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Developing a generic model for spray drift in fruit crop spraying

By H J HOLTERMAN and J C VAN DE ZANDE

Wageningen UR Plant Research International,
PO Box 616, 6700 AP, Wageningen, The Netherlands
Corresponding Author Email: henkjan.holterman@wur.nl

Summary

An empirical model has been developed for computing downwind deposits of spray drift after spray applications in fruit orchards. A database of downwind spray deposits from experiments during 20 years of field trials was used in regression analysis to show the relevant parameters: wind speed, wind direction, ambient temperature, growth stage (BBCH code), the sprayer's fan setting and orchard size. The basic regression model was modified into a generic drift model for fruit crops like apple and pear, using known or logical relationships between in the input parameters and their effect on spray drift. A major advantage of the new model with respect to current practice in regulations is the possibility to estimate drift as a continuous function of growth stage, rather than using only a few fixed growth stages. This study also describes the implementation of the spray drift model into a risk assessment model to evaluate the risk for aquatic organisms regarding exposure to pesticides in watercourses surrounding fruit orchards. The risk assessment model takes account of regional differences with respect to presence of fruit orchards, types of water bodies and weather conditions. Multiple spray applications during the growing season are accounted for into the risk model. Both the spray drift model and the risk assessment model are still under development. Preliminary results show a good correlation between modelled deposits and measured deposits: a correlation coefficient of 90% was obtained. The risk assessment model indicates that different regulatory measures may be required for fast-degrading and persistent pesticides.

Key words: Spray drift, modelling, pesticides, fruit crops, surface water, risk assessment

Introduction

Downwind off-target deposits of spray drift have been investigated for many years. For spray applications in fruit crops downwind spray deposits are significantly higher than those for field crops. This is mainly due to differences in the initial direction of the spray produced and the use of air assistance to guide spray drops towards the fruit trees. In the Netherlands, orchards with fruit trees cover an area of about 17,000 ha, mainly apple and pear trees (year 2012; CBS, 2013). These orchards are not evenly spread across the country, but five regions can be distinguished where fruit orchards are concentrated. These regions differ by weather conditions, soil type and water body types present. At present, Dutch regulations for spray application in fruit orchards consider only two crop stages for fruit trees: bare and full-leaf. Typically, fruit trees are considered 'bare' before 1 May, and 'full leaf' on 1 May and thereafter. This affects the estimated risk regarding deposits of spray drift onto edge-of-field surface waters. Clearly, in reality the canopy of fruit trees develops more gradually. Phenological development stages are identified by the BBCH scale. If estimates of spray drift could be adjusted to account for the appropriate phenological stage and regional differences, regulations regarding the authorization of plant protection products (PPPs) could be adapted accordingly and would become more robust.

For field crops various spray drift models are described in literature. IDEFICS is one of such models which is based on the physics of droplet transport through air (Holterman *et al.*, 1997). However, developing a similar model based on physical principles for spray drift in fruit crop spraying proved difficult, since modelling the forced flow of droplet-laden air through rows of trees is not straightforward at all. After 20 years of field experiments with fruit crops, a considerable amount of experimental data on spray drift is available, primarily for apple and pear crops. Using these data to develop a regression model for spray drift seems attractive.

The present study describes the development of a generic model for downwind deposits of spray drift while spraying fruit crops. Relying on regression analysis alone appeared not to give a satisfactory model. Therefore physical constraints were built in wherever necessary and possible. The model takes into account the gradual growth stages of the crop. The BBCH stages are linked to the average day of year (DOY) at which these stages occur. In principle, this allows refinement of the model for other DOY dependent factors such as weather conditions.

The model is being implemented in a risk assessment tool for pesticides reaching edge-of-field surface water bodies. This tool is intended to be as realistic as possible; it considers one or more spray applications during the growing season, choice of pesticide and dose, and intelligent application timing schedules. It also accounts for regional location of fruit orchards and their orientation with respect to various types of water bodies. Weather conditions vary regionally and during the year. A stochastic selection process is implemented to obtain a probabilistic distribution of estimated spray drift deposits per region or nation-wide.

Materials & Methods

Model for spray drift in fruit crops

Downwind deposition of spray drift depends on application technique, weather conditions (wind speed and direction, ambient temperature, relative humidity), crop type and growth stage. For fruit orchards, a large number of experimental results on spray drift were available. These experiments were done during some 20 years in orchards of apple trees at different times during the growing season. From these experiments the trials involving a reference spray application (a standard axial fan sprayer) were combined in a database. Trees were about 2.3 m high, distance between rows was $\Delta b = 3.0$ m. This database was used for regression analysis to generate an empirical model of spray drift for spray applications in fruit orchards. Basically, an exponential function of downwind distance (x) could describe spray deposits (B) well:

$$B(x) = q_1 \cdot e^{-q_2 x} \tag{1}$$

Parameters q_1 and q_2 depend on crop type, growth stage and environmental factors. By definition, x is the downwind distance from the centre of the first row of trees. A clear disadvantage of the above equation is the fact that for decreasing x the deposits B tend to increase progressively. However, often a flattening of deposits is observed for small distances. Therefore the following modification of the exponential model was proposed:

$$B(x) = \frac{q_1 \cdot e^{-q_2 x}}{1 + c_0 \cdot e^{-q_2 x}} \tag{2}$$

For large enough downwind distances this equation approximates Eq.(1), while for small and negative distances B approaches a finite value. Choosing the value of c_0 such that B=100% (relative to the applied dose) at the position of the second row of trees ($x = -\Delta b$) proved to give best results. Although the above equation seems simple, a relational description of parameters q_1 and q_2 in terms of the various input factors appears not to be simple at all. Regression analysis revealed the relevant input factors for downwind spray deposition: growth stage (BBCH code), the number of treated rows in the trial, wind speed, wind direction relative to the field edge, ambient temperature. Since only the reference application technique was considered in the model, this technique was not a factor (apart from its fan setting: 'high' or 'low'). Similarly, crop type or tree height were not factors as these were about the same for all trials. It turned out that regression analysis alone could not describe parameters q_1 and q_2 in a satisfactory way, as some unexpected dependencies occurred. Therefore several physical or 'logical' constraints were applied to the mathematical descriptions of q_1 and q_2. The resulting semi-empirical equation could describe downwind deposits sufficiently well.

Risk assessment model for exposure of aquatic organisms to pesticides

The spray drift model described above is embedded in a risk assessment model for the exposure of aquatic organisms to pesticides on a national scale. A risk assessment scenario consists of spray drift simulations for all combinations of water body types and regional environmental conditions. Currently, five regions are distinguished where fruit orchards are relatively abundant. Together with 66 types of water bodies (Massop *et al.*, 2006), this gives 330 unique combinations. Fortunately, many of these combinations are in fact non-existing, since the number of water body types actually occurring in a certain region is much less than 66. The number of combinations is reduced further by eliminating those with water body types that dry up during summer, thus obviously causing no risk for aquatic organisms. Each combination is weighted according to the size of the region and the frequency of occurrence of the water bodies in that region.

While the spatial quantities mentioned above are implemented in all possible combinations, other quantities, typically temporal quantities like wind speed and wind direction, cannot be implemented that way since the total number of combinations would become too large to handle. Therefore, the temporal quantities are selected randomly from their frequency distributions. To obtain statistically precise results, scenario simulations should cover at least a 20-year period.

Finally, the scenario simulations yield a large set of possible pesticide concentrations in water bodies throughout the country. From this set a cumulative probability curve of pesticide concentrations can be formed, of which the 90th percentile is taken to be used in the analysis of exposure risk for aquatic organisms. For some pesticides one application per year is sufficient, while other pesticides require frequent applications during the growing season. Usually application timing is based on growth stage (BBCH). The number of applications will affect the risk for aquatic organisms. Therefore, both single and multiple spray application scenarios need to be considered.

For multiple spray application in one season, two extreme cases can be distinguished. Firstly, pesticide concentration in a water body may vanish between subsequent spray applications. This may be due to fast degradation, fast sedimentation or uptake by the soil underneath, or fast transport due to a high flow rate in the watercourse. In this case, the risk for aquatic organisms in a watercourse is caused by the application giving the highest pesticide concentration (MAXPEC; PEC = predicted environmental concentration). Secondly, pesticide concentration may remain constant between two spray applications. Subsequent applications lead to increased pesticide concentrations, since these add up during the season. In that case, the risk for aquatic organisms in the watercourse is caused by the final pesticide concentration after all applications. For ease of comparison, it is convenient to use the average pesticide concentration instead (AVGPEC), defined by the final concentration divided by the number of applications.

The flow-chart of the risk assessment model is shown in Fig. 1. The left part shows the loops of spatial quantities and the *n*-year loop. The dashed rectangle represents the stochastic loops of temporal quantities including multiple (*m*) spray applications per season. This is shown in detail in the flow-chart on the right-hand side. In the following sections the various frequency distributions used in the risk assessment model are described.

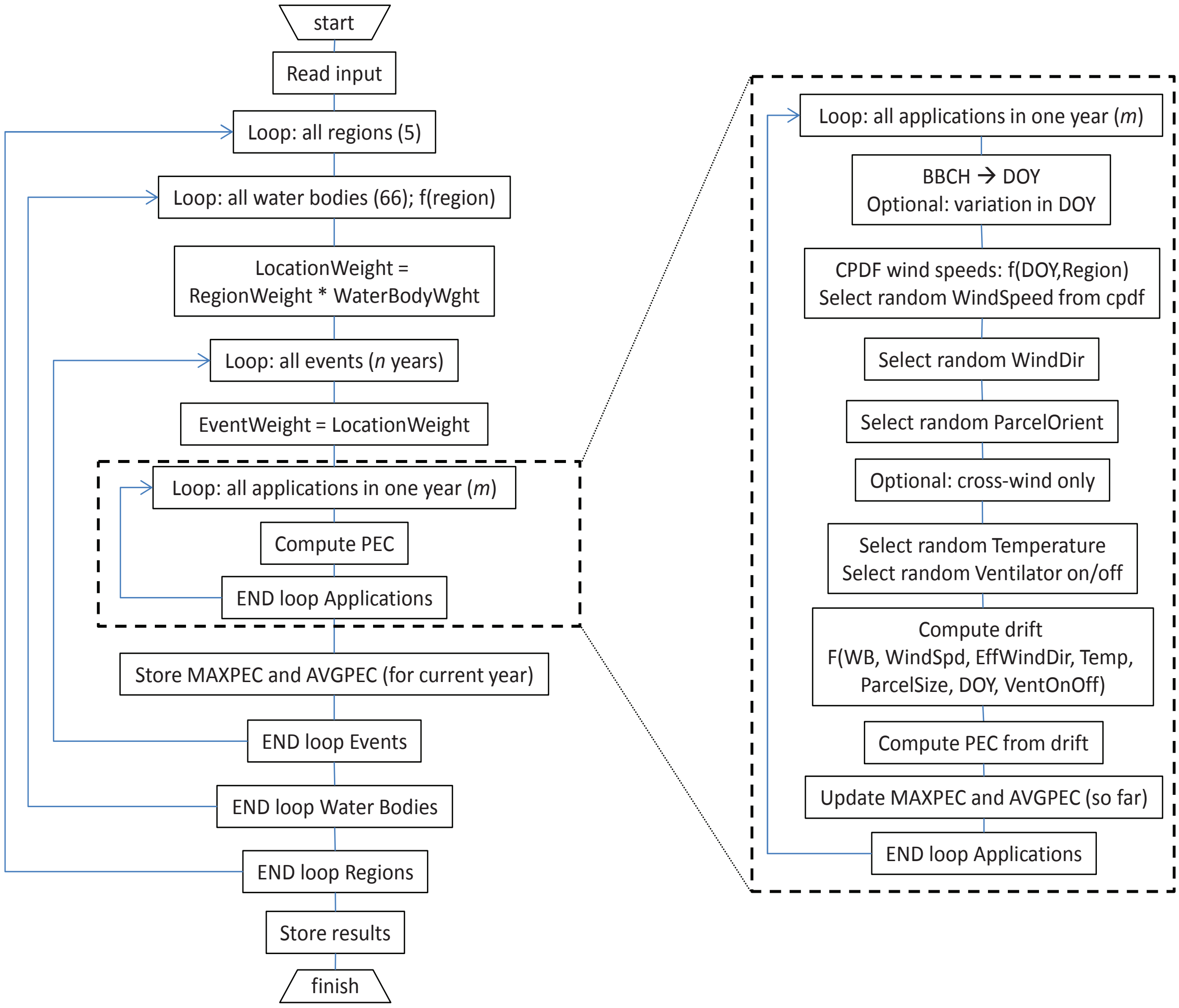

Fig. 1. Flow-chart of the risk assessment model (*left*). The dashed block in the centre is the 'stochastic heart' and is expanded on the right-hand side.

Frequency analysis of meteorological data

Meteorological data were obtained from KNMI[1] weather stations representative for five regions where fruit is grown. Hourly averaged values of wind speed, wind direction and air temperature were gathered for daylight hours only, since spray applications only take place during the day. Data during 20 recent years (1991–2010) were used. In the following sections these data will be discussed in more detail, for one weather station only. Each weather station has its own set of distribution curves and averages to be used in the risk assessment tool.

Frequency distribution of wind speeds

Fig. 2, left, shows the 20-year averaged frequency distribution of wind speeds at 10 m height during daylight hours for the weather station in Herwijnen (representative for the central rivers area). The median wind speed is 4.0 m s^{-1}, though occasionally very high wind speeds have been measured. Sprays are applied only when average wind speed is below 5 m s^{-1} (at 2 m height above cut grass). The frequency values for wind speeds up to 10 m s^{-1}were fitted using a 6th grade polynomial (the black curve in Fig. 2, left). In winter, wind speeds are on average higher than in summer. Fig. 2, right, shows the weekly averaged wind speeds during the year, roughly following a sinusoidal curve. The year-averaged frequency distribution was scaled in such a way, that for each DOY the appropriate distribution was obtained (i.e. having a mean wind speed equal to that given by the sinusoidal curve). In this way, the DOY-adjusted polynomial frequency distribution could be used for stochastic selection of wind speeds in the risk assessment tool.

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[1] KNMI = Royal Dutch Meteorological Institute.

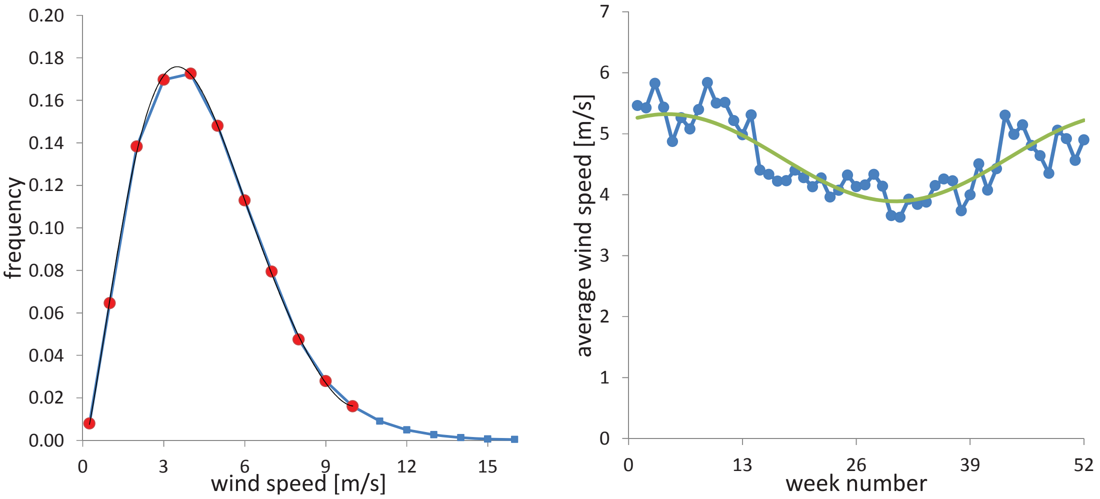

Fig. 2. *Left*: normalized frequency distribution of hourly averaged wind speeds at 10 m height through the year (at daylight only); blue squares: measurements; red dots: measurements selected for curve fitting a 6th grade polynomial fit (black line). *Right*: weekly averaged wind speeds during the year; blue dots: measurements; green line: Fourier fit. (Meteorological station Herwijnen; central rivers area; 1991–2010).

Frequency distribution of wind directions

In the Netherlands, wind often blows from the SW direction. This is clearly supported by Fig. 3 showing the angular frequency distribution of wind direction at the Herwijnen weather station. 'Effective' wind direction is defined as the wind direction relative to a cross wind and therefore it is related to the orientation of the fruit orchard concerned. Usually, fruit orchards are not oriented randomly; often the rows of trees are oriented along the NS direction, such that both sides of the trees receive the same amount of daylight. Sometimes orientation depends on local situation as well (e.g. orientation of neighbouring roads or water bodies). Frequency distributions of wind direction and orchard orientation are combined to give the frequency distribution of effective wind direction, to be used in the risk assessment tool.

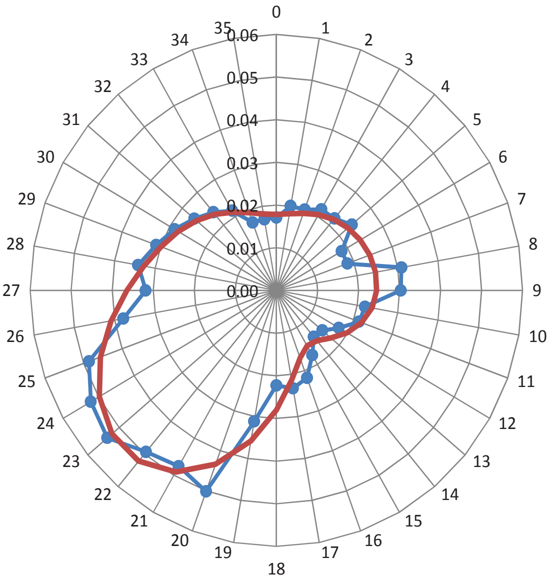

Fig. 3. Angular frequency distribution of hourly averaged wind direction (at daylight hours only); blue dots: measurements; red line Fourier fit. (Meteorological station Herwijnen; central rivers area; 1991–2010).

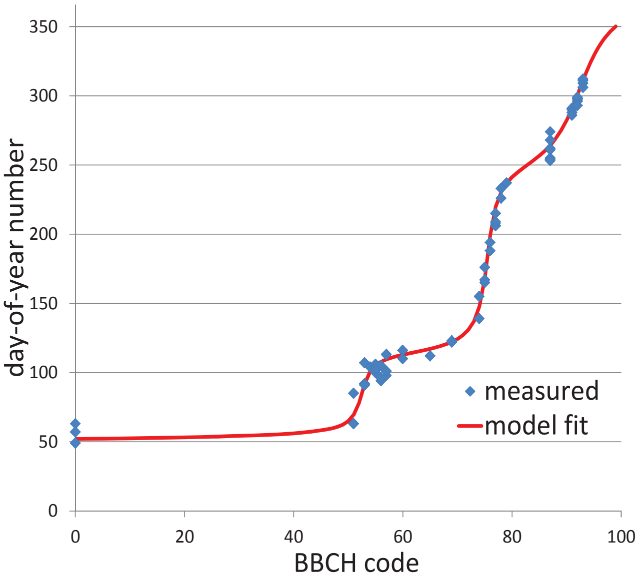

Fig. 4. Graph of BBCH codes for apple trees in the Netherlands as related to the day-of-year. Dots: from observation; red line: curve-fit to be used in risk assessment modelling.

BBCH vs DOY

Growth stage of a crop can be described by a BBCH code (ranging from 0 through 100). Thus, in principle, BBCH code is a measure of canopy density. To estimate downwind deposits of spray drift, knowledge of the canopy density on the day of spray application is required. For apple trees in the Netherlands, Fig. 4 shows the relation between BBCH and DOY, from expert observations in the orchard where spray drift experiments were carried out. The fitted curve gives the average DOY on which a certain BBCH occurs. Observed BBCH-DOY pairs may vary due to varying weather conditions each year.

Frequency distribution of ambient temperatures

Fig. 5, left, shows the weekly averaged air temperature during daylight hours, as a function week number. Actual hourly-averaged temperatures differ considerably from their weekly average. Fig. 5, right, shows the distribution of these temperature differences, averaged for all weeks and 20 years. Air temperatures appear to be almost normally distributed around their weekly average, with a standard deviation of about 4°C. Using the Fourier fit of weekly averaged temperatures and the normal distribution per week, stochastic temperatures can be selected for a given DOY.

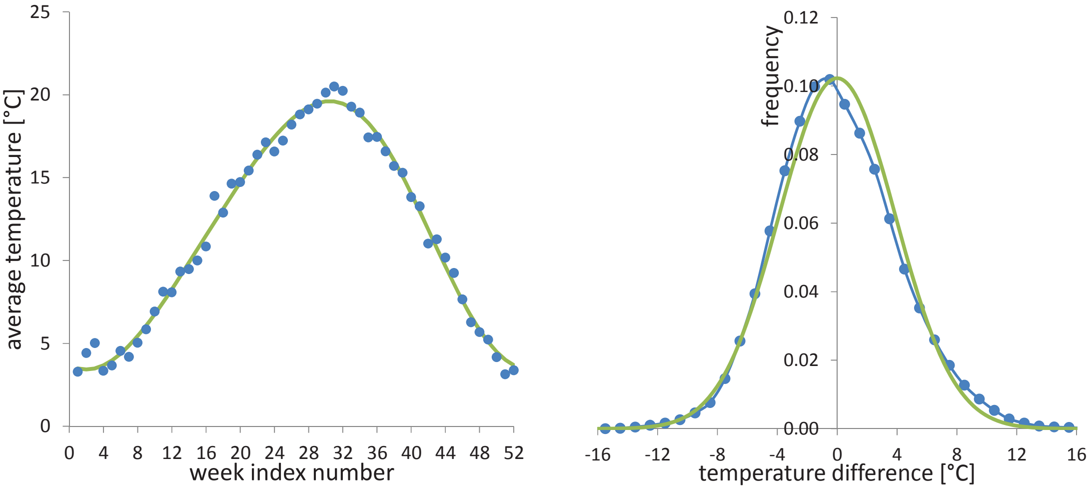

Fig. 5. *Left*: weekly averaged temperatures (during daylight) as a function of week number; meteorological station in Herwijnen (central rivers area). Blue dots: measured temperatures; green line: Fourier fit. *Right*: frequency distribution of hourly averaged temperature differences with respect to its weekly average; blue dots: from measurements; green line: best-fitting normal distribution.

Frequency distribution of water bodies

In the Netherlands, water bodies with water surface width <6 m have been classified into 66 standard profiles according to soil type, water body geometry and flow rate (Massop *et al*., 2006). Regionally often only a few standard profiles are present. Besides, some profiles are likely to dry up in summer and therefore are excluding from risk assessment for exposure of water organisms to pesticides. Consequently, the regional frequency distribution of water bodies only consists of very few profiles (4–19 for the regions selected currently). Although this simplifies the computations in the risk assessment model, it tends to enhance the regional differences in exposure risk.

Results

Model of spray drift for fruit crops

The new spray drift model is a continuous function of growth stage (BBCH code) and other input parameters thus allows a more realistic use during the year. The newly developed semi-empirical model fits the experimental spray drift data relatively well (correlation coefficient 90%), see Fig. 6.

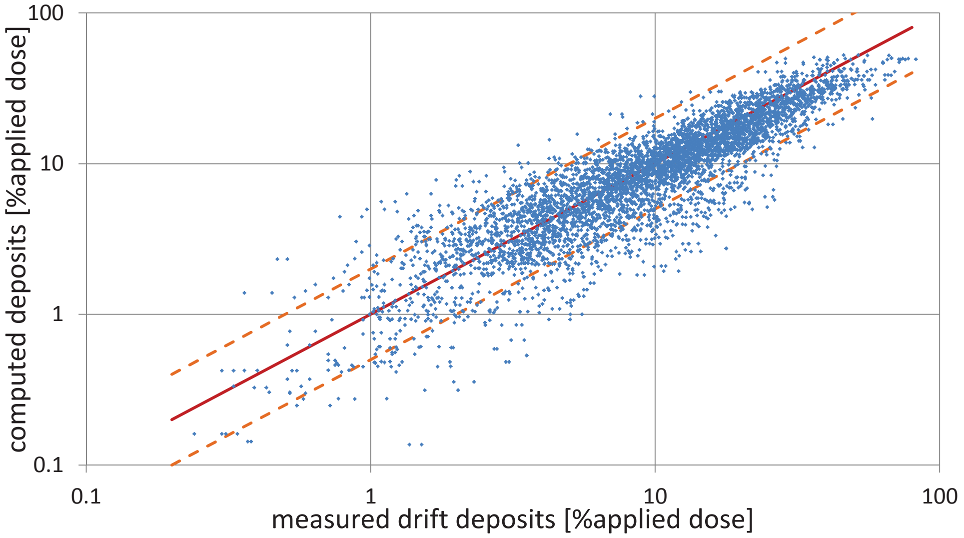

Fig. 6. Correlation between measured deposits and their fitted values; correlation coefficient: 90%. Solid red line: ideal fit ($y = x$). Dashed orange lines: fitted values differ by factor 2 from measured values ($y = \mathbf{0.5}x$; $y = \mathbf{2}x$).

All field trials were done with two parallel sets of deposition samples. A pairwise comparison of samples gave a correlation coefficient of 97%. This is an indication of the accuracy of the sampling method. Since the input parameters for each sample pair at exactly the same, no spray drift model based on these inputs can perform better than 97%. This indicates that the current model performance is not too bad, although the graph of Fig. 6 show several samples for which measured and modelled values may differ by a factor of up to 10. Yet, for 88% of the spray samples the ratio of the modelled deposit and measured deposit is between 0.5 and 2 (i.e. the dots between the dashed lines in Fig. 6). Fig. 7 show some examples of downwind spray deposits as a function of distance computed using the spray drift model. The left graph shows four curves for different growth stages. From BBCH code 50 (spring; see also Fig. 4) through 80 (summer) the canopy density increases, leading to lower downwind deposits. For BBCH 90 (autumn) the canopy density has decreased slightly, giving rise to increased deposits with respect to those in summer. All other parameters are kept constant. The graph on the right-hand side shows the deposition curves in summer, for three average wind speeds. Apparently the model is not very sensitive to changes in wind speed. Higher wind speeds lead to lower deposits near the orchard, while further downwind deposits increase.

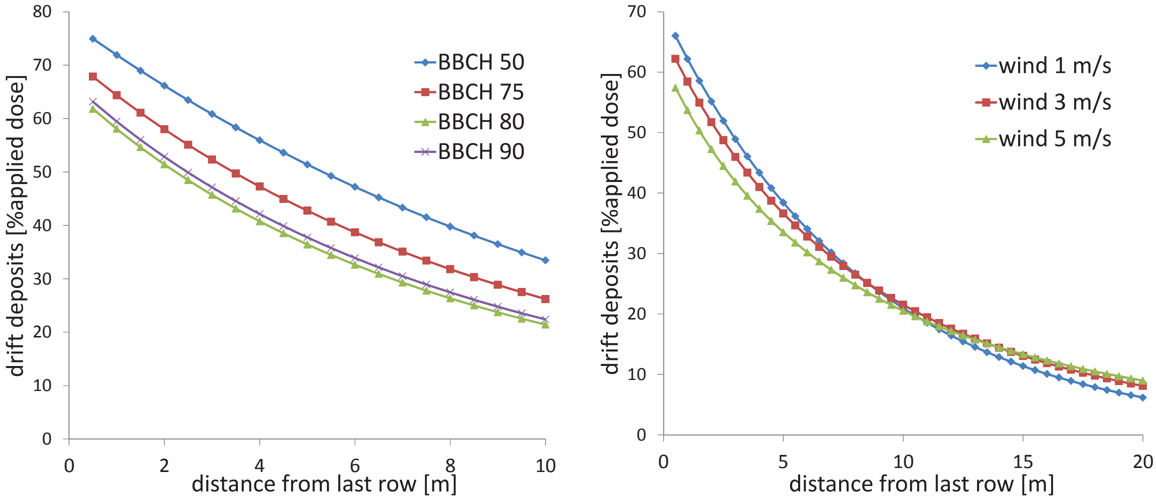

Fig. 7. Examples of downwind deposits computed with the spray drift model for fruit crops. *Left*: deposition curves for various growth stages (BBCH) at wind speed 3 m s^{-1}. *Right*: deposition curves for various wind speeds at growth stage BBCH 80. Constants: ambient temperature: 15°C, number of rows: 10; fan setting 'high'.

Some examples of using the risk assessment model are shown in Fig. 8. The left graph shows the cumulative probability density function (cpdf) for MAXPEC after 1, 3 and 10 spray applications. First application is assumed at BBCH 75 (DOY 168); subsequent applications are assumed to take place at 7-day intervals. All regions are considered and the evaluation period is 20 years. Similarly, the graph on the right-hand side shows the cpdf curves for AVGPEC. The 90th percentile for MAXPEC increases from about 170 mg m^{-3} for 1 application to 210 mg m^{-3} after 10 applications. It can be shown that this value tends to stabilize when the number of applications increases. For AVGPEC, the 90th percentile decreases from about 170 mg m^{-3} for 1 application down to 70 mg m^{-3} after 10 applications. Note that in the latter case the actual risk is the summed PEC over all applications, i.e. about 700 mg m^{-3}.

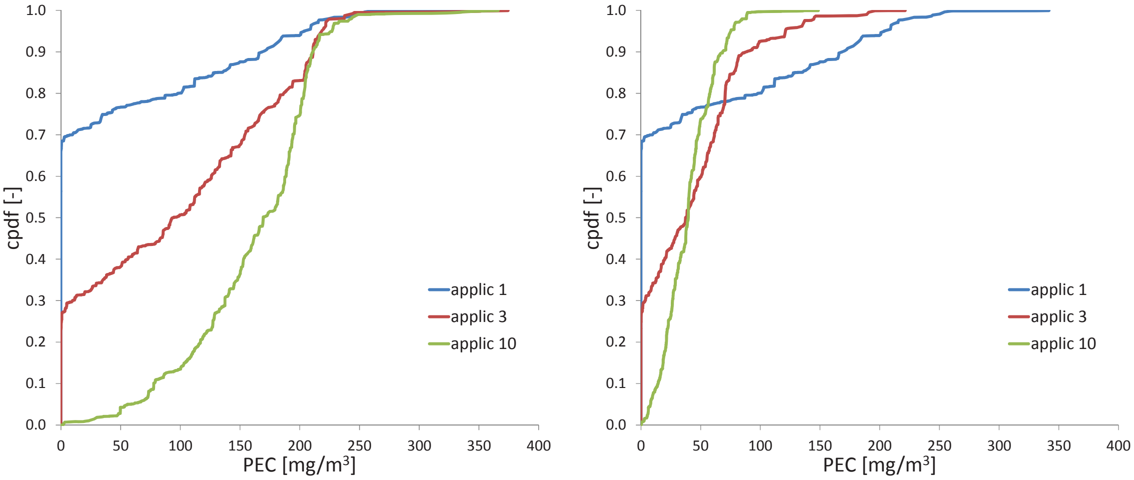

Fig. 8. Examples of cumulative probability curves for PECs in edge-of-field watercourses for spray applications in fruit orchards in the Netherlands. Number of applications during the season: 1, 3 and 10. Number of years in the evaluation: 20. *Left*: curves for MAXPEC. *Right*: curves for AVGPEC.

Discussion

The newly developed drift model for spray applications in fruit crops is based on a large number of experimental data throughout the growing season. Correlation between measured deposits and modelled deposits is reasonably good: correlation coefficient is 90%. Some unexpected results appear to come forward, like the low sensitivity of downwind deposits to wind speed. Indeed the experimental data show the same low sensitivity. Possibly a higher wind speed causes the spray cloud to drift downwind further before touching the ground. Currently the model has to be refined and various effects have to be tested and evaluated.

The risk assessment model can compute pesticide concentrations in edge-of-field water bodies for all regions in the Netherlands where fruit orchards are present. In the present model only five regions are available, not fully covering all fruit orchards in the Netherlands. Currently, a nation-wide regional set-up is elaborated to be able to do real nation-wide risk assessment.

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