SPRAY DRIFT AS AFFECTED BY METEOROLOGICAL CONDITIONS

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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.
Spray drift was determined by sampling in a defined downwind area at different positions in a flat meadow using horizontal drift collectors (sedimenting spray drift) and pipe cleaners (airborne spray drift) 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 drift at various drift distances and atmospheric conditions (wind speed and temperature). This equation can be used to compare measurements using other spraying techniques under different weather conditions to the reference spraying.
In 2005, more measurements will be performed to validate the statements and the model reflected in this paper.

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. Factors that affect spray drift include the weather (Threadgill & Smith, 1975; Craig *et al.*, 1998), the physical properties of the spray solution (Buttler Ellis & Bradley, 2002; Klein & Johnson, 2002) and the spray application itself. Different spray application factors have already been evaluated like spray boom height (De Jong et al., 2000), air support (Van De Zande *et al.*, 2000 a), nozzle type and pressure (Heijne *et al.*, 2002; Klein & Johnson, 2002) and driving speed (Miller & Smith, 1997).
Although different drift data have already been published (Ganzelmeier *et al.*, 1995; Van De Zande *et al.*, 2000 b) there is still a need for field drift measurements to enlarge the international drift database. Moreover, more information is necessary about the effect of the climatological conditions on the amount of spray drift.

In this paper, some first results of field-drift experiments with a field sprayer, carried out in August and September 2004, are presented.

MATERIALS AND METHODS

Spray liquid

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.

Spray drift collectors

Measures of drift can relate to either the deposition of spray onto horizontal surfaces outside the treatment 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 is relevant for the risk assessment relating to inhalation effects and to the contamination of, for example, 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). Filter paper was selected after a series of experiments based on the retention and recovery characteristics (Brusselman *et al*., 2004).
The 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 a period of about 15 minutes. For all drift results, the recovery was each time taken into account.
Pipe cleaners with a length of 0.25 m were used to measure airborne spray drift (Figure 1). They have a defined collection area (diameter: 8 mm), a high collection efficiency and the tracer can accurately and reliably be recovered (Miller et al., 1989; Taylor and Andersen, 1991). In this paper, only sedimenting spray drift is considered.
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. These collectors are positioned at a safe distance, wind upward the directly sprayed zone, to avoid cross contamination by spraying. By measuring the amount of tracer after the drift experiment, a factor bringing into account the photodegradation and the recovery can be estimated. This factor is used to correct the initial drift values. After each drift experiment, the collectors were stored as quickly as

possible into UV-light resistant jars filled with an exact amount of water to solubilize the tracer. This happened in a way that cross contamination was minimized.

Determination of drift deposits

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 at an excitation wavelength of 441.96 nm and an emission wavelength of 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. The following formulas are used:

$$drift_{dep} = \frac{(R_{smpl} - R_{b\ln k}) \times F_{cal} \times V_{dil}}{C_{spray} \times A_{col}} \qquad (1)$$

$$drift_{\%} = \frac{drift_{dep} \times 1.10^{6}}{V_{app}} \qquad (2)$$

where $drift_{dep}$: 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) (-);
F_{cal}: Calibration factor ($mg.l^{-1}$);
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).

The collection area of a pipecleaner is defined as half of the cylindrical area.

Experiment design

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 (Figure 2). Depending on the wind direction, another spray line and measurement zone were 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 horizontal sampling area of 1.5 m².

An array of pipe cleaners is 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.

A co-ordinate reference system is used to describe the layout of the spray drift trial and the location of the spray drift collectors (Figure 2) with:

- X dimension is the axis in the direction of sprayer travel;
- Y dimension is the other horizontal axis 90° to X (normally wind direction);
- Z dimension is the vertical axis (90° to X and Y).

The origin for the co-ordinate system is situated at the mid-point of the directly sprayed area and at the furthest downwind edge of the directly sprayed area.

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. Figure 1 shows some pictures of the experimental set-up.

Sprayer and sprayer settings

The applications were done with a Hardi Commander Twin Force trailed field sprayer with 27 m boom, a nozzle spacing of 0.50 m, Twin air assistance and a tank volume of 3200 litres.

A reference spraying was used to obtain a first database with drift values (12 trials) for different weather conditions. This information can also be used to compare measurements under different weather conditions to the reference spraying.

Based on the Belgian and international agricultural practice, the reference spraying was defined as follows:

- a standard horizontal spray boom without air support
- a spray boom height of 0.50 m above the meadow
- a nozzle distance of 0.50 m
- ISO 110 03 standard flat fan nozzles at 3 bar (1.2 $l.min^{-1}$)
- a driving speed of 8 $km.h^{-1}$, resulting in an application rate of approximately 180 $l.ha^{-1}$

Figure 1: Some pictures of the experimental set-up for the field drift measurements

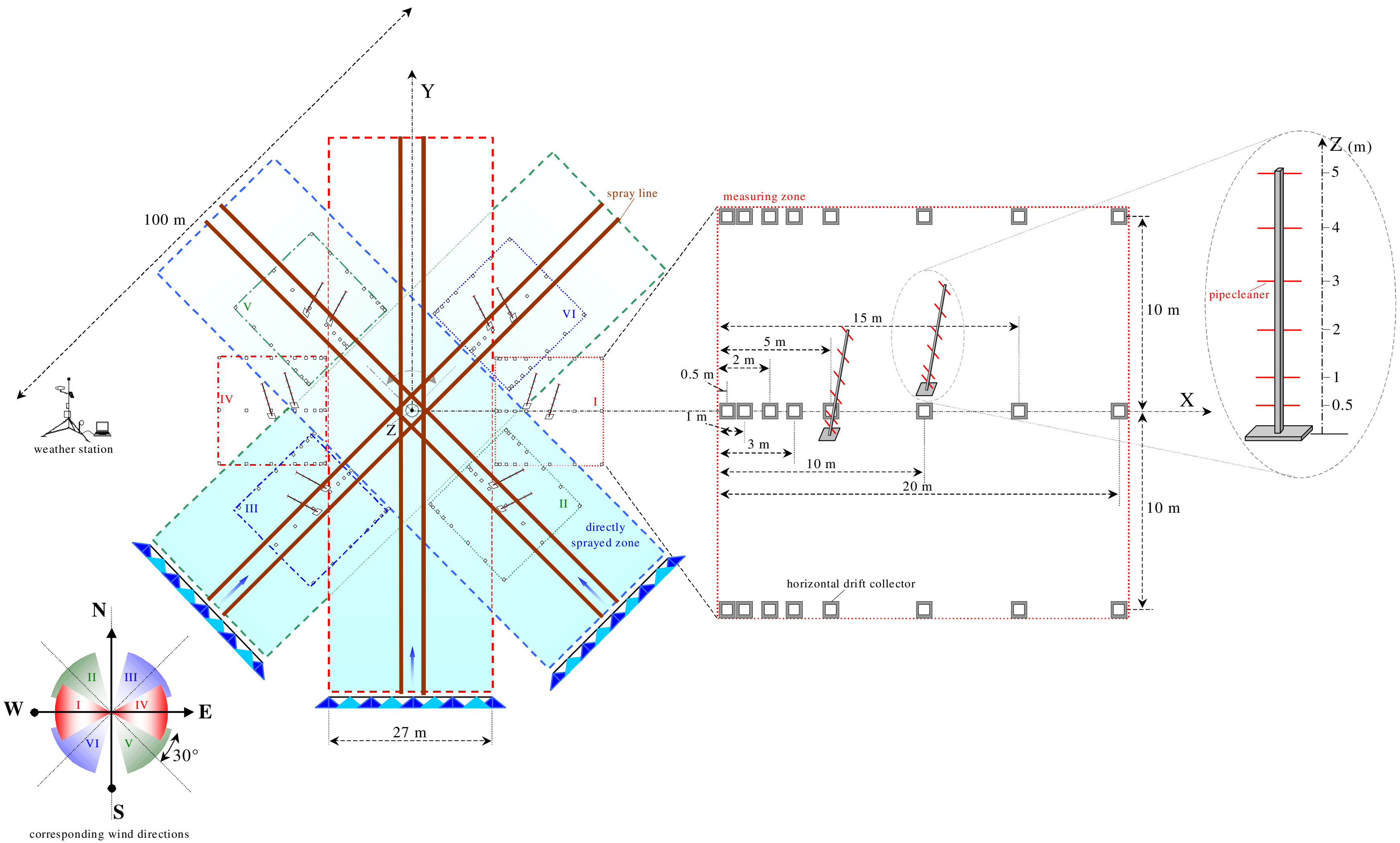

Figure 2 : Schematic overview of the experimental set-up for the field drift measurements

Meteorological measurements

Metereological 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 35° on the wind direction was allowed in the drift measurements. Based on these measurements, the following variables were calculated for each experiment:

$$\text{A.S. (°C)} = \text{Atmospheric stability} = T_{2.15m} - T_{1.25m} \quad (3)$$

$$\text{T.I.} = \text{Turbulence intensity} = \frac{v_{max} - v_{min}}{V_{avg}} \quad (4)$$

where v_{max}, v_{min}, and V_{avg} are the maximum, the minimum and the average wind speed during the drift experiment

$$T_d = \text{Dew-point temperature (°C)} = \frac{237.7 \times \log\left(\frac{10^{\frac{7.5 \times T_{avg}}{237.7+T_{avg}}} \times RH_{avg}}{100}\right)}{7.5 - \log\left(\frac{10^{\frac{7.5 \times T_{avg}}{237.7+T_{avg}}} \times RH_{avg}}{100}\right)} \quad (5)$$

where T_{avg} and RH_{avg} are the average temperature and relative humidity at the two measuring heights during the experiment.

RESULTS & DISCUSSION

Weather conditions

Table 1 shows some of the most important meteorological variables for the 12 drift trials with the reference spraying. In four cases, the deviation of the ideal driving direction exceeded 35°. Average temperature varied from 14.6 °C to 26.0 °C, average relative humidity from 58.5 % to 87.6 % and average wind speed from 1.10 m.s^{-1} to 5.72 m.s^{-1}.

Table 1: Meteorological variables with the different reference experiments

Experi-ment	$RH_{1.25m}$ (%)	$RH_{2.15m}$ (%)	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)
Ref1	66.3	61.1	63.7	23.8	23.5	23.7	2.38	3.47	2.93	56.8*	-0.33	0.51	16.4
Ref2	67.7	62.4	65.0	23.9	23.7	23.8	4.89	6.00	5.44	49.9*	-0.22	0.65	16.8
Ref3	68.2	62.5	65.3	25.2	24.8	25.0	4.10	5.21	4.66	44.0*	-0.43	0.57	18.2
Ref4	76.7	82.3	79.5	18.3	18.6	18.5	3.60	2.92	3.26	13.3	0.28	0.56	14.8
Ref5	77.3	82.6	80.0	18.2	18.5	18.4	3.20	2.57	2.89	15.4	0.24	0.39	14.8
Ref6	84.3	89.7	87.0	14.9	15.1	15.0	4.38	3.29	3.84	17.5	0.19	0.62	12.8
Ref7	84.4	78.7	81.6	16.1	15.7	15.9	2.62	3.12	2.87	32.7	-0.33	0.63	12.7
Ref8	90.2	85.0	87.6	14.9	14.6	14.7	1.09	1.11	1.10	16.3	-0.32	0.41	12.7
Ref9	86.5	81.5	84.0	15.8	15.4	15.6	1.29	1.36	1.33	49.3*	-0.37	0.47	12.9
Ref10	82.8	77.2	80.0	16.4	16.0	16.2	2.00	2.47	2.24	18.1	-0.42	0.48	12.7
Ref11	64.1	59.5	61.8	22.2	21.8	22.0	3.12	3.67	3.40	18.5	-0.40	0.65	14.3
Ref12	60.7	56.2	58.5	26.4	26.0	26.2	5.23	6.21	5.72	8.2	-0.43	0.77	17.4
Average	*75.7*	*73.2*	*74.5*	*19.7*	*19.5*	*19.6*	*3.16*	*3.45*	*3.30*	*28.3*	*-0.21*	*0.56*	*14.7*

* deviation of ideal driving direction > 35°

Drift data

The sedimenting spray drift results of the 12 reference sprayings are presented in Figure 3 together with the average drift values of these 12 reference sprayings. Note the logarithmic scale of the drift axis. The drift distances (drift dist.) are calculated by multiplying the distance of the horizontal collectors (coll. dist.: 0.5, 1, 2, 3, 5, 10, 15 & 20 m) with the cosine of deviation of the ideal driving direction δ. Each drift value is the average of the three sampling lines at a certain distance. Moreover, for reference spraying 1, the 90% confidence interval is presented on the graph. Also for the other measurements, the variation is of the same order. Hence, it is clear that there is a considerable variation in drift values between the three spraying lines probably due to spray boom movements and secondarily because of variations in wind speed, wind direction and spray line while passing the different sampling lines.

Besides the variation between the three sampling lines for each reference spraying, there is also a large variation between the different reference sprayings. For example, on the collector placed at 1 metre of the directly sprayed zone, drift deposits varied from 0.43% to 11.45%. 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.

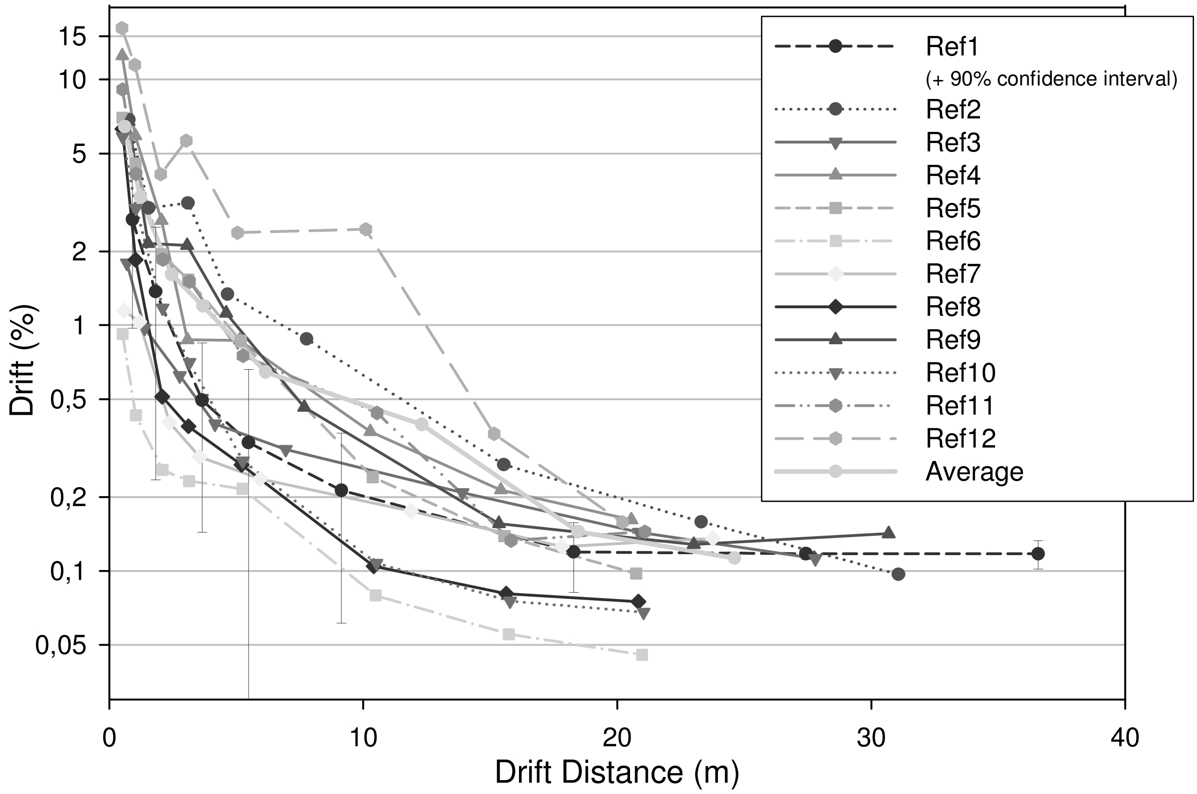

Figure 3: Drift data for the different reference sprayings (+ average)

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 drift at various distances and atmospheric conditions. That is why a regression analysis in different steps was performed on the data (using SPSS 10.0) to come to a final statistical drift prediction equation for the reference spraying. A description of the equation, some graphs and the conclusions are presented.
Measurements where the deviation of the ideal driving direction exceeded 35° (Ref. 1, 2, 3 & 9) were not used in the analysis. This resulted in an analysis based on a total of 192 drift measurements. The amount of spray drift is the dependent variable of the regression model.
As already mentioned before, 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:

$$Drift_{\%} = 3.86 \times (drift\_dist.)^{-1.04} + 0.11 \times V_{3.25m}^{2} + 0.08 \times T_{avg} - 2.77 \quad (6)$$

where drift$_{\%}$: Spray drift percentage (%);
drift_dist: Drift distance parallel with wind direction (m);
$V_{3.25m}$: Average wind speed at a height of 3.25m (m.s^{-1});
T_{avg}: Average temperature (°C).

A summary of the statistics of this non-linear regression is presented in table 2. An R^2 of 0.788 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 = 2197.82	6	MSR = 366.30
Error	SSE = 589.25	186	MSE = 3.17
Total	SSTO = 2787.08	192	

$$R^2 = 1 - \frac{SSE}{SSTO} = \frac{SSR}{SSTO} = 0.778$$

Discussion of the drift equation

With this drift equation it is possible to predict spray drift on grassland for reference sprayings under various atmospheric conditions for drift distances up to at least 20 metres by measuring wind speed, direction and temperature. This equation can also be used to compare drift measurements under different weather conditions with the reference spraying. Based on the available drift data, the model is usable for temperatures varying from about 15° C to 25 °C and wind speeds from about 1 $m.s^{-1}$ to 5 $m.s^{-1}$. For some specific climatological conditions, the results of the spray drift model for the reference spraying on a meadow are presented in Figure 4.

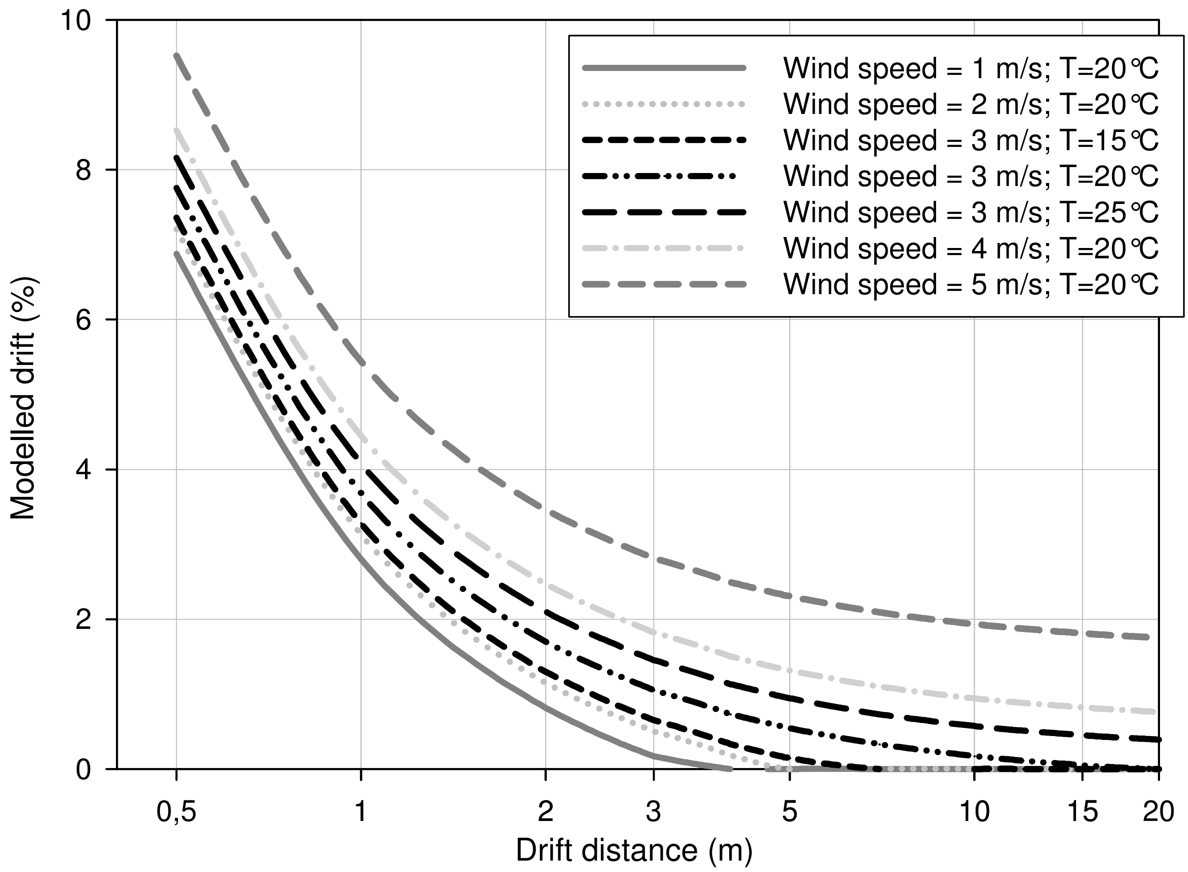

Figure 4: Drift curves for the reference spraying on a meadow under different climatological conditions

Note that for a combination of small wind speeds and large spray distances, the model may result in small negative drift values. These values may be assumed to be zero.

The most important variable in the drift equation is by far the drift distance. Logically, higher drift distances result in lower drift values (Figure 4). A non-linear regression only bringing into account the spray distance results in an R^2 of 0.685. Adding the wind speed to the model raises the R^2 to 0.782. Higher wind speeds result in higher drift values and the influence of the wind speed is more clear for higher drift distances (Figure 4).
Finally, a small improvement in the equation can be achieved by adding the temperature (R^2 = 0.788). Higher temperatures result in higher drift values (Figure 4) but the influence of the temperature is less pronounced than the influence of the wind speed. Hence, wind speed is the most important climatological parameter related to spray drift.
Because of the strong correlation (coefficient of correlation = 0.92) for these series of experiments between temperature and relative humidity, another possibility is to incorporate relative humidity instead of temperature. A higher relative humidity would result in lower drift values. Further experiments have to indicate whether this correlation between temperature and relative humidity is coincident or not.
In Figure 5, a comparison between average measured drift values and the modelled drift values, using the corresponding weather conditions, is presented. Moreover, the distances from the horizontal collectors to the spray swath are indicated. In general, the correlation between measured and predicted drift values is satisfying (R^2 = 0.68).

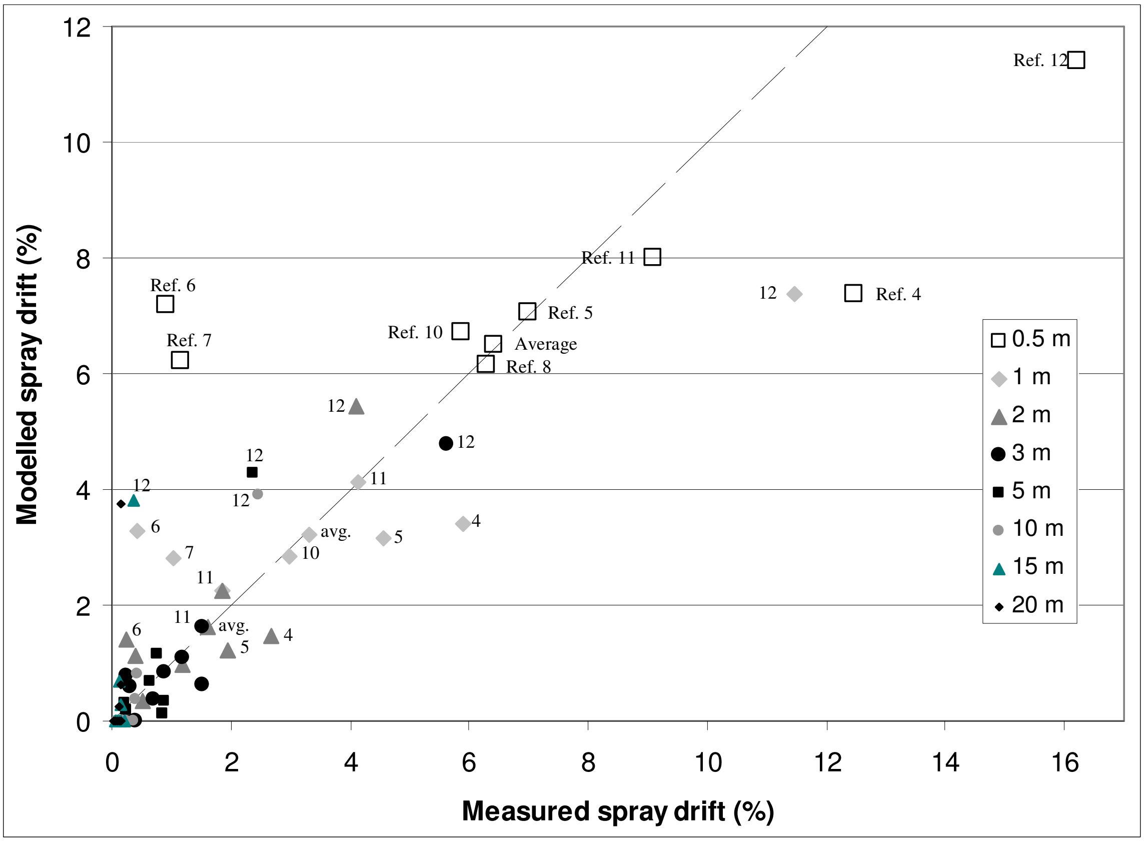

Figure 5: Comparison between average measured drift values and modelled drift values

For very small drift distances (0.5 m and 1 m), the spreading of the measured drift values is wider than the one of the modelled drift values. This is because small variations in spray line and spray boom movements, have a larger impact on these lowest drift distances. These variations are less important for larger drift distances.
In some cases, the model overestimates the amount of sedimenting spray drift. For small drift distances, this is the case for reference spraying 6, where the measured drift values were less than expected (Figure 3). The fact that the climatological related terms in the drift equation

are not related to the drift distance, results in an overestimation for large drift distances when temperature and wind speed are high (e.g. Ref. 12).
To conclude, this equation gives a good indication of the amount of sedimenting drift for reference spray applications on a flat meadow and of the influence of the weather conditions but it is clear that more measurements are necessary to refine and validate this model.

Future research

During 2005 further experiments will be carried out to validate and refine the model and to extend the model for a wider range of climatologically conditions. Besides, several drift measurements with other spraying techniques will be performed to evaluate the effect of spray boom height, nozzle type and pressure, driving speed and air support on the amount of spray drift. In total, 90 drift experiments will be carried out.

CONCLUSIONS

A reliable and feasible spray drift measuring protocol for boom sprayers is formulated and several drift experiments were successfully carried out. These measurements proved the important effect of the weather conditions on the amount of sedimenting spray drift. A drift prediction equation for a reference spraying was set up to predict the expected magnitude of sedimenting drift for various drift distances and atmospheric conditions (wind speed and temperature). Wind speed is by far the most determinative atmospheric condition considering drift.
In 2005, this equation will be used to compare measurements using different spraying techniques under different weather conditions with the reference spraying. Nozzle type as well as spray pressure, driving speed, air support and spray boom height, will be evaluated. More measurements will be performed to validate the statements and the equation reflected in this paper.

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