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Experimental study of factors influencing the risk of drift from field sprayers, Part 1: Meteorological conditions

By D NUYTTENS[1], M DE SCHAMPHELEIRE[2], W STEURBAUT[2], K BAETENS[3], P VERBOVEN[3], B NICOLAÏ[3], H RAMON[3] and B SONCK[1]

[1]Ministry of the Flemish Community, Agricultural Research Centre
Department of Mechanisation - Labour - Buildings - Animal Welfare and Environmental Protection (CLO-DVL), Burg. Van Gansberghelaan 115, 9820 Merelbeke, Belgium
Contact: d.nuyttens@clo.fgov.be
[2]Department of Crop Protection, University Ghent, Belgium
[3]MeBioS, Department Biosystems, Catholic University of Leuven, Belgium

Summary

Spray drift can be 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. This continues to be a major problem in applying agricultural pesticides. The purpose of this research is to measure and compare the amount of drift for different climatological conditions under field conditions. Sedimenting spray drift was determined by sampling in a defined downwind area at different positions in a flat meadow using horizontal drift collectors for a reference spraying. Meteorological conditions were monitored during each experiment. A drift prediction equation for the reference spraying was set up to predict the expected magnitude of sedimenting at various drift distances and atmospheric conditions. The measurements proved the important effect of weather conditions (temperature, relative humidity and wind speed) on the amount of spray drift. A lower wind speed or a higher relative humidity decreases the amount of spray drift. Taking into account the correlation between temperature and relative humidity, a lower temperature will also result in lower drift values due to the cumulative effect of relative humidity. This equation can be used to quantify the effect of meteorological conditions, to compare measurements using other spraying techniques under different weather conditions to the reference spraying and to perform spray drift risk assessments.

Key words: Spray drift, meteorological conditions, field experiments, drift prediction equation

Introduction

Spray drift continues to be a major problem in applying agricultural pesticides. Recently, spray drift and its effects have also become an important aspect of risk assessment in the registration process of pesticides in Belgium. Besides the physical properties of the spray solution (Bode et al., 1976; Buttler Ellis & Bradley, 2002; Klein & Johnson, 2002) and the spray application, the weather conditions have an important effect on the amount of spray drift (Threadgill & Smith, 1975; Craig et al., 1998; Ozkan, 1998). Although different drift data have already been published (Ganzelmeier & Rautmann, 2000; Van De Zande et al., 2000), there is still a need for field drift measurements to enlarge the international drift database. Moreover, additional information is necessary about the effect of the climatological conditions on the amount of spray drift to compare measurements different spraying techniques to a reference spraying under different weather conditions. The results will also be used to validate a Computational Fluid Dynamics drift-prediction model. A whole series of field-drift experiments was carried out in 2004 and 2005 to quantify the effect of meteorological conditions on the amount of spray drift.

Materials and Methods

For the assessment of drift, a fluorescent tracer Brilliant Sulfo Flavine (BSF) was used at a concentration of 3 g.litre^{-1}. This tracer is highly water-soluble, has a low toxicity and has already been used successfully in other deposit measurements (Bode et al., 1976; Van De Zande et al., 2000; Heijne et al., 2002). Moreover, it offers high sensitivity with a very low limit of detection. This tracer was selected after a series of recovery, stability and wind tunnel experiments with other possible tracers like minerals, a salt and a fungicide (Brusselman et al., 2004). These experiments indicated that it is important to bring into account the photodegradation of BSF in the field experiments. With the addition of a water-soluble surfactant, i.e. Tween 20 at a volumetric concentration of 0.1 %, the spray liquid has properties representative of liquids typically used in the application of plant protection products.

Measures of drift relate to either the deposition onto horizontal surfaces outside the treated area or to airborne spray profiles that can be characterised at given downwind distances of the treatment area. Deposition onto horizontal surfaces is relevant for the assessment of the risk of contamination of, for example, surface waters whereas the measurement of airborne profiles (Miller et al., 1989; Taylor & Anderson, 1991) is relevant for the risk assessment relating to inhalation effects and to the contamination of e.g. vegetative structures at field boundaries.

Ground deposit was measured on horizontal collection surfaces placed at ground level with Machery-Nachel filter paper (type 751, 0.25 x 0.25 m²). Recovery of BSF on filter paper into water is relatively high and constant provided that the liquid solution with the filter paper is intensively shaken for about 15 minutes (Brusselman et al., 2004). Before each treatment, the spray solution was thoroughly mixed and a tank sample of the spray solution was taken immediately before application to measure the actual fluorescent concentration. The potential tracer degradation and the recovery are estimated for each trial using three filter paper collectors loaded with a measured volume of the tracer solution with a known concentration originating from the tank sample, by measuring the amount of tracer recovered after the drift experiment. This factor is used to correct the initial drift values. These collectors are positioned at a safe distance, wind upward the directly sprayed zone, to avoid cross contamination by spraying. After each drift experiment, the collectors were stored as quickly as possible (maximally 10 min.) into UV-light resistant jars filled with an exact amount of water to solubilize the tracer, while avoiding cross contamination. Deposits of the spray tracer were extracted from the samples by wash-off in pre-determined volumes of water (i.e. 700 ml for the filter papers and 200 ml for the pipe cleaners) immediately after the drift experiment. After 20 minutes of intensive shaking, the concentration of the tracer was measured in a Cary Eclipse fluorimeter (excitation wavelength: 441.96 nm, emission wavelength: 497.01 nm). The reading of the fluorimeter is related to the amount of tracer in solution through a calibration curve determined through sampling known concentrations of the tracer. Hence, the calibration factor F_{cal} determines the relationship between the fluorimeter reading (-) and the tracer concentration (mg.l^{-1}). From the reading of the fluorimeter, the calibration factor, the collector surface area, the spray concentration and the volume of dilution liquid, the amount of spray deposit per unit area can be calculated. From this spray drift deposition figure the percentage of spray drift on a collector can be calculated relating spray drift deposition to the amount applied in the field on the same unit of area. Hence, drift deposition is calculated as a percentage of the deposition on the sprayed area:

$$drift_{dep} = \frac{(R_{smpl} - R_{b\ln k}) \times F_{cal} \times V_{dil}}{C_{spray} \times A_{col}} \qquad drift_{\%} = \frac{drift_{dep} \times 1.10^{6}}{V_{app}}$$

With $drift_{dep}$: Spray drift deposit ($ml.cm^{-2}$); $drift_{\%}$: Spray drift percentage (%); V_{app}: Spray volume ($l.ha^{-1}$); R_{smpl}: Fluorimeter reading of the sample (-); R_{blnk}: Fluorimeter reading of the blanks (collector + dilution water) (-); V_{dil}: Volume of dilution liquid (l); C_{spray}: Spray concentration of tracer ($g.l^{-1}$); A_{col}: Collection area of the spray drift collector (cm^2); F_{cal}: Calibration factor ($mg.l^{-1}$).

The applications were done with a Hardi Commander Twin Force trailed field sprayer with 27 m boom, a nozzle spacing of 0.50 m and a tank volume of 3200 litres. Based on the Belgian and international agricultural practice, a reference spraying was defined as follows: a standard horizontal spray boom without air support, a spray boom height of 0.50 m, a nozzle distance of 0.50 m, ISO 110 03 standard flat fan nozzles at 3 bar ($1.2\ l.min^{-1}$) and a driving speed of $8\ km.h^{-1}$, resulting in an application rate of approximately $180\ l.ha^{-1}$. In this study, the reference spraying was used to obtain a database with drift values for different weather conditions. In total, 27 reference drift experiments (648 drift measurements) were carried out.

Experiments were conducted in a flat mowed meadow (average height: 10 cm) in order to allow the driving direction to be almost perpendicular to the wind direction at application time. The trial site was in an exposed area with a minimum of obstructions which may influence the airflow in the region of the measurement. Three spray lines and six measuring zones were marked in the field. Depending on the wind direction, another spray line and measurement zone was chosen. The directly sprayed zone is defined as the spray boom length plus half the average nozzle spacing at each end of the boom. Hence, in our case an area with a length of 100 m and a width of 27 m was directly sprayed in a single pass.

Spray drift was determined by sampling in a defined downwind area. Three sampling lines of horizontal drift collectors were positioned in the centre of the spray swath with a distance of 10 m between them. For each sampling line, horizontal drift collectors were placed at 0.5, 1, 2, 3, 5, 10, 15 and 20 metres wind downward the sprayed area at a level corresponding to the top of the vegetation for sampling sedimenting spray drift. So, in total 24 horizontal drift collectors were used for one drift measurement corresponding with a total sampling area of 1.5 m².

An array of pipe cleaners was also used to estimate the airborne spray drift at heights of 0.5, 1, 2, 3, 4 and 5 metres (two pipe cleaners for each height) using two poles or a total of 24 pipe cleaners. These poles were placed near the centre of the spray line at distances of 5 and 10 metres downwind from the edge of the directly sprayed area in a way that the support system does not prevent the effective sampling of airborne spray droplet drift. In this paper, only sedimenting spray drift is considered. Since drift is expressed as a proportion of the application rate, it is important that some direct assessments of target deposits are made as part of the drift measurement procedure by placing three filter paper collectors randomly in the directly sprayed zone. An overview of the experimental set-up for the field measurements is given in Figures 1 and 2 of part 2 of this paper.

Meteorological parameters are monitored every 3 seconds upwind of the sprayed area. In this way, measurements are not disturbed by the movement of the sprayer or the spray application. A Campbell Scientific weather station supporting sensors at an upwind distance of approximately 20 m from the track is used to determine average wind speed, actual wind speed and wind direction at heights of 1.50 m ($V_{1.50m}$, $v_{1.50m}$ & $dir_{1.50m}$) and 3.25 m ($V_{3.25m}$, $v_{3.25m}$ & $dir_{3.25m}$) (ultrasonic measurement), temperature and relative humidity at heights of 1.25 m ($T_{1.25m}$ & $RH_{1.25m}$) and 2.15 m ($T_{2.15m}$ & $RH_{2.15m}$). V is the average wind speed during the spray experiment (duration of spraying: ± 45 s for a driving speed of $8\ km.h^{-1}$), v is the actual wind speed when passing a sampling line. When the measuring height is not mentioned, the average of the two heights is used. The mean wind direction shall preferably be at 90° to the spray track during the period of spraying. Hence, an average maximal deviation of the ideal driving direction δ (°) of 40° on the wind direction was allowed in the drift measurements. Based on these measurements, atmospheric stability (A.S), turbulence intensity (T.I.) and dew-point temperature (°C) were calculated for each experiment:

$$\text{A.S. } (^\circ\text{C}) = T_{2.15\text{m}} - T_{1.25\text{m}} \qquad \text{T.I.} = \frac{v_{\max} - v_{\min}}{V_{avg}} \qquad T_d \ (^\circ\text{C}) = \frac{237.7 \times \log\left(\frac{10^{\frac{7.5 \times T_{avg}}{237.7 + T_{avg}}} \times RH_{avg}}{100}\right)}{7.5 - \log\left(\frac{10^{\frac{7.5 \times T_{avg}}{237.7 + T_{avg}}} \times RH_{avg}}{100}\right)}$$

where $v_{\max}$, $v_{\min}$, and V_{avg} are the maximum, the minimum and the average wind speed during the drift experiment and T_{avg} and RH_{avg} are the average temperature and relative humidity at the two measuring heights during the experiment.

Results

Weather conditions

Table 1 shows some of the most important meteorological variables for the 27 drift trials with the reference spraying. In 7 cases, the deviation of the ideal driving direction exceeded 40°. For 4 other experiments, there were problems with the spray boom height and a pressure fall (Table 1). These data were not used in the further analysis. Average temperature varied from 8.9 °C to 30.7 °C, average relative humidity from 38.3 % to 95.8 % and average wind speed from 1.00 m.s^{-1} to 5.72 m.s^{-1}. Hence, a wide range of climatological conditions was covered.

Table 1: *Meteorological variables for the different reference experiments*

Experiment	$RH_{1.25m}$ (%)	$RH_{2.15m}$ (%)	RH_{avg} (%)	$T_{1.25m}$ (°C)	$T_{2.15m}$ (°C)	T_{avg} (°C)	$V_{1.50m}$ (m.s^{-1})	$V_{3.25m}$ (m.s^{-1})	V_{avg} (m.s^{-1})	δ (°)	A.S. (°C)	T.I	T_d (°C)
Ref 1$^{\$}$	66.3	61.1	63.7	23.8	23.5	23.7	2.38	3.47	2.93	56.9*	-0.33	0.51	15.4
Ref 2$^{\$}$	67.6	62.5	65.0	23.9	23.7	23.8	4.89	6.00	5.44	49.9*	-0.22	0.65	15.8
Ref 3	68.2	62.5	65.3	25.3	24.8	25.0	4.10	5.21	4.66	44.0*	-0.43	0.57	16.8
Ref 4	44.2	39.8	42.0	31.1	30.4	30.7	2.08	2.73	2.41	23.8	-0.74	0.76	15.3
Ref 5	76.7	82.3	79.5	18.3	18.6	18.5	3.60	2.92	3.26	13.3	0.28	0.56	14.0
Ref 6	77.3	82.6	80.0	18.2	18.5	18.4	3.20	2.57	2.89	15.4	0.24	0.39	14.0
Ref 7	77.0	72.4	74.7	11.6	11.4	11.5	0.58	0.68	0.63	36.1	-0.22	0.80	6.9
Ref 8$^{\$}$	74.5	69.2	71.9	11.2	10.9	11.1	1.51	1.72	1.62	48.3*	-0.34	0.33	6.0
Ref 9	77.3	72.2	74.8	11.7	11.4	11.5	2.46	2.98	2.72	40.0	-0.34	0.58	7.0
Ref 10	67.4	62.3	64.9	12.8	12.5	12.7	1.82	2.24	2.03	99.5*	-0.33	0.60	6.1
Ref 11	76.5	71.6	74.0	12.8	12.4	12.6	4.42	5.34	4.88	18.1	-0.37	0.79	7.8
Ref 12	72.3	67.7	70.0	12.8	12.5	12.6	3.73	4.52	4.12	14.8	-0.30	0.75	7.1
Ref 13	70.1	66.0	68.1	13.8	13.4	13.6	3.94	4.62	4.28	1.3	-0.37	0.71	7.6
Ref 14	68.1	63.3	65.7	13.2	12.9	13.1	3.42	4.03	3.73	8.4	-0.29	0.69	6.6
Ref 15	84.3	89.7	87.0	14.9	15.1	15.0	4.38	3.29	3.84	17.5	0.19	0.62	12.2
Ref 16‡	84.4	78.7	81.6	16.1	15.7	15.9	2.62	3.12	2.87	32.7	-0.34	0.63	12.1
Ref 17	79.6	74.4	77.0	16.5	16.2	16.3	2.29	2.81	2.55	75.8*	-0.20	0.44	11.7
Ref 18	95.8	90.5	93.1	9.0	8.8	8.9	0.94	1.06	1.00	16.5	-0.26	0.69	7.6
Ref 19	90.2	85.0	87.6	14.9	14.6	14.7	1.09	1.11	1.10	16.3	-0.32	0.41	12.1
Ref 20	86.5	81.5	84.0	15.8	15.4	15.6	1.29	1.36	1.33	49.3*	-0.37	0.47	12.3
Ref 21	82.8	77.2	80.0	16.4	16.0	16.2	2.00	2.47	2.24	18.1	-0.42	0.48	12.1
Ref 22	64.1	59.5	61.8	22.2	21.8	22.0	3.12	3.67	3.40	18.5	-0.40	0.65	13.6
Ref 23	60.7	56.2	58.5	26.4	26.0	26.2	5.23	6.21	5.72	8.2	-0.43	0.77	16.3
Ref 24	65.2	60.3	62.8	13.9	13.6	13.8	2.68	2.97	2.83	11.0	-0.37	0.29	6.6
Ref 25	68.1	63.1	65.6	9.5	9.1	9.3	1.58	1.86	1.72	23.8	-0.40	0.82	3.1
Ref 26	42.5	37.7	40.1	13.5	13.1	13.3	2.77	3.06	2.92	7.5	-0.41	0.79	0.0
Ref 27	38.3	34.1	36.2	14.2	13.7	13.9	3.57	4.29	3.93	6.5	-0.48	0.50	-0.8
Average	**71.3**	**67.5**	**69.4**	**16.4**	**16.1**	**16.3**	**2.80**	**3.20**	**3.00**	**28.6**	**-0.29**	**0.60**	**9.8**

* Deviation of ideal driving direction > 40° $^{\$}$ Spray boom too high or too low during measurement

‡ Pressure fall during measurement

Drift data

The sedimenting spray drift results from three arbitrarily chosen reference sprayings (Ref 14, 18 & 24) are presented in Figure 3 together with the average drift values of the 27 reference sprayings. Note the logarithmic scale of the drift axis. The drift distances are calculated by dividing the distance of the horizontal collectors (0.5, 1, 2,…, 20 m) by the cosine of the deviation of the ideal driving direction δ.

Each drift value is the average of the three sampling lines at a certain distance. Moreover, the 90% confidence interval is presented on the graph for each reference spraying. Other sprayings show similar repeatabilities. The considerable variation in drift values between the three sampling lines may be due to spray boom movements and secondarily to small variations in wind speed, wind direction and spray line while passing the different sampling lines.

More important is the fact that besides the variation between the three sampling lines for each reference spraying, there is also a large variation between different reference sprayings. For example, drift deposits varied from 0.4% (Ref 15) to 16.7% (Ref 26) on the collector placed at 1 metre of the directly sprayed zone. It is reasonable that this variation is mostly caused by variations in weather conditions. This hypothesis is investigated by carrying out a detailed regression analysis.

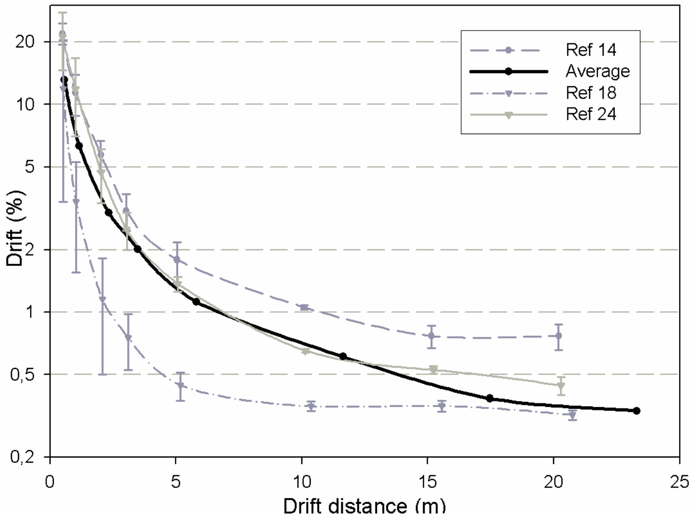

Fig. 3. Drift data for three different reference sprayings (Ref 14, 18 & 24) + the average drift curve based on 27 reference sprayings.

Statistical drift prediction equation

Because of the obvious effect of the weather conditions on the amount of spray drift, it would be beneficial to predict the expected magnitude of sedimenting drift at various distances and atmospheric conditions. A regression analysis in different steps was performed on the data (using SPSS 10.0) to come to a final statistical drift prediction regression for the reference spraying with the amount of spray drift as the dependent variable.

Different independent variables were determined for each experiment: $RH_{1.25m}$, $RH_{2.15m}$, RH_{avg}, $T_{1.25m}$, $T_{2.15m}$, T_{avg}, $V_{1.50m}$, $V_{3.25m}$, V_{avg}, $v_{1.50m}$, $v_{3.25m}$, v_{avg}, δ, A.S., T.I, T_d, drift distance and collector distance. Besides these first order variables, different second order combinations of these variables were also selected after a first statistical analysis. All of this resulted in the following non-linear statistical drift prediction equation for the reference spraying:

$$Drift(\%) = (drift\_dist.)^{-1.03} \times (48.89 + 1.08 T_d + 0.5 V_{3.25m} - 0.45 RH_{avg} - 1.41 T_{avg})$$

With Drift (%): Spray drift percentage (%); drift_dist: Drift distance parallel with wind direction (m); T_d: Dew-point temperature (°C); $V_{3.25m}$: Average wind speed at a height of 3.25m ($m.s^{-1}$); RH_{avg}: Average relative humidity (%); T_{avg}: Average temperature (°C).

A summary of the statistics of this regression is presented in table 2. An R² of 0.873 (= 1 – SSE/SSTO) is obtained using the average of the three sampling lines as dependent variable.

Table 2: *Non-linear regression statistics*

Source of Variation	Sum of squares (SS)	df	Mean square (MS)
Regression	SSR = 19549.85	6	MSR = 3285.31
Error	SSE = 2853.85	450	MSE = 6.34
Total	SSTO = 22403.71	456	

Variable	Coefficient	SE	Variable	Coefficient	SE
drift_dist	-1.03	0.04	$V_{3.25m}$	0.50	0.13
Constant	48.89	6.97	RH_{avg}	0.45	0.08
T_d	1.08	0.32	T_{avg}	1.41	0.28

Discussion of the drift equation

With this drift equation it is possible to predict sedimenting spray drift on grassland for reference sprayings under various atmospheric conditions for drift distances up to at least 20 metres by measuring wind speed, relative humidity and temperature. Based on the available drift data, the model is usable for temperatures varying from about 10° C to 25 °C, relative humidities from 40 % to 90 % and wind speeds from about 1 $m.s^{-1}$ to 5 $m.s^{-1}$.

Some drift curves based on the drift equation for the reference spraying on a meadow are presented in Figures 4 and 5. In Figure 4, the effect of relative humidity (Fig. 4a) and wind speed (Fig. 4b) on the amount of spray drift is shown, starting from standard meteorological conditions defined as a relative humidity of 70 %, a wind speed of 3 $m.s^{-1}$ and a temperature of 15 °C. Regarding meteorological conditions, relative humidity has the most important impact on the amount of spray drift. The lower the humidity, the higher the amount of drift due to the effect of evaporation which reduces droplet sizes. In most cases, relative humidity is situated between 60 % and 85 %. The effect of relative humidity is even more important than the effect of the wind speed. Logically, higher wind speeds result in higher amounts of spray drift but the effect of the wind speed on the amount of sedimenting spray drift is less pronounced compared to the effect of relative humidity. Despite the fact that a higher temperature raises the amount of evaporation, the effect on drift seems at first sight opposite. For a constant relative humidity, lower temperatures result in higher drift values (Fig. 5a). This rather surprising conclusion can be explained by the fact that there is a strong correlation between temperature and relative humidity for the different experiments (Fig 5b). This is illustrated in Figure 6 where drift curves are presented for some realistic combinations of temperature and relative humidity, based on a first order regression (Fig. 5b). It is clear that under realistic conditions an increase of the temperature (involving a decrease of RH) increases the amount of spray drift. Note that despite the general relation between temperature and relative humidity, it is still necessary to measure and to bring into account both variables to achieve an accurate drift prediction.

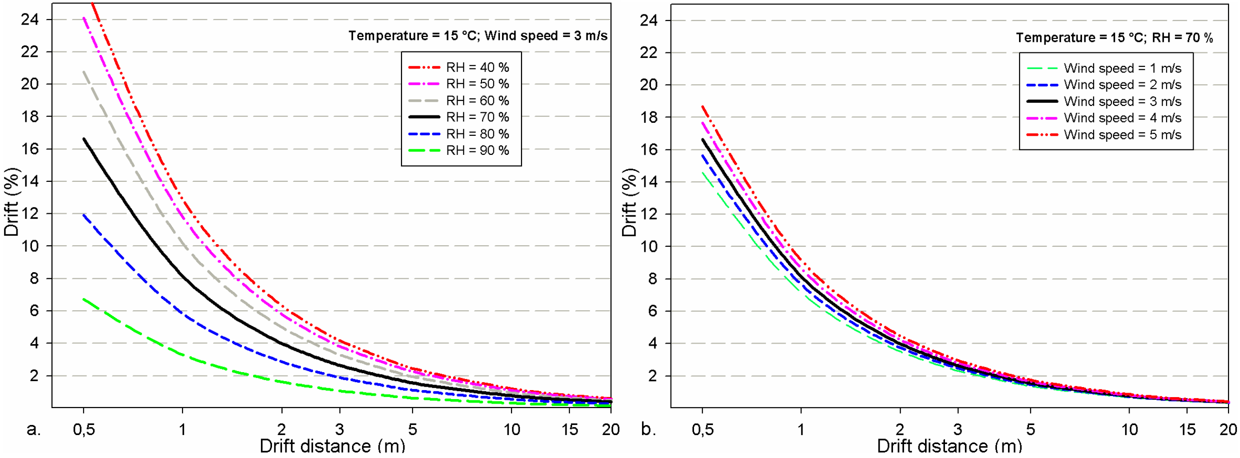

Fig. 4. Drift curves for the reference spraying on a meadow under different climatological conditions. a. Effect relative humidity b. Effect wind speed

In Fig. 7, a comparison is made between measured drift values and predicted drift values, using the corresponding weather conditions, specifying the collector distances (Fig. 7a) and experiments (Fig. 7b). In general, the correlation between measured and predicted drift values is very satisfying ($R^2 = 0.83$) again proving the good predictive power of the drift equation. Considering the collector distance, the drift equation gives a little overestimation for very small measured drift values (< 0.2 %) corresponding with high collector distances (Fig. 7 a). For some specific experiments, the drift equation gives a small global underestimation (e.g. Ref 9 & 23) or overestimation (e.g. Ref 15 & 27) compared to the measured values. These deviations can be attributed to factors like deviation of spray boom height and spray boom movements.

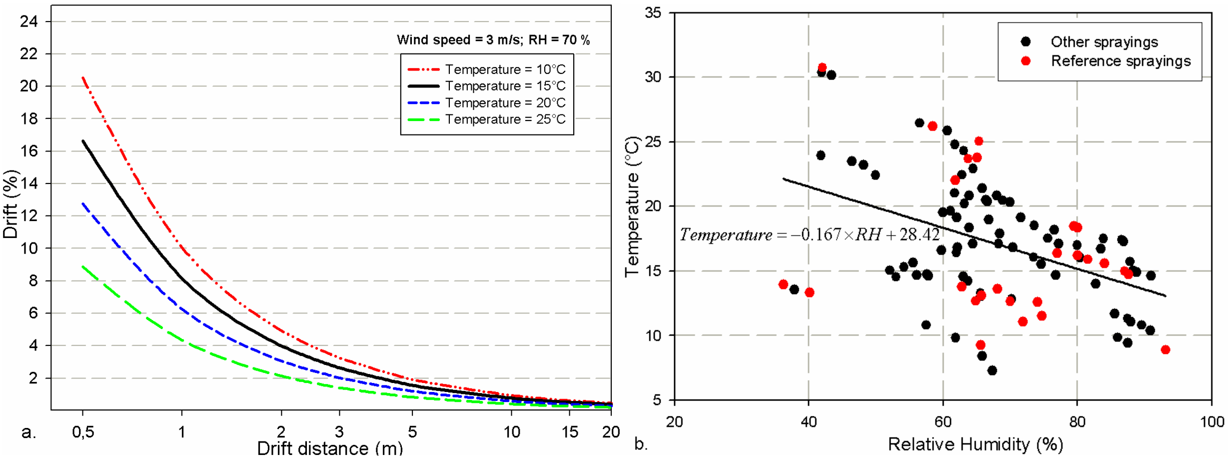

Fig. 5. a. Drift curves for the reference spraying for different temperatures b. Relation between temperature and relative humidity for different sprayings.

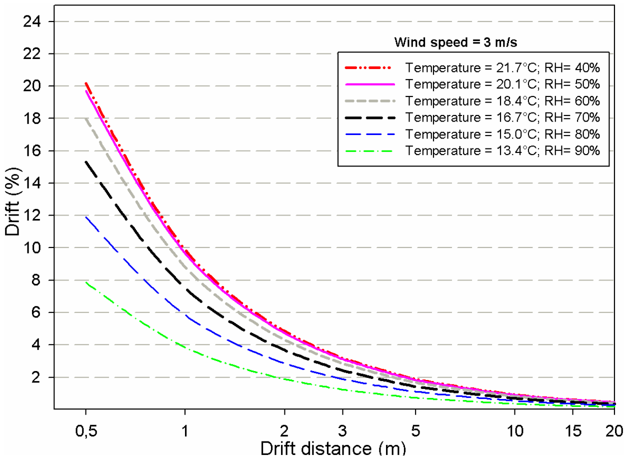

Fig. 6. Drift curves for the reference spraying for different realistic combinations of temperatures and relative humidity and a wind speed of 3 $m.s^{-1}$.

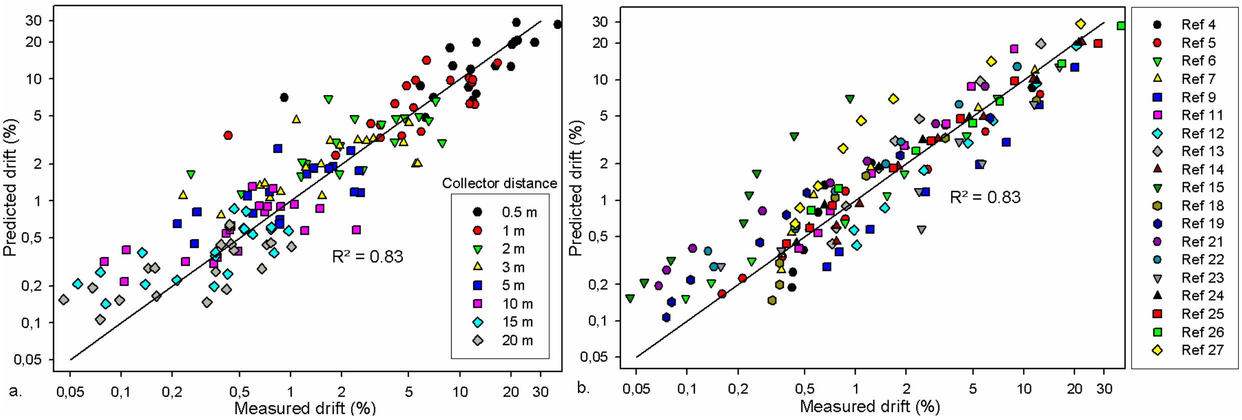

Fig. 7. Comparison between average measured drift values and modelled drift values. a. Effect collector distance b. Effect experiment

Conclusions

A reliable and feasible spray drift measuring protocol for boom sprayers is formulated and 27 reference drift experiments were successfully carried out under different weather conditions. A drift prediction equation for the reference spraying was set up to predict the expected magnitude of sedimenting drift for various drift distances and atmospheric conditions. These measurements proved the important effect of the weather conditions (temperature, relative humidity and wind speed) on the amount of sedimenting spray drift. Decreasing wind speed and increasing relative humidity decreases the amount of sedimenting spray drift. Taking into account the correlation between temperature and relative humidity, a lower temperature will also result in lower drift values due to the cumulative effect of relative humidity. This equation can be used to quantify the effect of meteorological conditions, to compare measurements using other spraying techniques under different weather conditions to the reference spraying and to perform spray drift risk assessments (See part 2 of this paper). Moreover, the measurements will be used to validate a Computational Fluid Dynamics drift-prediction model.

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