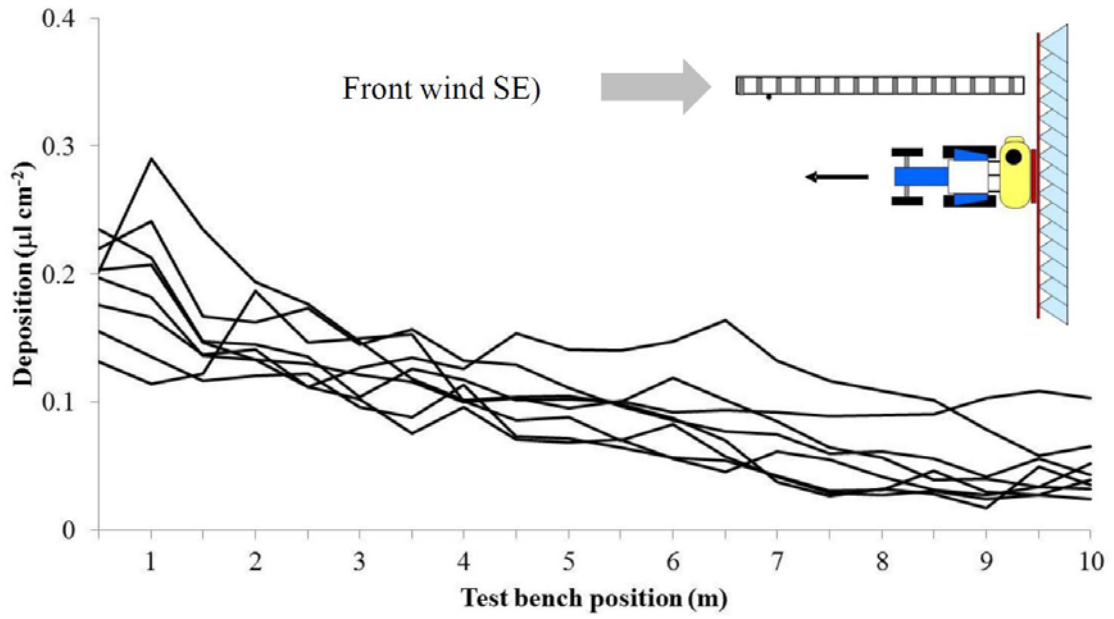414

415   Figure 4

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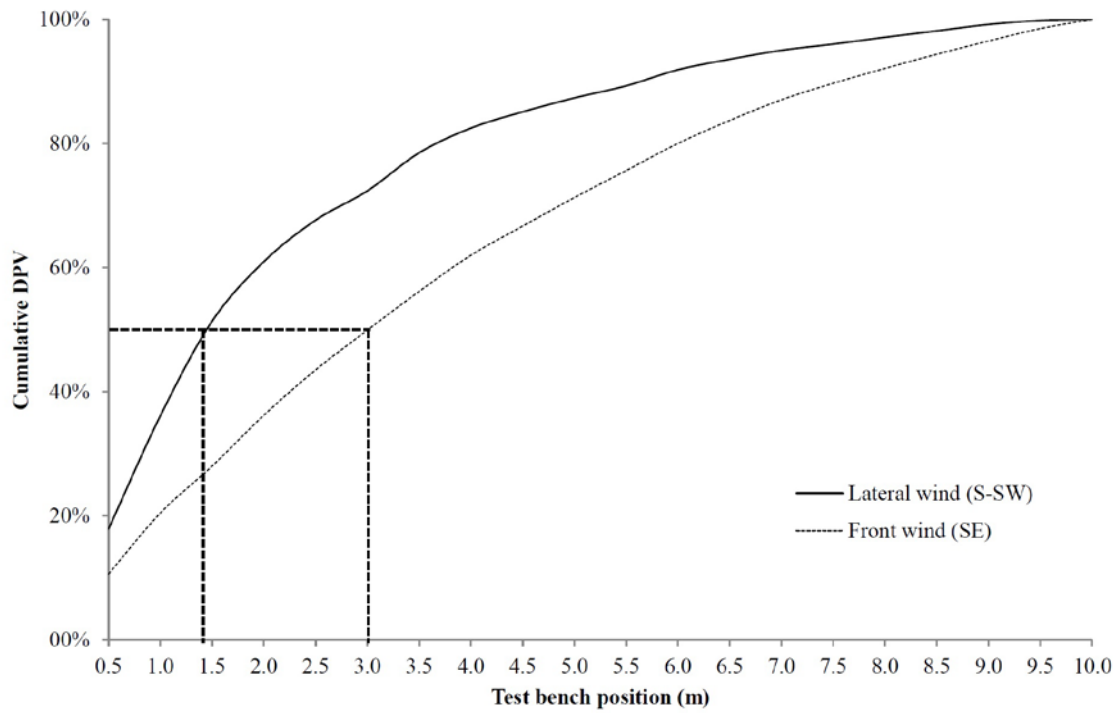
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418   Figure 5

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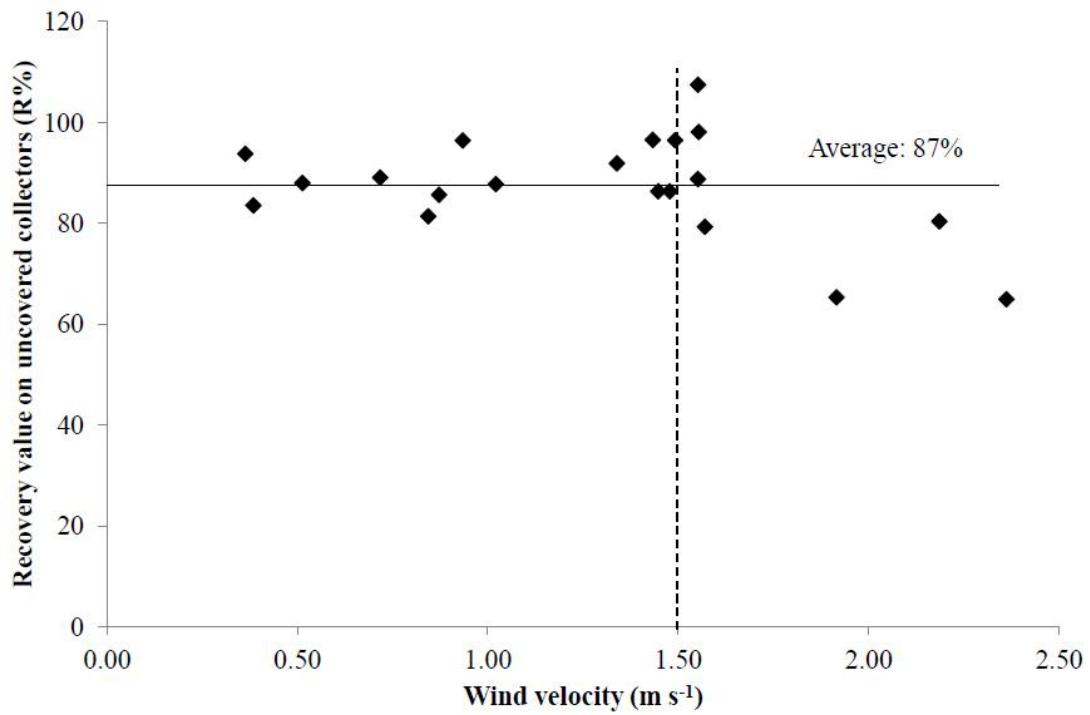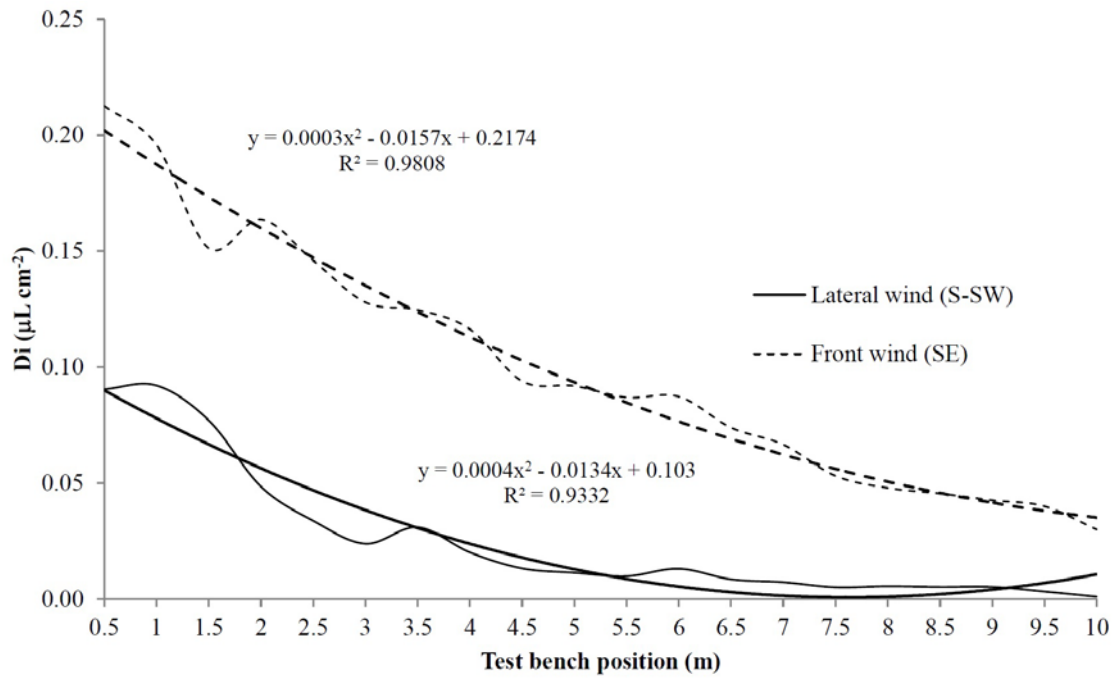420   Figure 6

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423   Figure 7

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426   Figure 8

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428   Figure 9

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430   Figure 10

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