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AN APPROACH FOR PESTICIDE LOSS ESTIMATION ADAPTED TO FIELD CROPS IN MEDITERRANEAN CONDITIONS

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ABSTRACT During chemical crop spraying, important pesticide amounts are transferred to the environment, with negative impacts on the ecosystem, the health and the economy. Tunisian crops are sprayed in extreme conditions (high temperature and low humidity) and with low technology machines. The amounts of lost pesticides are unknown and a combined approach with laboratory experimentation and modeling has been chosen to evaluate these quantities. To evaluate drift and plant retention tests were set up i) in a wind tunnel and ii) under a mobile boom in laboratory conditions. A set of wind tunnel tests were used to develop a low complexity drift simulation model. The model is based on an advection-diffusion representation for diameter classes representing the spray. It includes evaporation simulation. Tests with the mobile boom were used to evaluate plant retention with different nozzle settings. Both wind tunnel and mobile boom tests were used in a combined approach to evaluate the amount of droplets lost in the air (volatilization). Predictions of these approaches were finally compared to field test results with two spraying setups (spraying Volume Median Diameter of 127 and 322 micrometers). These comparisons showed that the combined laboratory and modeling approach gave coherent results that could be used with few improvements to achieve a global balance of pesticide losses and provide farmers with a tool to decrease them.

Keywords: modeling, model, advection-diffusion, pesticide, sprayer, spraying, drift, runoff, pollution, ground, air, field measurements.

Introduction. Tunisia imports every year 3 750 tons of pesticide, mainly used for weed crop spraying on cereals. Sprayed amounts are high (about 5 kg/ha) and also doses (about 300 L/ha). During spraying, pesticides are lost in the environment and can be found on the ground (under the crop, or on the plot surroundings) or in the air. Quantifying these losses in the Tunisian conditions is a challenging task to improve spraying and manage operations to lower the impact to the environment.

A lot of papers relate experiments setup to evaluate these losses in field conditions but they mainly concern ground measurements. To take into account air dispersion, modeling approaches are usually chosen. But a balance approach of the total amount of lost pesticides is usually not provided (Sinfort and Vallet, 2003). In this paper, we propose a combined method with experimental and modeling approach to quantify losses during cross spraying and their variation due to external conditions. This approach was setup for Tunisian conditions but it could be generalized.

The work relies on experiments setup i) in a wind tunnel, ii) under a mobile boom and iii) in field conditions. Then, the methodology consisted in the evaluation of amounts deflected by drift by a model setup from observations in the wind tunnel. An equation was included to the model to predict evaporation. The amounts lost under the plants were analyzed by measurements under the mobile boom. Finally, the results of both methods were compared with results collated during two field test campaigns.

1. Material and methods

1.1. Measuring pesticide losses. Several methods can be found in the literature for the measurements of pesticide deposits. They rely either on the direct measurement of the used pesticides or in the use of a tracer. The first solution is not usually elected because of the danger of the pesticide and the cost of the analysis which is usually made through GC/MS. On the contrary tracer or dyes are commonly used. Some of them are analyzed by colorimetry. For instance, Salyani and Whitney used colorimetry for copper detection on leaves, and Gaskin et al. (2005) or Forster et al. (2005) used tartrazine, an alimentary dye, to measure deposits on plants. An other possibility concerns the use of metallic tracer analyzed with mass spectrometry as in Cross and al. (2001a, b, 2003) who tested Zinc, Manganese, Strontium and Copper. Fluorescent tracers were more and more elected in the last years because of their very low level of detection. First uses were related by Speelman (1971) and Barry (1978). The weakness of these tracers are their sensibility to the light. Cai and Stark (1997) tested several fluorescent dyes and concluded that Brillant Sulfo Flavine (BSF) had the better performance. This dye was then used by several authors (see for instance, Holterman et al., 1997, Herbst and Molnar, 2002, Gil and Sinfort, 2005). It was selected for this study and used with a concentration of 1g.L^{-1}.

It was then important to select the collectors to trap the sprayed droplets in the air, on the ground and on the plants. For the air, PVC lines of 2mm diameter were used. These collectors were tested by Gil et al. 2007 and he evaluated their performance (or collection efficiency), theoretically and by experiences in a wind tunnel, at 80%. For ground measurements, these PVC lines could not be used because the amounts of collected liquid were too much important and several other collectors were tested. Small plastic carpets sizing 20cm x 30cm were finally selected. Their efficiency was measured by comparing the amounts collected on the carpets to the amounts measured on the same width on a patternator: it was also about 80%. To measure the amounts of deposits on weeds, the method was to cut the entire plant which acted then as a collector. To represent weeds, wheat seedings were cropped in 20cm x 30 cm boxes and used at the 4-5 leaves stage. Their efficiency was of 85%. All these collectors are shown in Figure 1.

After spraying, fluorescent dye was recovered by washing the collectors with a given amount of water at neutral pH (500mL for weeds and carpets, 200 mL for PVC lines) and the concentration was later determined by fluorimetry. The emission and excitation values for BSF used in fluorescence determination were 500 and 455 nm, respectively.

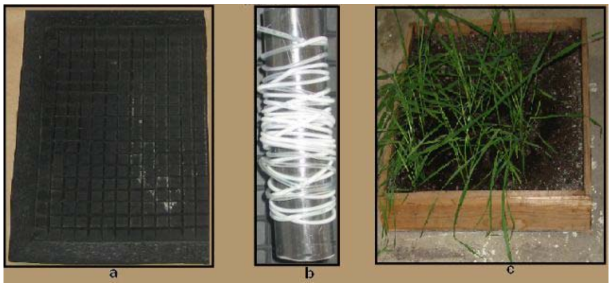

Figure 1. Collectors selected for droplet trapping : a) on the ground b) in the air c) on plants.

1.2. Evaluation of drift. Quantities that can be lost by drift were measured by several authors. For crop weeding, they mainly depend on the distance between the nozzles and the ground and on external conditions. They can exceed 30% of the sprayed amount (Southcombe et al., 1997). An important effort was produced by the scientific community to provide modeling tools for drift simulations. Reviews of the main models are presented in Unsworth et al. (1999) and Gil and Sinfort (2005). In Europe, the legal reference is a statistical model developed from a huge amount of observed data for any kind of crops (Ganzelmeier et al., 1995). This model produces drift distances computed for the 50th or the 90th percentiles of the observed data, in any conditions. Some other models are based on the computation of droplet trajectories (Walklate, 1992, Reichard et al., 1992, Holterman et al., 1997, Teske et al., 2001). These models are obtained from the equation of force balance onto the drops. They usually take into account the turbulence of the air through several ways, more or less detailed, and can include evaporation modeling. Other models are based on the representation of the behavior of the emitted cloud of droplets using an advection-diffusion representation (De-Leeuw et al., 2000, Raupach et al., 2001, Teske et al., 2001, Craig, 2004). Usually, these models suppose that wind velocity and turbulent diffusion are invariant in time and space. The advection-diffusion equation can then be integrated in a gaussian function.

For this study, we developed a model based on an advection-diffusion approach, applied to the droplet population, giving then a sum of gaussian functions that fits correctly the observations in a wind tunnel. The interest of such development by Baetens *et al.* (2009). The droplet population was described with 100 diameter classes. The model was parameterized with two factors. The first one, b, is a velocity factor allowing to compute the initial velocity of the droplets, V_0, through the relation :

$$V_0 = -b\sqrt{\frac{2 \times P}{\rho_l}}$$

where P is the pressure on the nozzles and ρ_l is the density of the sprayed product. For the computation V_0 was supposed vertical.

The second one, D, allows to compute the standard deviation of the gaussian laws, σ_d, by the relation :

$$\sigma_d{}^2 = D \times t_d$$

where t_d is the time elapsed from the ejection of the droplet.

These two factors were computed from observations in a wind tunnel equiped with a patternator with 3 flat fan nozzles (gauge 02, 03 and 06) plus an air-injection one (gauge 03), 2 ejection heights (50 and 80cm), 2 pressures (2 and 4 bars) and 2 wind velocities (0.56 and 1.94 m/s). Relative humidity was 100% thus no evaporation could take place (sprayed material was pure water). b was shown to depend only on the nozzle and D depends on the nozzle and on the ejection height. Mean square errors observed between simulated and measured distributions vary between 7 and 10%.

The evaporation model proposed by Holterman (2003) was included. This model computes the evolution of the droplet diameter, *d(t)*, under the hypothesis that the evaporation rate is constant. The expression is:

$$d(t)^2 = d_0{}^2 - q_0\left(1 + q_1 d(t)\right)\Delta T_v t$$

where d_0 is the initial diameter, ΔT_v is the wet bulb depression and q_0 and q_1 are two coefficients depending on the properties of the evaporating material.

The model is then able to compute i) the distribution on the ground ii) the amount of evaporated material and iii) the amount of material entrained in the air beyond a given distance from the sprayed area.

1.3. Deposits under the plants. To evaluate the deposits on the ground under the weeds, a mobile boom was built as shown in Figure 2. The boom can be moved along 6m rails with velocity varying between 3 to 10 km/h. Boom height and feed pressure can be adapted .

Figure 2. Mobile boom built to measure deposit under the weeds.

To compute losses on the ground, measurements were made on plants grown on a 20x30cm² box (cf. Fig.1a) and on a plastic carpet of same size (cf. Fig.1c). Losses were then obtained by difference of the amounts obtained on both collectors.

Measurements were made for the configurations already described in the previous chapter for the fitting of the drift model (4 nozzles x 2 pressures x 2 ejection height) and for two driving velocities: 0.56 m/s (4 km/h) and 1.94 m/s (7 km/h). The choice of this setting of values was suited to use full factorial designs (Jiju, 2003) and obtain a way to compute ground losses with a linear combination of the variables. All tests were repeated three times.

1.4. Field test measurements. Two test series were setup in October 2006 and 2007. In both cases, two configurations were tested : one with small droplets (VMD 127 µm, obtained with gauge 02 at 4 bars) and the other with bigger ones (VMD 322 µm, obtained with gauge 06 at 2 bars). Nozzles were mounted with 0.5m spacing on a 12m boom setup at 0.5m from the ground. Driving velocity was 7 km/h. Each measurement was repeated 10 times. Meteorological conditions were measured on the border on the plot. They are resumed in Table 1.

Table 1. Meteorological conditions observed during the tests.

Campaign	2006		2007	
VMD (µm)	127	322	127	322
Wind velocity (m/s)	4.1	2.1	1.8	4.6
Temperature (°C)	32	30	29	24.5
Relative Humidity (%)	54	55	46	50.5

Deposits deported by the wind were measured on the ground on collectors placed 1, 3, 6 and 10m from the boom tip. Deposits were also measured in the riding axis, both on plastic carpets and on plants. Quantities escaped in the air beyond 5m from the boom were captured on 2.85m long PVC lines tightened horizontally at 0.5, 1 and 1.5 m above the ground.

2. Results.

2.1. Drift deposits. Figure 3 shows the estimated distribution in two extreme cases observable in Tunisian conditions, 'D+' and 'D-'.

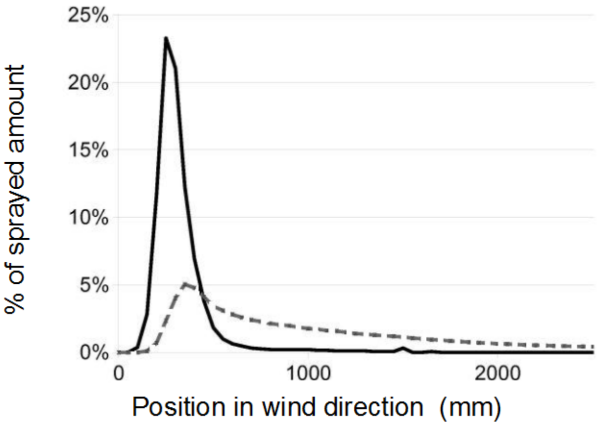

Figure 3. Deposits observed and simulated in the extreme cases. So line: D- conditions ; Dashed line: D+ conditions

D+ stands for conditions enhancing drift: VMD was 127 µm, boom height was 0.8m and wind speed was 7 km/h. D- stands for opposite conditions: VMD was 322 µm, boom height 0,5m and wind speed, 4 km/h. In D+ conditions, the amount of product under the nozzle is lowered 5 times when compared with D- ones. It was also observed that the deposits became lower than 1% at 0,8m in D- conditions and 2,5m in D+ conditions.

2.2. Deposits under the plants Deposits measured on the plastic carpets and on the plants under the mobile boom are shown in Table 2.

Table 2. Deposits measured on the ground (plastic carpets) and on the plants under the mobile boom: mean of three tests. FF: Flat Fan nozzle; AI: Air Injection nozzle.

Nozzle	Pressure (bars)	VMD (µm)	Boom velocity (km/h)	Boom height (m)	Deposits (%)	
					Ground	Plants
FF 02	4	127	4	0.5	75	14
				0.8	76	13
			7	0.5	59	29
				0.8	46	28
	2	144	4	0.5	79	11
				0.8	78	11
			7	0.5	67	22
				0.8	65	20
FF 03	4	162	4	0.5	82	11
				0.8	80	12
			7	0.5	71	21
				0.8	66	20
	2	210	4	0.5	86	9
				0.8	83	13
			7	0.5	76	18
				0.8	76	15
FF 06	4	234	4	0.5	89	7
				0.8	88	8
			7	0.5	86	9
				0.8	84	8
	2	322	4	0.5	92	5
				0.8	91	5
			7	0.5	92	5
				0.8	90	5
AI 03	4	438	4	0.5	78	20
				0.8	78	17
			7	0.5	61	32
				0.8	60	30
	2	641	4	0.5	80	18
				0.8	80	16
			7	0.5	72	25
				0.8	70	23

The deposits on the carpets are between 46 and 92% while plant deposits are between 5 and 32%. For the flat fan nozzles, the results are compliant to the usual observations: deposits on the ground are higher for higher VMD’s. They are also higher when the boom and the ride velocity are the lowest. The opposite tendencies are observed for plant deposits. For the air injection nozzle, deposits on the plants are rather high: about the same amounts and even higher than with flat fan nozzles with low VMD's.

Losses under plants can be obtained by subtracting the amounts collected on the carpets and on the plants. Obviously, the lowest value (18%) is observed when plant retention is maximum (lowest VMD, higher boom and velocity). In the worse case, losses under the plants are of 82%. They are obtained with the FF06 nozzle at 2 bar (highest VMD) with the boom at 0.5m height and with both velocities.

Application of full factorial design method gave the following expressions:

$$M_{ground}=2{,}33+1{,}17C_n+0{,}19C_p-0{,}62C_v+0{,}14C_h+0{,}12C_nCp-0{,}29C_nC_v-0{,}1C_nC_v-0{,}13C_pC_h$$

$$M_{plants}=0{,}23-0{,}026C_n+0{,}061C_p-0{,}028C_v-0{,}037C_h$$

Where M_{ground} and M_{plants} stand for the mass of sprayed material (in mg) on the carpets and on the plants. C_n, C_p, C_v, C_h are coefficients called "levels" varying continuously with the factors n (nozzle gauge), p (operating pressure), v (velocity) and h (boom height). They worth –1 for the lowest values of the factors (respectively 02, 2 bar, 4 km/h and 0.5m) and +1 for their highest values (06, 4 bar, 7 km/h and 0.8m).

2.3. Comparison with field measurements Table 1 shows comparisons of amounts obtained during the field campaigns with predicted values either by experimental data with the mobile boom (amounts on ground under plants) or by the model. Evaporation was not measured during field tests. The sum of obtained value was also computed.

Table 3. Comparison of field data with evaluated ones with the same conditions.

	Plants		**Ground under plants**		**Drift (deport on a 10m swath)**		**Air losses beyond 5m**		**Evaporation**		**Total**	
	Eval*	Field	Eval*	Field	Eval.	Field	Eval.	Field	Eval.	Field	Eval.	Field
2006 VMD127	29	8	30	51	18.5	36	8	12	1	-	86.5	107
2006 VMD 322	5	4	87	82	0.8	1.3	2	2	0	-	94.8	89.3
2007 VMD 127	29	12	30	40	1.7	21	7	8	1	-	68.7	81
2007 VMD 322	5	4	87	85	2.6	0.4	2	2	0	-	96.6	91.4

* Values evaluated with velocity=1.94m/s

For evaluated deposits on the plants and under the plants, the expressions obtained with full factorial design were not applicable because the wind velocity measured on the field (up to 4.6 m/s) was over the range of tested values (0.56 – 1.94 m/s). Evaluated values given in table 3 were those obtained with 1.94m/s. Evaluated and field values are very similar for VMD 322 (D-) but not for VMD 127 (D+) even if tendencies are correct (increasing deposits on plants and lowering losses on the ground).

Amounts deported by drift are quite different. The worse difference was observed for 2007 test with D+ conditions (low VMD, low wind). Nevertheless amount lost in the air beyond 5m were much more comparable. Evaporation was only observed for the low VMD and did not exceed 1%.

Total values are comprised between roundly 70% and 100%. Lower values are observed for the D+ condition in 2007 (1.94m/s wind), both for estimated and observed data.

Discussion Some methodological points must be discussed in relation with this work. Concerning the evaluation of deposits on the plants and under the plants, the experimental method gives a good prediction of field observations. The use of full factorial design could provide a very efficient method, supposing that one could estimate the deposits through a linear combination of the variables or their interactions. In our approach, we supposed that the wind effect was comparable to the relative wind due to boom velocity. The mobile boom was not able to exceed 2 m/s and the method was then not usable to predict deposits for the higher velocities, observed in field conditions. In a next step, the mobile boom will be included within a wind tunnel to cope with this limitation. Added to this, it will be necessary to check the validity of the model for one or more central points.

The prevision of deposits with the advection-diffusion model correctly fitted the measurements in the wind tunnel but in some cases, they were unable to predict the amounts measured in field conditions. One reason comes probably from the hypothesis that the ejection velocity of droplets is vertical. Wind tunnel evaluation are correct because the nozzles were setup perpendicular to the wind and the cone angle is flat thus the hypothesis was correct. In field conditions, the wind was parallel to the bigger axis of the nozzles and it could be a reason why the predictions of the model are not good, mainly for low VMD and low wind. Another reason can be the validity of the experimental field data. First, sampling is maybe not enough accurate near the boom, where the collected amounts vary rapidly. Secondly, although 10 repetitions were run, important fluctuations in wind velocity were also observed and the coefficient of variations of measures on the drift area could be up to 80%.

The total amounts are never equal to 100% but are not so far. For the evaluated data, the difference is higher for low VDM and it comes certainly from the under-estimation of drift deposits. For field data, totals can be higher or lower than 100% and the same remarks than previously can be arisen about the methodology.

Conclusion The paper presents a methodology set-up to evaluate the becoming of the pesticides for weed spraying in cereal crops in Tunisian conditions. Deposits on plants and under the ground are evaluated through an experimental approach with a mobile boom. Interpretation through full factorial design was proposed. Drift deposits, losses in the air and evaporation were obtained through the development of a model based on an advection-diffusion representation applied on diameter classes representing droplet population within the spray and including an evaporating model.

Both methods give an estimation of the pesticide balance in plant, ground (under plants and near the plot) and air, during spraying operations. In the worse case, observed with high VMD (322 μm), only 5% of product is collected on the plants. Losses to the ground were then about

80% and other losses were rather low (about 5% in total). For low VMD's, evaluated values can differ from observed data in field, probably due to abusive simplifications of the model considering ejection velocity. Nevertheless, amounts on the plants never exceed 30%, drift deposits are around 20-30% and losses to the air are about 10%.

Considering that spraying setup is always a compromise between efficiency for the plant and environmental losses, the approach proposed here, even if it needs to be improved for some aspects offer the possibility to select the best conditions in a given configuration including sensibility of the area near the plot and meteorological conditions.

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