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Modelling spray drift from boom sprayers

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Abstract

A random-walk model, IDEFICS, is described to compute downwind spray drift from conventional boom sprayers in chemical crop protection. Spray deposits are computed downwind from the sprayed crop field. The model basically is two-dimensional (2D), but close to the spray nozzle the model is 3D, incorporating driving speed and entrained air-currents below the nozzle. Input parameters are related to the geometry of the field, to the boom sprayer settings and to environmental factors. The model was calibrated with a set of field trials using an experimental single-nozzle sprayer in a cross wind. In the trials, tap water containing a fluorescent dye was used as the spraying liquid, and downwind deposits were measured by fluorimetry. Variations of boom height, spray nozzle size, driving speed and liquid pressure were examined, at varying wind speeds. Both experiments and simulations showed that boom height, wind speed and nozzle size were the major factors affecting spray drift. Surprisingly, liquid pressure did not affect downwind spray deposits at all. A comparison between model results and results of a practical field trial showed a good agreement if field trials were averaged over several replications. The variation between individual replications is however too large to use single trials for model verification. Further calibration trials are needed to investigate the effect on drift of multi-nozzle arrangements, crop height and medium- and coarse-sized spray nozzles. © 1997 Elsevier Science B.V.

Keywords: Spray drift; Computer simulation; Crop protection

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1. Introduction

Agricultural production in the Netherlands has reached a high level. To maintain this level chemical crop protection is still inevitable. However, unlimited use of chemicals may severely damage the environment. In the Multi-Year Crop Protection Plan (Ministry of Agriculture, 1991) the Dutch government, in co-operation with the farmers' board, plans to restrict the use of chemicals in crop protection. The three major goals are:

reduction of dependence on pesticides;

reduction of the amount of pesticides used;

reduction of emission and drift of pesticides.

Especially spray deposits onto surface water surrounding the sprayed field has gained much attention. Reduction of the amount of chemicals used as well as reduction of spray drift may be achieved by improved and new application techniques.

Investigating spray drift from boom sprayers by field studies is a cumbersome job. The large number of articles on this subject during several decades shows that clear quantitative results are very hard to obtain. Inevitable variation of too many parameters at the same time may obscure an unambiguous interpretation of those results. Using computer simulation to investigate spray drift may help to clarify some of the problems, since all parameters can be changed freely.

Models to simulate drift can be divided roughly into plume models and random-walk models. The former type of model is preferred to describe drift of pesticides over long distances (Bache and Sayer, 1975; Reid and Crabbe, 1980; Oeseburg and Van Leeuwen, 1984), although recently also for short-range drift good results have been obtained (Kaul et al., 1996). However, it still is difficult to describe short-range drift by plume models, mainly because of the problems to account for near-nozzle features of the spray cloud (including mathematical singularity at the nozzle outlet) as well as sedimentation of evaporating droplets. Complementarily, random-walk models are more suitable to describe short-range spray drift rather than long-range drift.

Several drift simulation programs have been developed the last few decades (Williamson and Threadgill, 1974; Hall, 1975; Thompson and Ley, 1983; Miller and Hadfield, 1989; Reichard et al., 1992) Some have been restricted to specific circumstances such as wind tunnel experiments (Williamson and Threadgill, 1974) or single-drop simulations leaving out typical nozzle features (Williamson and Threadgill, 1974; Reichard et al., 1992). Sometimes the authors were aware of the descriptive problems near the nozzle but could not handle them properly and the trajectory calculations were started at some rather undefined 'release height' (Thompson and Ley, 1983).

The existence of entrained air in the spray below the nozzle has been known for some time (Briffa and Dombrowski, 1966), but until recently (Miller and Hadfield, 1989) never accounted for in drift simulation. Entrained air affects the initial trajectories of the smaller spray drops, and can be considered as an important 'natural' drift-reducing phenomenon.

The useful model described by Hobson et al. (1993), which is a modification of the model by Miller and Hadfield (1989), considers airborne drift from a field of infinite size. Downwind deposits onto the ground outside the crop field are not considered. Their modelling of entrainment, however, still was rather simple, but was much improved recently (Smith and Miller, 1994). These authors also validated their model with wind tunnel experiments.

The considerations given above increased the need for a validated drift model that would predict ground deposits downwind from the sprayed field and that would be complementary to field experiments and able to simulate practical spray applications. In this study the computer program IDEFICS (IMAG program for drift evaluation from field sprayers by computer simulation) to predict downwind spray deposits from conventional boom sprayers is described. Both the mathematical structure and the experimental verification are included.

2. Model description

2.1. Conceptual model

The IDEFICS-model is a mixed 2-/3-dimensional (2D/3D) random-walk model to describe the trajectories of drops produced by a single nozzle (see Fig. 1). The downwind distribution of deposited drops in a cross wind is computed. The accumulated pesticide deposits on the crop and the soil are recorded as a function of downwind distance. The vertical distribution of droplets still airborne at a certain distance is calculated as well. Optionally the model can be provided with a ditch parallel to the crop boundary.

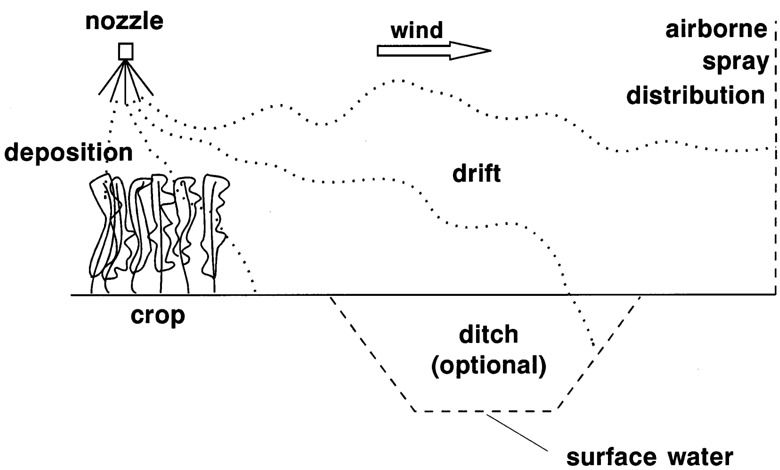

Fig. 1. Typical field lay-out for the simulation model.

Each drop leaves the nozzle at a constant speed, calculated from liquid pressure and corrected for pressure loss in the nozzle. The initial direction of a drop is chosen from the angular distribution of the flow rate across the spray cone just below the nozzle. The droplet trajectory is computed from the equations of motion (Newton's second law of mechanics). The forces experienced by the droplet are the gravitational force and the drag force due to air resistance. Whereas computation of the former is straightforward, the latter changes continuously. The drag force depends on the droplet velocity and the local air velocity. Both velocities will change continuously in magnitude as well as in direction.

Below the nozzle the friction between the spray droplets and the air results in an entrained airflow directed downward (Briffa and Dombrowski, 1966). Entrainment velocity is highest at the axis of the spray cone, showing an exponential decay with distance below the nozzle. In a plane perpendicular to the cone axis, entrainment velocity decreases with increasing distance to the axis and is angled outward. The entrainment velocity profile is affected by wind speed, driving speed of the sprayer, and the vicinity of the ground. It is assumed that wind and driving speed merely cause the entrainment airflow to shift sideward (in the direction of the local horizontal airflow), neglecting any deflections. To account for the vicinity of the ground, which obviously must be impenetrable to airflow, an imaginary nozzle spraying upward is assumed subsoil, and its imaginary entrainment velocity profile is added to the profile of the real nozzle. This 'image-concept' results in a horizontal plane, half the way between the two nozzles, with horizontal airflow only.

As long as the drop trajectory is influenced by entrainment or driving speed, the model calculations are 3D. At a certain distance from the nozzle only cross wind remains. In that case the component parallel to the travelling direction is no longer relevant, therefore the model calculations can be turned into 2D.

Above the crop canopy and bare soil the average wind speed is assumed logarithmic with height (Hartley and Graham-Bryce, 1980). Air turbulence depends on average wind speed and atmospheric stability and is introduced as an air velocity vector, with random direction and its length representing its intensity, added to the average wind velocity. Within the crop canopy the wind profile has to be adjusted (Hartley and Graham-Bryce, 1980).

Along its path from nozzle to crop or soil the droplet diameter decreases gradually due to evaporation of water contained in the droplet. According to the 'solid core' phenomenon (Elliott and Wilson, 1983), which assumes that all suspended materials gather in the drop centre, evaporation takes place as if the drop merely contains water. After complete evaporation of the water content the remaining dry particle (which usually will be extremely small) is considered to stay airborne.

As the model computes spray drift from just one nozzle at a time, drift from a whole boom sprayer can be obtained by summing the drift computed separately for a representative set of nozzles along the sprayer boom.

2.2. Mathematical structure

The essential mathematical processes of the IDEFICS drift model are shown in Fig. 2(a). As usual, most blocks are concerned with data input, data output and interactive processes. The actual trajectory computations take place in the block marked with an asterisk (*). This block is shown in detail in Fig. 2(b). As can be seen from this scheme the stepwise trajectory calculations will go on until: (1) the drop passes the vertical downwind boundary; (2) the drop deposits onto crop or ground; (3) the drop has evaporated completely; or (4) the number of iterations has reached a certain maximum. The last option was added to prevent infinite loops. Since option (4) clearly does not present a physical phenomenon, break-off due to this option must not occur too often.

The block 'compute time interval' in Fig. 2(b) deals with the estimation of the optimal length of the time step. This estimate depends on the rate of change of drop velocity relative to surrounding air, and the rate of change of drop size due to evaporation. In case of high rates of change the time step must be short, whereas in case of low rates of change it is possible to allow a larger time step (see below).

By subsequent integration of Newton's second law ($F = ma$) the drop velocity $\vec{v}$ and its position $\vec{x}$ are obtained respectively. Provided that the forces acting upon the drop can be considered constant during time interval Δt, velocity and position at time $i+1$ are given by:

$$\vec{v}_{i+1} = \vec{v}_i \alpha_i + \vec{v}_{s,i}(1 - \alpha_i)$$
$$\vec{x}_{i+1} = \vec{x}_i + \vec{v}_i \Delta t + \tau_i(\vec{v}_{s,i} - \vec{v}_i)(\alpha_i - 1 + \beta_i) \tag{1}$$

where $\vec{v}_{s,i}$ is the sedimentation velocity of the drop (i.e. the velocity of the drop when all forces balance), β_i is defined by $\Delta t/\tau_i$, with τ_i the relaxation time of the drop, and α_i is defined by $\exp(-\beta_i)$. All quantities are time dependent and therefore are suffixed i, which will be omitted from now on for clarity. The equations given above are similar to those given by Thompson and Ley (1983), however, essentially they are quite different (see Section 4).

The relaxation time τ represents the characteristic time a drop needs to adapt to the local air flow, and equals the ratio of drop mass and air friction coefficient (the latter being the ratio of drag force and velocity v_r relative to the surrounding air). For a drop with diameter D and velocity v_r relative to the surrounding air the relaxation time can be written as

$$\tau = \frac{4\rho_s D}{3\rho_a v_r C_d} \tag{2}$$

In this equation ρ_s and ρ_a are the mass densities of the spray drop and air, respectively, and C_d is the drag coefficient. The drag coefficient is very well described by the relation

$$C_d = \left(\left(\frac{a}{\mathrm{Re}}\right)^c + b^c\right)^{1/c} \tag{3}$$

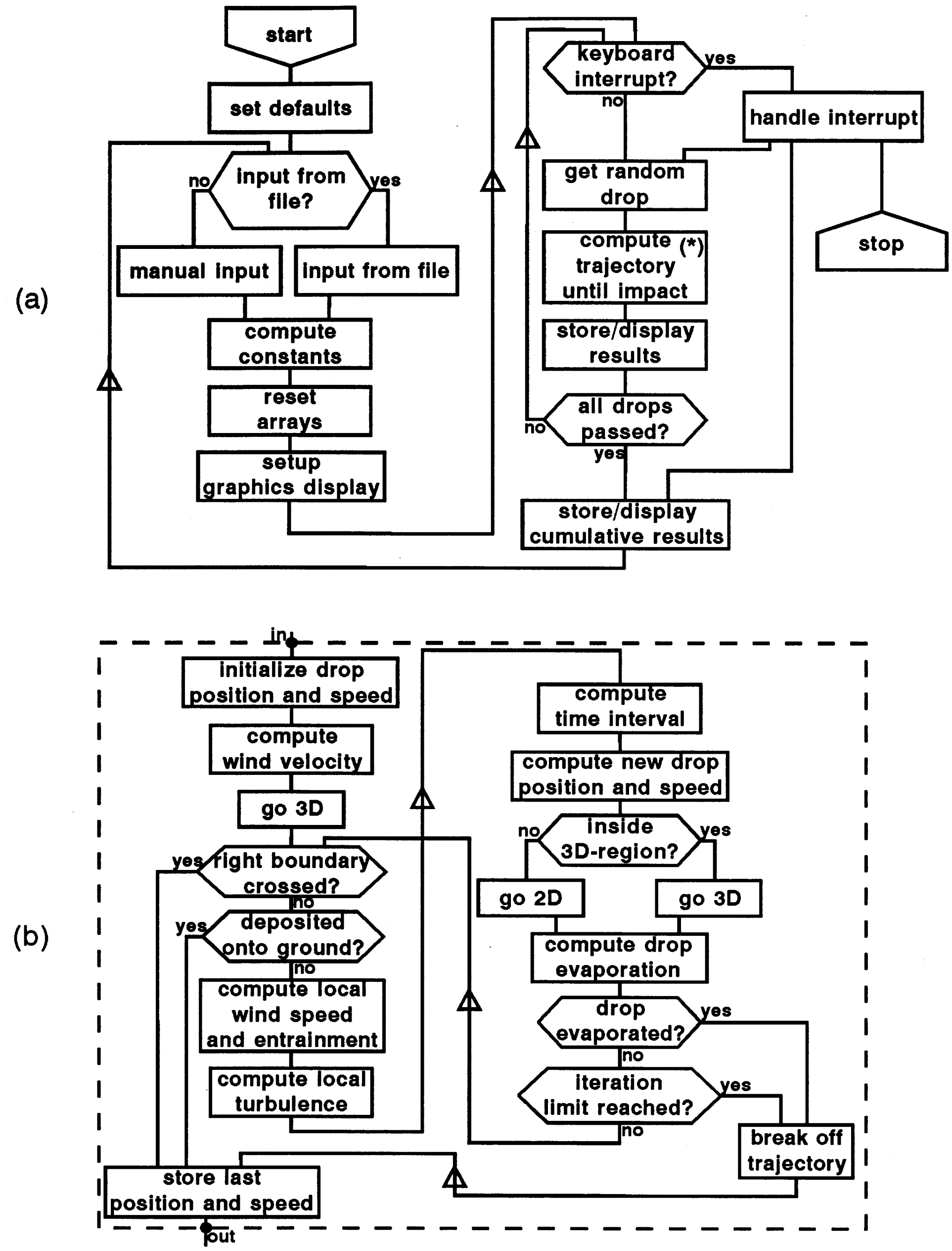

Fig. 2. Flow scheme of the IDEFICS drift model (a). The actual trajectory computations take place in the block marked with an asterisk (∗). The structure of this block is shown in detail in (b).

where Re is Reynolds' number, and with the empirical constants $a = 24$, $b = 0.32$ and $c = 0.52$. This relation fits very close to experimental drag coefficients of solid spheres (Eck, 1961) for Reynolds' numbers up to 10^4, which is far beyond Reynolds' numbers occurring in all types of ground applications.

The sedimentation velocity $\vec{v}_s$ depends on gravitation and wind velocity:

$$\vec{v}_s = \tau\vec{g} + \vec{u} \quad (4)$$

where the first term represents the vertical settling velocity due to gravitation and the second term the local wind speed. The latter comprises average wind speed and local air turbulence.The suffix i with $\vec{v}_{s,i}$ and τ_i (and subsequently with α_i and β_i) reflects that these quantities may change continuously but must be considered constant during interval Δt. This is only acceptable as long as they do not change 'too much' during Δt, or more precisely, time interval Δt should be short enough to sufficiently limit their changes. It can be shown that in all practical cases the relative change of τ limits Δt much more than that of $\vec{v}_s$ does. By taking the time derivative of Eq. (2) the relative change $|\Delta\tau/\tau|$ (i.e. its absolute value) during Δt can be obtained, which is a function of Δt. Inversely, this relation limits Δt if $|\Delta\tau/\tau|$ is not allowed to exceed a preset value (between 0 and 1).

To prevent the steps along the trajectory becoming too large or too small, it is convenient to restrict the possible values of the time step. The higher limit can be set manually, but should be chosen in accordance with the intended spatial resolution of the ground deposits.

The lower limit is set by the approximate time for a drop to pass the liquid sheet just below the nozzle outlet:

$$\Delta t_{\mathrm{min}} = \frac{z_{\mathrm{sh}}}{v_0} \quad (5)$$

where z_{sh} is the length of the liquid sheet and v_0 is the initial drop velocity at the nozzle outlet.

In the region where entrained air is present (entrainment region) the higher limit usually is too large, due to the fact that the gradient of $\vec{v}_s$ locally is too large to be neglected. Therefore, in the entrainment region the time step is not allowed to exceed the time needed to fall 1/10th of the nozzle height above the ground:

$$\Delta t_{\mathrm{e,max}} = \frac{0.1h_0}{|\vec{v}|} \quad (6)$$

where h_0 is the nozzle height and $|\vec{v}|$ is the local velocity of the drop.

To overcome occasional problems just after a drop has left the nozzle, the first few time steps of each drop are set equal to the lower limit Δt_{min}.

2.3. Essential parameters

A large number of physical parameters are involved. These parameters are divided into three categories (the essential parameters added between brackets):

(a) field related parameters (crop height, geometry of the ditch);

(b) sprayer related parameters (nozzle height above crop, distance of nozzle to edge of crop, droplet size spectrum and top angle of the nozzle, liquid pressure, entrainment, forward speed of the sprayer, concentration of active ingredients);

(c) atmospheric parameters (average wind speed, air turbulence and stability, relative humidity, temperature).

2.4. Field related parameters

With respect to the crop, it is assumed that its height is the only parameter in the model. Other parameters, such as crop density or structure of the foliage are neglected. It seems obvious that density and structure of the crop have little effect on drift, since drifting drops will hardly ever experience the vicinity of the crop. Strictly speaking, the logarithmic wind profile above the canopy (see below) may be affected by crop structure, but a significant effect on spray drift is not likely. In the model, small droplets are allowed to penetrate the canopy to a depth depending on their momentary diameter, before settlement on the crop occurs. Theoretically, this gives small droplets the opportunity to leave the canopy by turbulence at the top or, more important to drift, at the downwind edge of the crop. However, since only few droplets will act like this, their contribution to downwind deposits will be rather small.

Downwind from the crop a field of cut grass (height 0.05 m) is assumed. The optional ditch is symmetrical, with adjustable depth, width and slope. The width of the free zone between crop and ditch is adjustable also.

2.5. Sprayer related parameters

The position of the nozzle (height above the crop, distance to the edge of the crop) is a major parameter affecting the amount of drift. Boom movements are not accounted for in the model.

Nozzle type and liquid pressure determine the drop size distribution, the top angle of the spray cone and the initial velocity of drops just below the nozzle. The model only deals with hydraulic flat fan nozzles, which are common practice in field spraying in the Netherlands. Drop size distribution, initial velocity and angular liquid distribution were measured using laser-interferometry (phase-Doppler particle analyzer (PDPA), Aerometrics).

The velocity vector of small drops at various positions in a stationary spray cloud below a nozzle was determined with the PDPA system. These data were used to determine the entrainment velocity distribution below the nozzle. Close to the nozzle outlet the measured velocities had to be corrected for inertia of the drops, which caused the entrainment velocity to be significantly lower than the average velocity of the small drops.

At the axis of the spray cone, the relation of Briffa and Dombrowski (1966) can describe the velocity of the entrained air very well:

$$u_{\mathrm{e,ax}}(h) = v_0\left(\frac{z_{\mathrm{sh}}}{h}\right)^{K_{\mathrm{e}}} \tag{7}$$

where h is the distance below the nozzle outlet and K_{e} is a constant. It appeared for various flat fan nozzles at different pressures that K_{e} was approximately equal to 0.7.

In a plane perpendicular to the axis of the spray cone, and at a distance h below the nozzle, the velocity (amplitude) of entrained air is modelled by

$$u_{\mathrm{e}}(p,q,h) = u_{\mathrm{e,ax}}\frac{1}{4}\left(\cos\left(\frac{\pi p}{f_h\, p_0}\right)+1\right)\left(\cos\left(\frac{\pi q}{f_h q_0}\right)+1\right) \tag{8}$$

where p and q represent the two orthogonal distances from the axis (respectively parallel and perpendicular to the flat fan spray cone), and p_0 and q_0 represent the theoretical outer limits of the spray cone and are proportional to h, depending on top angle and 'lateral' top angle. The constant f_h is an extension factor for entrained air outside the actual spray cone, and empirically set between 1.2 and 1.8, depending on nozzle height above the ground and based on patternator experiments.

It is assumed that the lateral top angle of the spray cone is small enough to neglect the component of the entrainment velocity in the q-direction. The components in h- and p-direction (respectively, downward and sideward, in the plane of the flat fan) are assumed to be related with the relative position in the spray cone:

$$\frac{u_{\mathrm{e},p}}{u_{\mathrm{e},h}} = f_{ph}\frac{p}{h} \tag{9}$$

where the constant f_{ph} represents the deviation of the direction of airflow from a straight line back to the nozzle outlet, due to inflow of air into the spray cone. This constant is empirically set to 0.9, based on the PDPA measurements.

Obviously the entrained air-current cannot penetrate the ground and must deflect sidewards in the vicinity of the ground. An imaginary nozzle below the ground and spraying upward, causes an entrained air which is also directed upward. In fact, the same equations as given above can be used, except that the h-direction is upward now, and h is the vertical distance above the imaginary nozzle subsoil. This 'image concept' was verified with stationary measurements of spray deposition on a patternator, for a flat fan nozzle at different heights.

The interaction between entrainment and wind speed was estimated empirically from calibration experiments described below.

Forward speed will affect entrainment, and thus may also be important. In a first approach, it is assumed that the vectorial sum of natural and apparent wind velocity, the latter due to forward speed, causes the entrained air flow to shift sideward. Deflection of the entrained air is neglected. When the distance, in the driving direction, between a drop and the nozzle exceeded a preset value (arbitrarily set to 1 m) the model turned from 3D to 2D. An accurate assessment of the 3D/2D boundary regarding the extent of the entrainment region did not give different results, nor did it reduce computing time.

Since for all aqueous sprays the evaporation rate of water is much higher than that of the pesticide ingredients, it is reasonable to assume that during spraying the pesticide does not evaporate at all. Therefore the initial concentration of the formulation in the tank of the sprayer determines the final particle diameter when all water has evaporated.

2.6. Atmospheric parameters

The average wind speed, u, is assumed logarithmic with height z above the ground (Hartley and Graham-Bryce, 1980):

$$u(z) = \frac{u_*}{k} \ln\left(\frac{z - d_z}{d_r}\right) \tag{10}$$

where u_* is the 'friction velocity', k is von Karman's constant (approximately equal to 0.41), d_z is the zero plane displacement, and d_r is the roughness length. The wind profile parameters d_z and d_r are roughly proportional to crop height (Monteith and Unsworth, 1990). Air turbulence is quantified by the turbulent exchange coefficient (or eddy diffusivity), which depends on average wind speed and atmospheric stability. The latter, quantified by the Obukhov length, depends on the vertical gradient of air temperature and wind speed.

Inside the crop the logarithmic profile is not valid. Following Thom (1971), the model assumes an average wind speed inside the crop described by

$$u(z) = \frac{u_c}{(1 + K(1 - z/h_c))^2} \tag{11}$$

where u_c is the average wind speed at crop height h_c. For continuity, u_c must equal the wind speed given by Eq. (10) at crop height. The constant K depends on crop structure, and is set to 2.0, being a coarse average of the range given by Hartley and Graham-Bryce (1980).

Although the logarithmic wind profile is valid only in situations of neutral stability, it is used throughout. The slight adjustments of the profile under stable and unstable conditions are neglected. At the edge of the crop, crop height decreases abruptly to the height of cut grass. However, the wind speed profile, whose exact form depends on crop height, is allowed to change gradually downwind from the edge of the crop, and eddy recirculation effects were ignored.

Relative humidity, together with air temperature, determine the evaporation rate of water from droplets. More directly, the dry-bulb and wet-bulb temperature can be used instead. The rate of evaporation of water drops is described by Williamson and Threadgill (1974). If it is assumed that drops flow through air with a velocity close to their sedimentation velocity, the rate of evaporation can be simplified to

$$\frac{\mathrm{d}D^2}{\mathrm{d}t} = rD + s \tag{12}$$

where D is the drop diameter, and r and s are constants depending on dry- and wet-bulb temperature. Since large drops will settle to crop or ground before they have reached sedimentation velocity, this simplification is in fact only valid for small drops. However, as flight times of large drops are very short, there is no significant effect of evaporation for large drops.

While in practice relative humidity may be different at different locations (within the crop canopy, above the crop, just below the nozzle), in the model a constant relative humidity is assumed throughout.

3. Calibration

3.1. Materials and methods

Calibration experiments were carried out using an experimental carriage which was pulled over a 15 m rail track at an adjustable constant speed. A spray nozzle was mounted to the carriage in such a way that the wake behind the carriage could not affect the spray below the nozzle. The middle part (7 m length) of the track with the according up- and downwind areas are referred to as the measurement region. The stationary supply tank of spray liquid was placed outside this measurement region. The tank was connected to the nozzle at the carriage by a rubber hose, hauled by the moving carriage. The rail track was placed perpendicular to the mean wind direction. If during the day the mean wind direction changed, the track was repositioned accordingly.

The spray liquid was tap water containing a fluorescent dye (Brilliant Sulfo Flavin, BSF; Colour Index number CI 56205; 1.0 g/l) and a surfactant (Agral™ LN, Zeneca Agro Ltd; 1 ml/l). Spray deposits onto the ground were measured up to 5 m downwind from the rail track, using synthetic cloths (0.50×0.08 and 1.00×0.08 m^2) as collectors. Spray droplets still airborne at 5 m downwind were sampled using spherical synthetic cleaning pads (diameter 0.08 m) tied to a vertical string, at a spacing of 0.5 m, and up to 2.5 m height. The collectors were washed and the BSF concentration in the extracted fluid was measured by fluorimetry (Perkin Elmer LS-2B Fluorimeter). Wind speed and temperature were recorded at 5 s interval at 0.5 and 2.0 m height, using cup anemometers and Pt100 sensors (screened against solar radiation), respectively. Relative humidity and air temperature were recorded manually at a height of 1.5 m. The area upwind from the 7 m measuring track was kept free from instruments or obstructions. The distance from upwind obstacles (trees and buildings) was at least ten times their height, approximately. All trials were carried out on a field of cut grass (grass height ~ 0.05 m).

Calibration experiments comprised of four boom heights (0.35, 0.50, 0.75 and 1.00 m above cut grass), four driving speeds (0.1, 0.25, 1.0 and 1.5 m/s), three flat fan nozzle types (top angle 110^0; BCPC size classes fine (F; 0.9 l/min@300 kPa), medium (M; 1.6 l/min@300 kPa) and coarse (C; 3.2 l/min@300 kPa)), and three liquid pressures (200, 300 and 500 kPa). The situation with boom height 0.50 m, driving speed 1.0 m/s, nozzle size F (fine) at 300 kPa liquid pressure was chosen as a reference. Starting from this reference situation only one variable was changed at a time. In each situation drift was measured in three to four replications. The reference situation comprised a total of ten trials, at average wind speeds ranging from 1–5 m/s. Each trial consisted of 1–8 passes along the same track and in the same direction, before the cloths were collected. The number of passes was chosen in accordance with driving speed, roughly giving similar cumulative passing times in each situation. Table 1 shows the experimental parameter settings and meteorological data. Whenever two values are given, these represent the lowest and highest value of a range. Each row in Table 1 corresponds to a certain choice of variables. Only for trial B2 (boom height 0.75 m) a distinction is made for medium and high wind speed (B2a and B2b respectively). Drop size data were obtained from measurements with the PDPA system mentioned above.

3.2. Experimental results

Collection efficiency of the spherical collectors was estimated to be about 35%, assuming solid collectors and applying the method of May and Clifford (1967) for 75 μm spray drops at 2 m/s local velocity. Although drop size and velocity vary, these values represent acceptable averages, as is supported by simulation results. The corrected amount of airborne spray at 5 m downwind usually was below 3% of the nozzle output. Ground deposits and airborne spray collection resulted in a spray recovery of about 80–95%.

Preliminary (unpublished) results on degradation of BSF in sunlight indicate that the apparent loss of material may well be due to this degradation. Therefore all experimental results were corrected assuming a perfect recovery of spray liquid material.

Figs. 3–7 show measured and computed ground deposits as a function of downwind distance from the nozzle, while varying different parameters. The graphic symbols indicate measured deposits, whereas the solid lines represent simulation results. Vertical bars indicate typical deviations between the lowest and highest value observed. In all cases the relative variation between replications is very small close to the nozzle (<1 m downwind). Fig. 3 shows the effect of average wind velocity on downwind spray deposits in the reference situation (RF). Clearly the importance of wind speed with respect to spray deposits increases with downwind distance. The ratio between highest and lowest experimental deposits (as indicated by the error bars) is similar for each wind velocity. Close to the nozzle (<1 m distance) deposits are mainly determined by direct ground coverage of the nozzle spray cone.

An effect of similar magnitude is observed in Fig. 4, where nozzle height is raised from 0.35 to 1.00 m. Deposits directly below the single nozzle will decrease with nozzle height above the ground, due to the increasing area covered directly by the spray cone.

Fig. 5 shows the effect of changing nozzle size. Obviously the coarsest nozzle gives the lowest downwind deposits. The apparent similarity of the average deposits of the medium and fine nozzle is remarkable. However, the number of replications is rather small, so this observed similarity may well be coincidental.

Table 1
Experimental parameters and meteorological data

Trial code[a]	#	N	h (m)	v_d (m/s)	Nozzle size[b]	P_{liq} (kPa)	u_{avg} (m/s)	RH (%)	T_a (°C)
RF	10	5–8	0.50	1.00	F	300	0.8–5.3	65–79	15–18
B1	4	5	0.35	1.00	F	300	2.9–3.2	58–62	21–23
B2a	2	5	0.75	1.00	F	300	2.4–3.0	62	24
B2b	2	5	0.75	1.00	F	300	4.8–5.6	—	20
B3	4	5	1.00	1.00	F	300	2.4–3.6	52–55	22
S1	3	1	0.50	0.10	F	300	2.3–2.6	57–59	19
S2	4	2–3	0.50	0.25	F	300	1.8–3.1	46–54	25
S3	3	8	0.50	1.50	F	300	3.1–3.4	53–55	19
N1	4	5	0.50	1.00	M	300	2.7–2.9	69–71	18
N2	4	6[c]	0.50	1.00	C	300	1.8–3.3	67–88	11–19
P1	4	5	0.50	1.00	F	200	1.9–2.9	65	18
P2	4	5	0.50	1.00	F	500	1.9–2.7	78–80	12

#, the number of trials per situation; N, number of passes per trial before sampling; h, boom height above grass; v_d, driving speed; u_{avg}, average wind speed at 2.0 m height; RH, relative humidity at 1.5 m height; T_a, air temperature at 1.5 m height.

[a] RF, reference situation; B, boom height varied; S, driving speed varied; N, nozzle type varied; and P, liquid pressure varied.

[b] F, fine; M, medium; and C, coarse.

[c] First two collectors close to nozzle exchanged for new cloths after three passes to prevent leaking through.

Fig. 6 shows the downwind spray deposits when liquid pressure is changed using the same nozzle. Only insignificant differences are observed, which probably are due to slight variation of wind velocity between the trials.

Finally, the effect of driving speed is shown in Fig. 7. Again, observed differences are small and may well be due to slightly differing wind velocities.

So far only ground deposits were considered. In all cases, airborne drift data varied considerably and only a coarse effect of boomheight and wind speed could be observed.

3.3. Computational results and calibration

Figs. 3–7 show that in most cases the simulation results cover the experimental data very well at distances close to the nozzle (< 1 m). In this area drift usually does not play an important role and deposits are governed by straightforward ballistic rules. In most cases, with increasing distance the relative difference between simulation results and experimental results appears to increase. However, although the model overestimates downwind spray deposits systematically in absolute sense, the relative effect of separate parameters on spray deposits is very similar to experimental results.

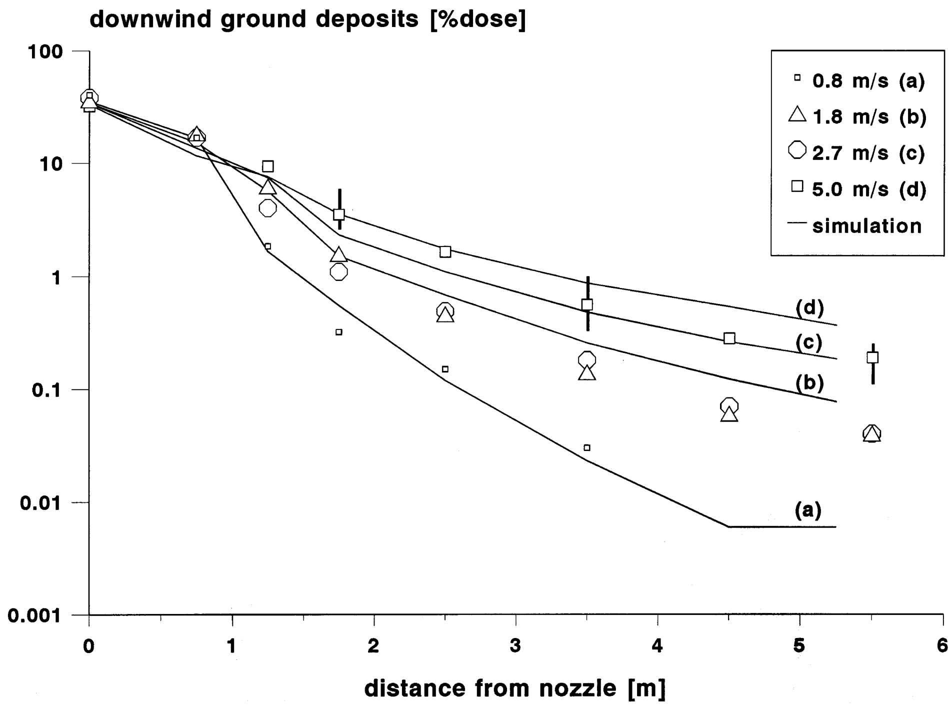

Fig. 3. Downwind spray deposits at various averaged wind velocities. Other parameter settings equal the reference situation. Symbols refer to experimental data. Solid lines with indices (a–d) refer to simulations. Error bars indicate typical deviations between lowest and highest value.

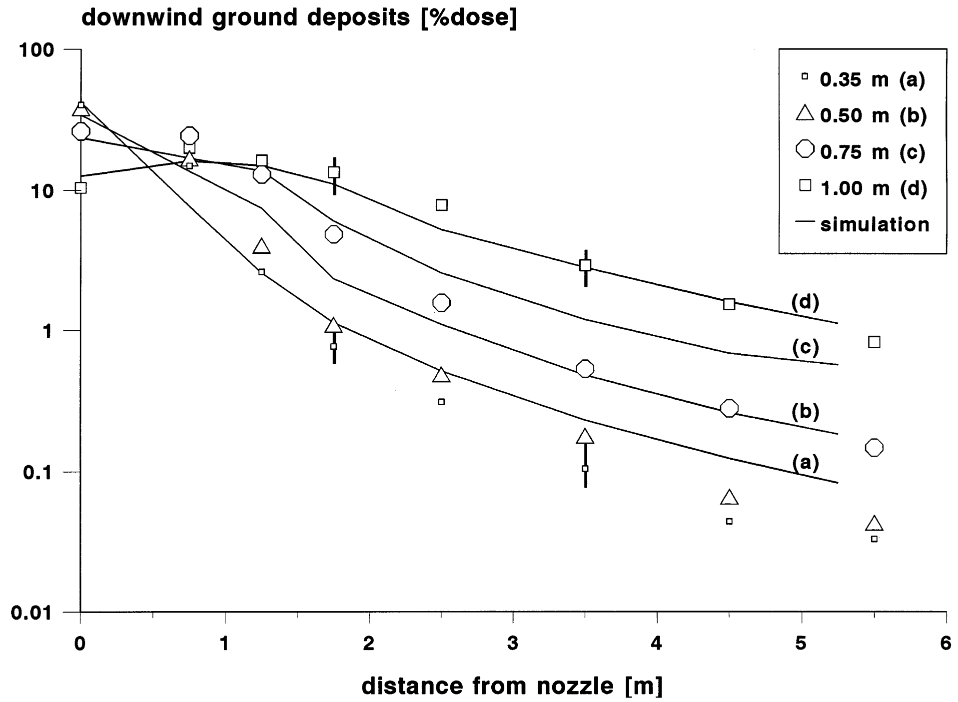

Fig. 4. Downwind spray deposits at various boom heights. Other parameter settings equal the reference situation. Symbols refer to experimental data. Solid lines with indices (a–d) refer to simulations. Error bars indicate typical deviations between lowest and highest value, for lowest and highest boom.

All experimental ground deposits were compared with the equivalent computational data. The ratios R of computational and experimental values were statistically analysed using regression analysis. It proved useful to define a dimensionless 'distance' X_r:

$$X_r = \frac{x}{h_z}\left(\frac{v_0}{u_{avg}}\right)^m \tag{13}$$

where x is the actual downwind distance from the nozzle, h_z is the nozzle height above the level of the zero plane displacement, v_0 the initial velocity of drops at the nozzle outlet and u_{avg} the average wind velocity measured 2 m high. X_r has no strict physical meaning, although it crudely represents the downwind distance relative to the point of intersection of the axis of the spray cone with ground level, if both v_0 and u_{avg} were constant throughout (with $m = 1$ as a trivial consequence).

The range of values for X_r was divided into five regions, on each of which the ratio R was fitted to a different empirical formula:

(a) $X_r < X_{r1}$: $\mathrm{Ln}(R) = a_1 + b_1 X_r + c_1 u_{avg} h_z$ $(X_{r1} = 4)$;

(b) $X_{r1} \leq X_r < X_{r2}$: $\mathrm{Ln}(R)$ = linear interpolation between (a) and (c);

(c) $X_{r2} \leq X_r < X_{r3}$: $\mathrm{Ln}(R) = a_2 + b_2 X_r + c_2 D_V$ $(X_{r2} = 6;\ X_{r3} = 15)$;

(d) $X_{r3} \leq X_r < X_{r4}$: $\mathrm{Ln}(R)$ = linear interpolation between (c) and (e);
(e) $X_r \geq X_{r4}$: $\mathrm{Ln}(R) = a_3 + b_3 D_V + c_3 (v_0/u_{avg})^m \quad (X_{r4} = 30)$.

Constants a_1–c_3 were determined statistically. The constant m preset at 0.63 appeared to give the best fit. D_V represents the volumetrically averaged drop diameter, defined by:

$$D_V = \left(\frac{\Delta V}{N}\frac{6}{\pi}\right)^{1/3} \tag{14}$$

where ΔV is the liquid volume, collected as N separate drops on a certain collector. D_V is a computational parameter, since it could not be determined from the experimental data.

Range borders (X_{r1-4}) were chosen arbitrarily. On ranges (b) and (d) regression analysis could not provide a significant correlation with experimental parameters. Therefore on (b) and (d) a linear interpolation between the fitted equations belonging to the neighbouring ranges was used. Fig. 8 shows the relation between computational and experimental deposits, before and after calibration. It clearly shows that after calibration the cloud of dots is shifted towards the line, $y = x$.

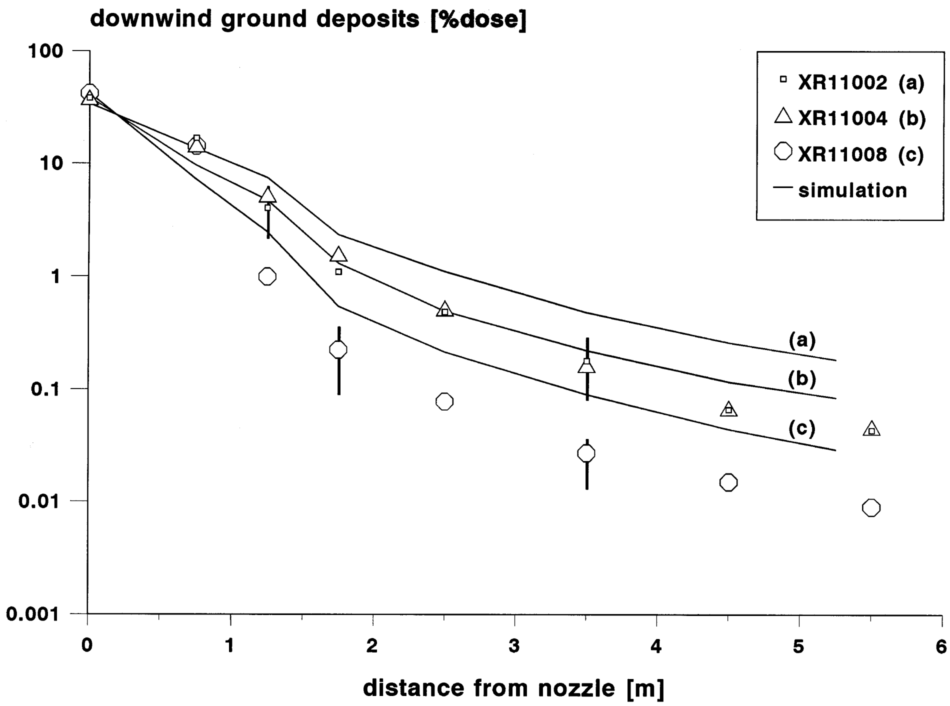

Fig. 5. Downwind spray deposits using different nozzle types. Other parameter settings equal the reference situation. Symbols refer to experimental data. Solid lines with indices (a–c) refer to simulations. Error bars indicate typical deviations between lowest and highest value, for finest and coarsest nozzle.

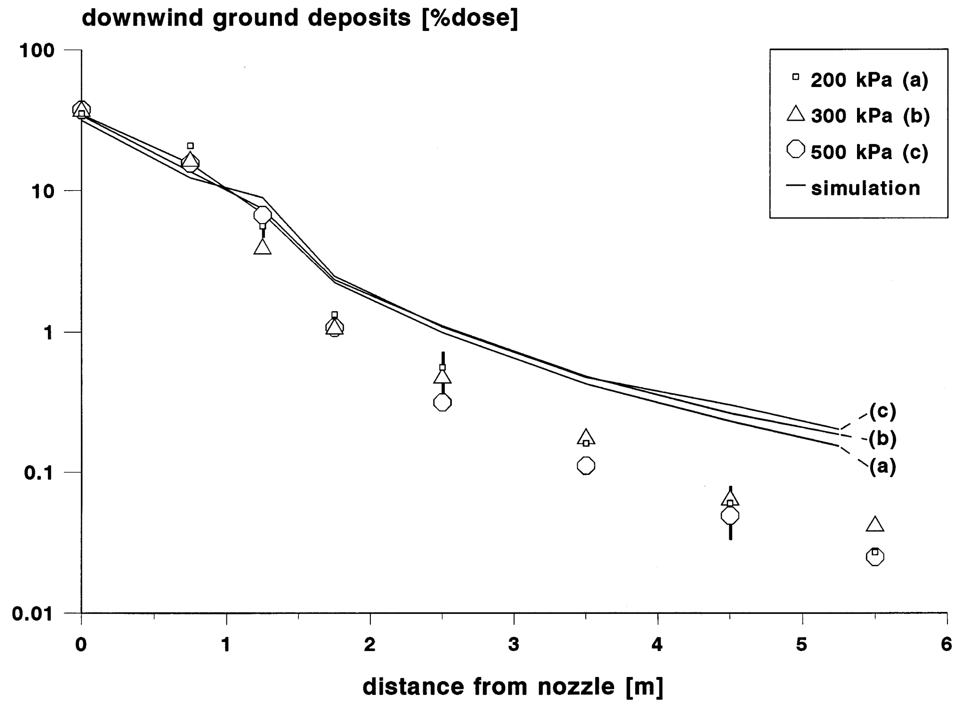

Fig. 6. Downwind spray deposits at different liquid pressures. Other parameter settings equal the reference situation. Symbols refer to experimental data. Solid lines with indices (a–c) refer to simulations. Error bars indicate typical deviations between lowest and highest value, for lowest pressure.

However, the spread of data has not decreased. This indicates that the spread of data is not related with average values of the essential parameters, but must be due to random deviations.

A comparison between measured downwind spray deposits in a field trial and calculated deposits is shown in Fig. 9. The squares represent an average over four replications using medium-sized nozzles on a conventional boom sprayer in a potato crop. Experimental data were obtained from Porskamp et al. (1995). The calibrated simulation results show a close agreement with averaged experimental results. The range of deposit values between individual replications, however, shows a ratio as high as factor ten between the lowest and the highest values (indicated by the vertical bars).

4. Discussion

The stepwise integration used in the IDEFICS model results in iterative equations for drop velocity and position (Eq. (1)). These equations look much like the equations given by Thompson and Ley (1983) (Eqs. (2) and (3)), apart from the random term not introduced here explicitly. However, a fundamental difference lies in the origin of their quantity α, which is related to the Lagrangian scale of turbulence τ_L, following Hall (1975). Strangely drop size seems not to enter their model equations. It can be shown, however, that for small drops τ is usually much smaller than τ_L. This implies that small drops will follow local air turbulence almost completely. Therefore, although their approach is essentially different from the one presented in this study, in practice they will lead to similar results.

In addition to this, one should distinguish Eulerian and Lagrangian turbulence. According to Smith (1959) Eulerian turbulence is much more important than Lagrangian turbulence for medium-sized drops ($\tau g > 0.5$ m/s; corresponding to water drops greater than 150 μm diameter). This means that only for small drops τ_L should be applied; in other cases the Eulerian equivalent τ_E would have been more appropriate.

In general, the IDEFICS drift model can predict spray drift from boom sprayers well. The model can be used in absolute sense after calibration, but especially in comparative studies its strength can be utilized fully.

Both experimental results and model calculations indicate that cross-wind speed, boom height and nozzle size are the major factors affecting spray drift. The trials

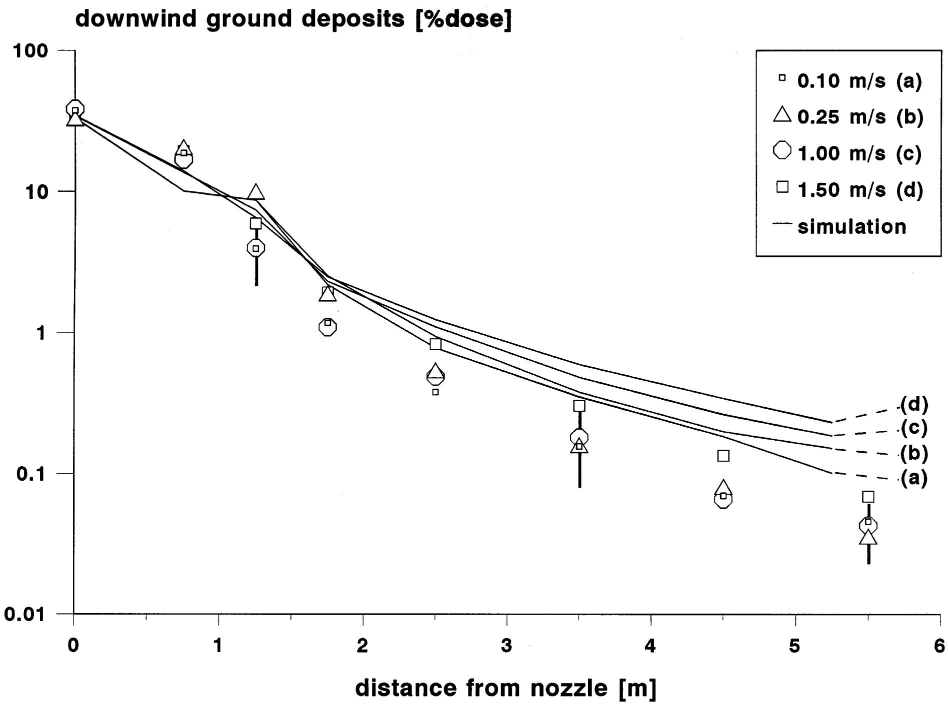

Fig. 7. Downwind spray deposits at various driving speeds. Other parameter settings equal the reference situation. Symbols refer to experimental data. Solid lines with indices (a–d) refer to simulations. Error bars indicate typical deviations between lowest and highest value, for driving speed 1.0 m/s.

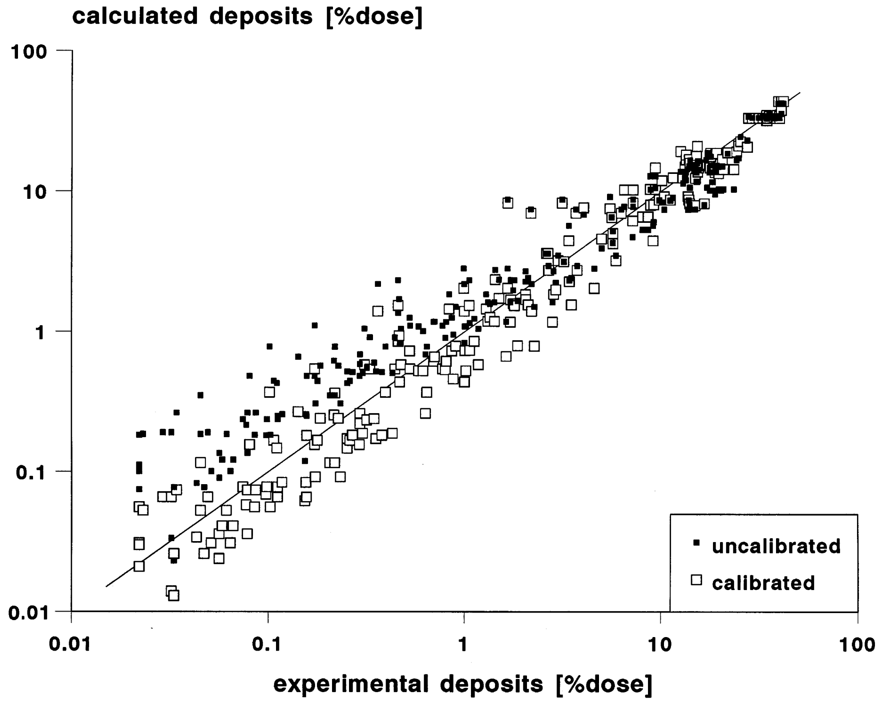

Fig. 8. Correlation between measured and calculated deposits, before and after calibration. The solid line shows the ideal relationship ($y = x$).

involving nozzle size show that even in this carefully designed set of experiments unexpected results may come out, still showing a wide spread of data under similar conditions. This demonstrates the basic problem of experimentally investigating factors affecting drift. The most likely coincidental factors are momentary wind direction and wind speed. Even taking into account a number of passes before samples were collected, this could not eliminate such momentary aspects completely. Allowing more passes probably would give better average results, however, leakage of spray liquid through the collectors may become a problem.

Remarkably, liquid pressure and driving speed hardly affect downwind spray deposits, as both experiments and simulations show. A raised liquid pressure increases the relative amount of small drops, and is therefore expected to increase drift. However, the initial velocity of drops at the nozzle outlet increases also, which would decrease drift. In the limited set of experiments these effects apparently cancel out, giving no net drift effect. Since this result is based on trials with a flat fan nozzle producing a fine spray, it is too early to state the reliability associated with this cancelling out as a general phenomenon, which may be limited to short-ranged downwind ground deposits. Further investigations should answer such questions. For the moment, it indicates that one must be aware that reducing liquid pressure may not reduce drift at all.

Driving speed in this study ranges from very low to realistic velocities. Really high-speed driving was not investigated, therefore the effect of high-speed driving on drift cannot be assessed. This study indicates that common driving speed probably does not affect spray drift considerably.

The comparison with averaged field trials shows that the IDEFICS model can simulate practical cases well. The wide variation between single field trials, however, indicates that such trials cannot be used to verify model results accurately. Practical cases not only give rise to problems involving the momentary aspects of wind, but also the problem of boom movements arises. With respect to drift the vertical boom movements are the worse. However, the increase of drift due to a boom height momentarily above its mean will be partly neutralized by boom heights below mean. Since horizontal boom movements may be considered as quick changes in driving speed, it is not likely that these will affect drift considerably.

Until now the IDEFICS model is calibrated only for a single nozzle spraying above grass. Most trials involved a nozzle producing a fine spray quality. Further investigations therefore should include multi-nozzle arrangements (e.g. entrained air-currents may be change considerably), trials above a crop canopy and nozzles producing medium and coarse spray qualities.

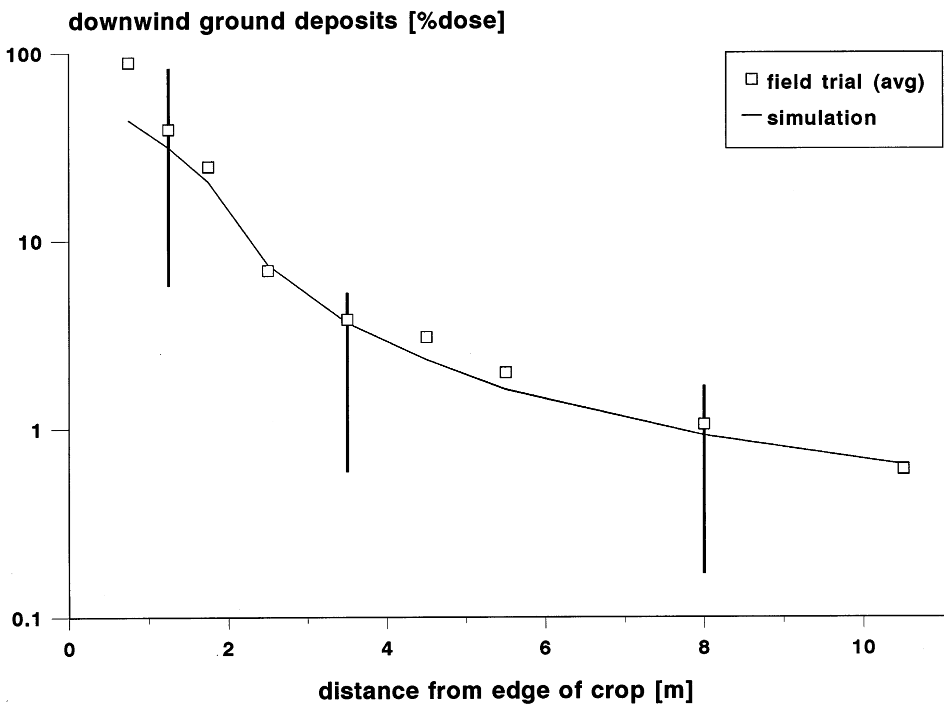

Fig. 9. Comparison of downwind spray deposits in practical field trial (average of four replications) and simulation results. Sprayed volume, 300 l/ha; wind velocity, 3.5 m/s; and boom height, 0.7 m above mature potato crop. Error bars indicate typical deviations between lowest and highest value.

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