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Probabilistic risk assessment for watercourses exposed to spray drift in the Netherlands

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Summary

Probabilistic countrywide risk assessment models have been developed to study the risk of exposure to pesticides for edge-of-field watercourses next to pome fruit orchards and avenue tree nurseries. Different models have been developed for upward and sideways (US) spray applications towards the trees and for downward (DWN) spray applications directed towards the ground below the trees. A spatio-temporal approach was followed to account for the spatial distribution of the orchard and nursery locations and the temporal variation in multi-year spray applications. Countrywide simulations resulted in 90th percentile concentrations of pesticides in edge-of-field watercourses, depending on factors such as the number of spray applications per year and the application techniques used. A single spatial configuration was selected to evaluate the countrywide risk level for each scenario. The spray drift exposure models, combined in the xSPEXUS model, were used in combination with the TOXSWA model for pesticide fate in the ditch. In this combined approach of exposure and fate a higher-tier risk evaluation for the authorization of plant protection products in fruit orchards and tree nurseries is possible.

Key words: Spray drift, fruit orchards, trees nurseries, surface water, risk assessment, probability

Introduction

Deposits of spray drift onto edge-of-field watercourses contribute significantly to the risk of exposure to pesticides for aquatic organisms. This risk is particularly high when pesticide sprays are applied in an upward or sideways (US) direction such as with pome fruit orchards and avenue tree nurseries. Few years ago the exposure model SPEXUS has been developed for spray drift with fruit orchards (Holterman *et al*., 2017). This model was implemented in a spatio-temporal probabilistic model for countrywide exposures assessment specifically for upward and sideways spray applications in fruit orchards (Van de Zande *et al*., 2018; Holterman *et al*., 2020; Boesten *et al*., 2021). Recently, a similar approach has been applied to investigate the risk of exposure for avenue tree nurseries in US spray applications and downward (herbicidal) applications below fruit and avenue trees (Holterman *et al*., 2022). Currently, the scenario for arable crops is being updated to allow a similar approach.

This paper describes the processes and aspects involved with the mentioned scenarios. Similarities and differences are discussed, e.g. regarding the spatial and temporal variables that were accounted for. Generally, for all scenarios the 90% exposure levels of predicted environmental concentrations

(PEC) of pesticides in surface water were determined for various spray application schemes including multiple spray applications during a year. In this way, realistic simulations could be carried out to study the exposure and fate of pesticides in edge-of-field watercourses next to fruit orchards and avenue tree nurseries, and surface waters. The exposure assessment models (combined in the 'extended-SPEXUS' model, xSPEXUS) serve the higher-tier evaluation for the authorization of plant protection products in these crops.

Materials and Methods

In the countrywide exposure models both spatial and temporal variables are distinguished. Spatial variables include regional distributions of treated orchards or nurseries, different types of edge-of-field watercourses, various water levels and varying growth stages during the year. Temporal variables include the meteorological conditions, such as wind speed, wind direction and ambient temperature. Predicted environmental concentrations (PEC) in the watercourses can be determined for various spray application schemes including multiple spray applications during a year. The PECs in the watercourses were computed in an extensive simulation study comprising a wide variety of possible spatial configurations. A spatio-temporal statistical analysis of the simulation results gave a quantitative risk assessment for a representative set of spray application schemes. This analysis formed a basis to evaluate the risk of exposure to spray drift for a wide range of spray application scenarios, including the use of spray drift mitigation application techniques and crop-free buffer zones. All these features result in the versatile and realistic exposure assessment model xSPEXUS. Together with the TOXSWA model (describing the fate of pesticides in a watercourse; Ter Horst *et al*., 2016), the xSPEXUS model was built into the DRAINBOW model (Ter Horst *et al*., 2021; Boesten *et al*., 2021). The DRAINBOW model evaluates the exposure of edge-of-field watercourses to spray drift deposits and drainage, and the fate of pesticides in watercourses in The Netherlands. The DRAINBOW model serves higher-tier assessment studies for the authorization of plant protection products.

Whereas for upward and sideways spray applications in fruit orchards a sophisticated exposure model (SPEXUS) has been developed, for the other scenarios less experimental data were available and a simpler approach had to be followed, basically using averaged spray drift curves. However, in all cases the local spray drift models were scaled up to a countrywide exposure assessment in a similar way. Exposures were evaluated at the 90th percentile level of PEC values in the edge-of-field watercourses. Next, the fate of pesticide in the ditch was modelled using the TOXSWA model. Ideally, a combined probabilistic model for both spray drift and fate would give rise to the countrywide assessment of PECs. For practical reasons, a single spatial configuration was selected for monitoring: in fact a common watercourse next to an orchard in a district with a lot of fruit orchards (Boesten *et al*., 2021). Essentially, the countrywide 90th percentile exposure levels were represented by equal PECs in the locally selected configuration, which occurred at different (local) percentiles. These so-called temporal percentiles were determined for all scenarios and a variety of application conditions.

Scenarios

Fig. 1 gives an overview of the scenarios for fruit orchards and avenue tree nurseries in this study. The five blue boxes are defined as 'scenarios'. Fruit-US refers to upward and sideways applications in pome and stone fruit orchards (Boesten *et al*., 2021). For small fruit, hop and vines no specific scenarios have been developed; the scenario for fruit orchards is used with some adaptations or boundary conditions. Avenue-US refers to upward and sideways applications in avenue tree nurseries (Holterman *et al*., 2022). The downward scenarios (DWN) refer to herbicide treatments below fruit or avenue trees. For Fruit-DWN a distinction is made between spray applications on tree strips (in the tree rows) and on grass strips (between the tree rows).

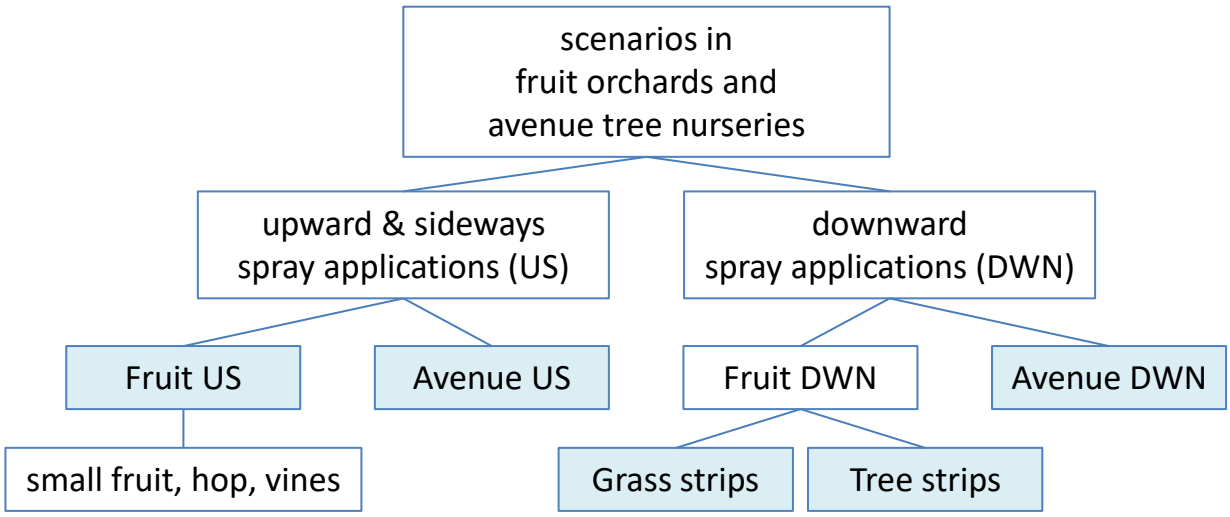

Fig. 1. Schematic layout of scenarios for spray applications in fruit orchards and avenue tree nurseries. The coloured blocks refer to the scenarios in this study (from Holterman *et al*., 2022).

Typically, avenue trees are grown in three stages: spindle trees, transplanted trees and high trees (Fig. 2). The cultivation of spindle trees is intensive and often takes place at specialized companies. With spindle trees, the lower trunk still has side branches. With transplanted avenue trees these lower branches are removed, leaving a crown on the tree. The transplanted avenue trees grow and become high avenue trees. In comparison to other tree nursery crops, the cultivation of transplanted and high avenue trees is relatively extensive. The trees are planted in rows with a distance of approximately 1.0 m between the trees in a row. The distance between the rows of trees is about 1.5 m for spindle trees and 2.0 m for transplanted and high avenue trees. These paths allow access to the trees. The cultivation of avenue trees is usually carried out on bare ground. The soil is kept free from weeds by applying herbicides or mechanical weed control.

Fig. 2. Avenue trees in three stages, from left to right: spindle trees, transplanted trees (pruned lower branches and developing crown) and high trees (>5 m).

Table 1 gives an overview of the available classes of application techniques that can be used in fruit orchards and avenue tree nurseries, for upward and sideways applications and for downward applications (DRT = drift reducing technology). Since January 2018 the Dutch Environmental Activities Decree requires the use of at least a 75% reducing application technique (DRT75) for all

PPP applications in outdoor crops. Therefore the DRT50 class was omitted form this table. Note that not all DRT classes are available, i.e. currently for some classes no real application techniques are available.

Table 1. *Available classes of spray application techniques for upward and sideways applications in fruit orchards and avenue tree nurseries*[1]

Scenario	Prchard type	Conventional	DRT75	DRT90	DRT95	DRT97.5	DRT99
Fruit-US	Variable canopy density	X	X	X	X	X	X
Avenue-US	High avenue trees	X	X		X		
	Transplanted trees	X		X			
	Spindle trees	X		X			
Fruit-DWN & Avenue-DWN	Fruit orchards and tree nurseries	X	X	X			

[1]Cells for technique classes that currently are not available are left empty.

Spatial and temporal variables

The scenario modelling for upward and sideways spraying in avenue tree nurseries is less complicated than that for upward and sideways application in fruit orchards. This also holds for downward applications in both fruit orchards and avenue tree nurseries. Table 2 shows the spatial and temporal variables involved with modelling the different spray application scenarios in fruit and avenue tree crops. The scenario for upward and sideways treatments in pome fruit orchards ('Fruit US') is most flexible; this case is described by the SPEXUS model (Holterman *et al*., 2017; Boesten *et al*., 2021). For Fruit-US, the spatial variables involve 14 meteorological districts (with distinct weather conditions), 44 waterbody types, nine water levels in the watercourses, 18 orchard orientations (orientation of tree rows with respect to geographical north) and the four sides of a rectangular orchard. These spatial variables are described in more detail elsewhere (Holterman *et al*., 2020; Boesten *et al*., 2021). Typically, for each spatial variable a probability distribution is derived (e.g. probability to find a certain waterbody type with a certain water level next to a random fruit orchard in some district). All spatial variables combine to approximately 74,000 distinct configurations. Regarding the temporal variables, these variables change over time (e.g. dependent on the day-of year, DOY). BBCH is used to represent the canopy density as a function of DOY, which affects the interception of the spray by the tree foliage. Clearly, the meteorological variables are temporal; they follow different frequency distributions for different regional districts.

In the other three cases of Table 2, currently there is no such sophisticated model to compute spray drift deposits onto edge-of-field waterbodies. Consequently, some spatial and temporal variables are not represented in their corresponding exposure models. Experimentally obtained and mathematically fitted deposition curves are used instead. Specifically, in these cases the only temporal variable is wind direction with respect to the orientation of the orchard or nursery. Considering spray drift deposits, the effective wind direction must be determined; this is defined as the wind direction with respect to the direction of a cross wind at the field edge (i.e. perpendicular to the field edge).

Countrywide and local exposure levels

For Fruit-US, the countrywide scenario consisted of a multi-year spray drift simulation (e.g. 100 years) for all spatial configuration, where the temporal variables were randomly drawn from their respective probability distributions (Holterman *et al*., 2020; Boesten *et al*., 2021). This resulted in about 7.4 million concentrations (PEC) of pesticides in the watercourses throughout the Netherlands; these PECs were ordered as a cumulative probability distribution (*cpd*). The 90th percentile value of these PECs (PEC_{90}) was selected for evaluating the exposure risk. This simulation process was

carried out for different dates of spray application, one or more applications per year (at one-week interval) and different crop-free buffer zones. These covered 350 simulations, each producing its own PEC_{90}.

Table 2. *Spatial and temporal variables in scenario models for fruit tree orchards and avenue tree nurseries* (*from Holterman* et al., *2022*)

Spatial variables	Fruit US [1]	Avenue US	Avenue DWN [1]	Fruit DWN
Districts	X			X
Waterbody types	X	X	X	X
Water level	X	X	X	X
Orchard orientation	X			X
Side of orchard where waterbody is located	X	X		X
Temporal variables				
BBCH (DOY)	X			
Wind speed	X			
Wind direction	X	X	X	X
Temperature	X			

[1]US = scenarios with upward and sideways applied sprays; DWN = scenarios with downward applied sprays (herbicide treatments underneath the trees).

The same simulations were carried out for the selected local configuration separately. By definition this involved just one spatial configuration, so the number of simulated years had to be increased (e.g. 10,000) to obtain a clear and reproducible local *cpd*. The PEC_{90} from the countrywide *cpd* was looked up in the local *cpd*, which would occur at a different cumulative probability. The latter local probability corresponding to the countrywide PEC_{90} was called the 'temporal percentile' T_{90}. In this way, each countrywide PEC_{90} corresponds to a local T_{90}. Thus, studying the local configuration for some spray application, the countrywide exposure risk can be evaluated by determining the PEC corresponding to the T_{90} in the local *cpd*.

A similar approach could be applied to the scenarios Avenue-US, Avenue-DWN and Fruit-DWN, even though these scenarios were limited in both spatial and temporal variables. For instance, in the Avenue-US scenario 216 spatial configurations could be identified, while on the temporal part 180 wind directions were assumed (i.e. full compass card, 2° resolution) (Holterman *et al*., 2022). As an example, the blue curve in Fig. 3 shows the *cpd* for a single conventional spray application in high avenue trees (for the whole of the Netherlands and for many simulated years). On the x axis the PECs due to spray drift deposition are given. Point A refers to the 90th percentile level, giving a PEC_{90} of about 16 $mg \cdot m^{-3}$ (assuming an applied dosage of 1 $kg \cdot m^{-2}$). The orange curve in Fig. 3 represents the *cpd* for the local selected configuration, represented by a common edge-of-field watercourse next to fruit orchards and tree nurseries. The variation of local PECs is purely temporal (due to varying wind directions over 1,000 simulated years), as the spatial conditions are fixed by the local selection. Point B reflects the situation where the local PEC equals PEC_{90} and returns the temporal percentile T_{90} (which is 80% here, approx.). This means that in 80% of all simulated years the PEC in the local ditch was lower than PEC_{90}, while in 20% of the years it was higher than PEC_{90}. Thus, in this example the 80th percentile PEC value for the selected local configuration equals the countrywide 90th PEC value. This example shows how the local situation can be used to estimate countrywide exposure levels.

This procedure was carried out for all scenarios of Fig. 1, for application techniques covering the classes of Table 1, for 1 to 10 spray applications per year and for additional crop-free buffer

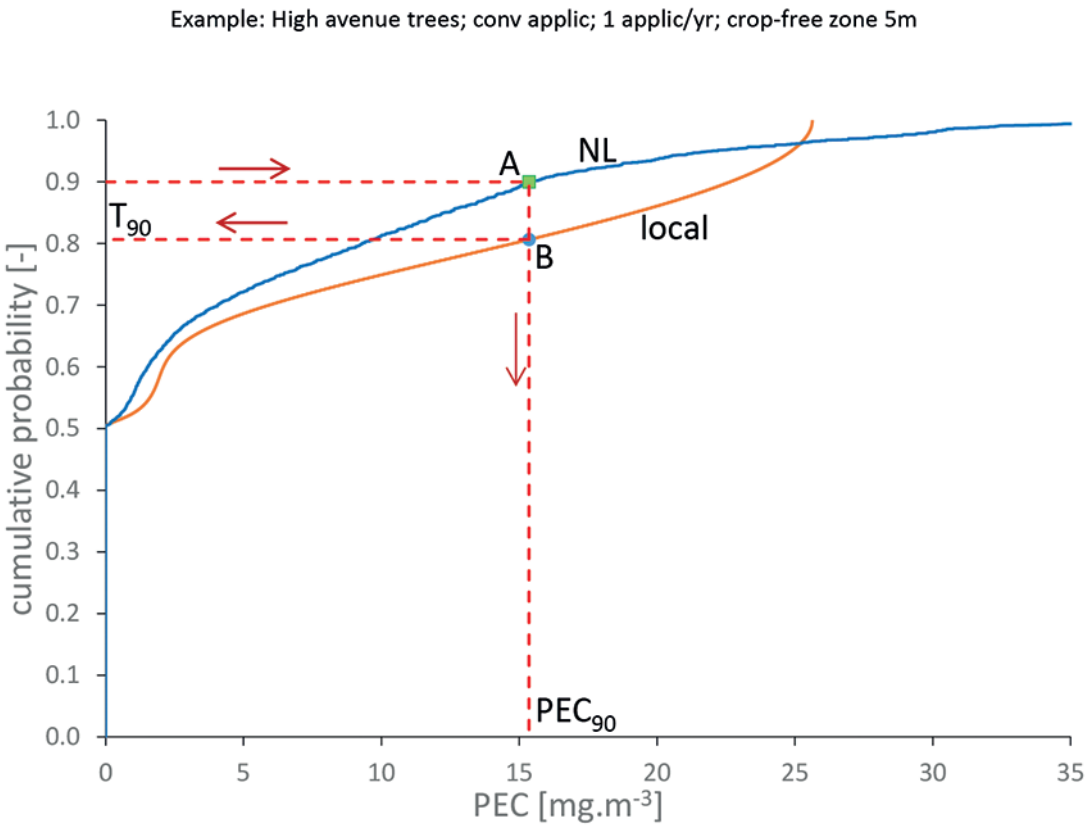

Fig. 3. Procedure to find the temporal percentile T_{90} for the local situation, representing the countrywide PEC_{90}. See text for detailed description. Blue curve: countrywide *cpd*; orange curve: local *cpd* (scenario: high avenue trees US, 1 conventional application/year, crop-free zone 5.0 m). (from Holterman *et al*., 2022).

zones 0 to 9 m. For instance, for high avenue trees (US) this meant 300 different cases (three technique classes, 10 application sequences, 10 crop-free buffer zones). Each of these cases returned a countrywide PEC_{90} and a corresponding local T_{90}. For Fruit-US also the day-of-year (DOY) was a factor considered, since the density of the fruit tree canopy changes throughout the year which affects the interception of the spray by the canopy. The DOY was not a factor with avenue trees since the spray drift model could not be resolved for canopy density (due to limited experimental data). It was also considered less important because of the different pesticide treatment scheme in avenue tree nurseries.

Results

Fig. 4 shows PEC_{90} and corresponding T_{90} values for fruit-US, with three spray applications in spring, for different drift reducing application techniques and different crop-free buffer zones. Generally, PEC_{90} decreases with increasing buffer zone and higher DRT class. The local T_{90} values appear to be relatively stable between 0.35 and 0.60, slowly rising with increasing crop-free buffer zone but without a clear relation to DRT class. Apparently, with minimal (zero) crop-free buffer zone the local temporal percentile T_{90} of about 0.4 can be used to find the countrywide PEC_{90}, while with a 9 m crop-free buffer zone a T_{90} of about 0.6 is needed. Full explanation of this effect is beyond the scope of this paper, but it reflects that the effect of a crop-free buffer zone is different for different waterbody types (i.e. a crop-free buffer zone appears to be slightly less effective for 'sensitive' (high-PEC) waterbodies than for other waterbodies). Similarly, Fig. 5 shows PEC_{90} and T_{90} values for the avenue-US scenario, with a conventional spray application and different crop-free buffer zones in all three growth stages.

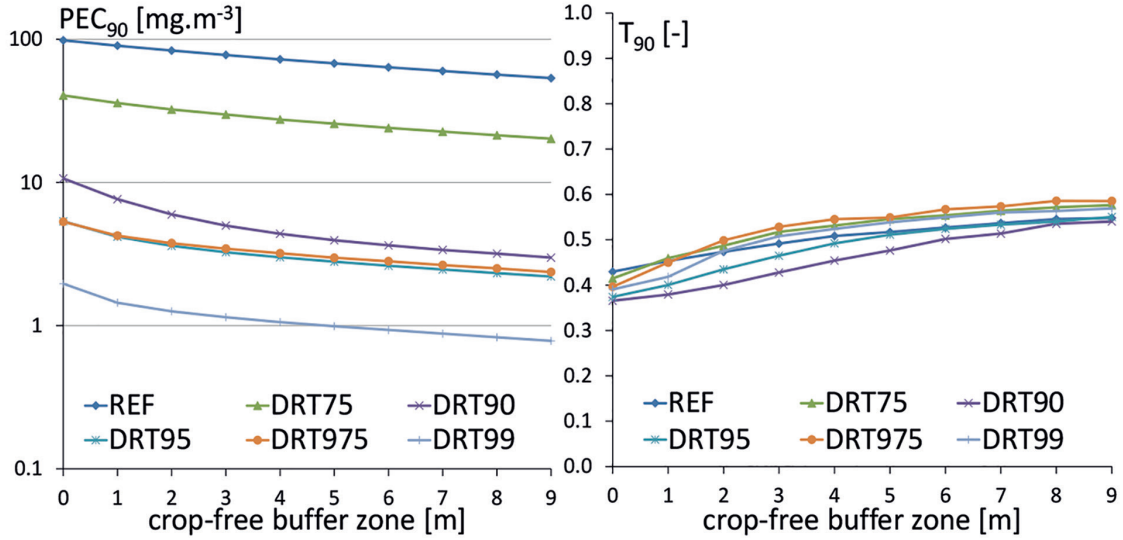

Fig. 4. Some results of countrywide simulations for fruit-US, for three successive applications in spring (1 week interval), different application techniques and crop-free buffer zones. *Left*: countrywide PEC_{90} values (applied in-field dosage 1 kg·m^{-2}); *right*: local T_{90} values.

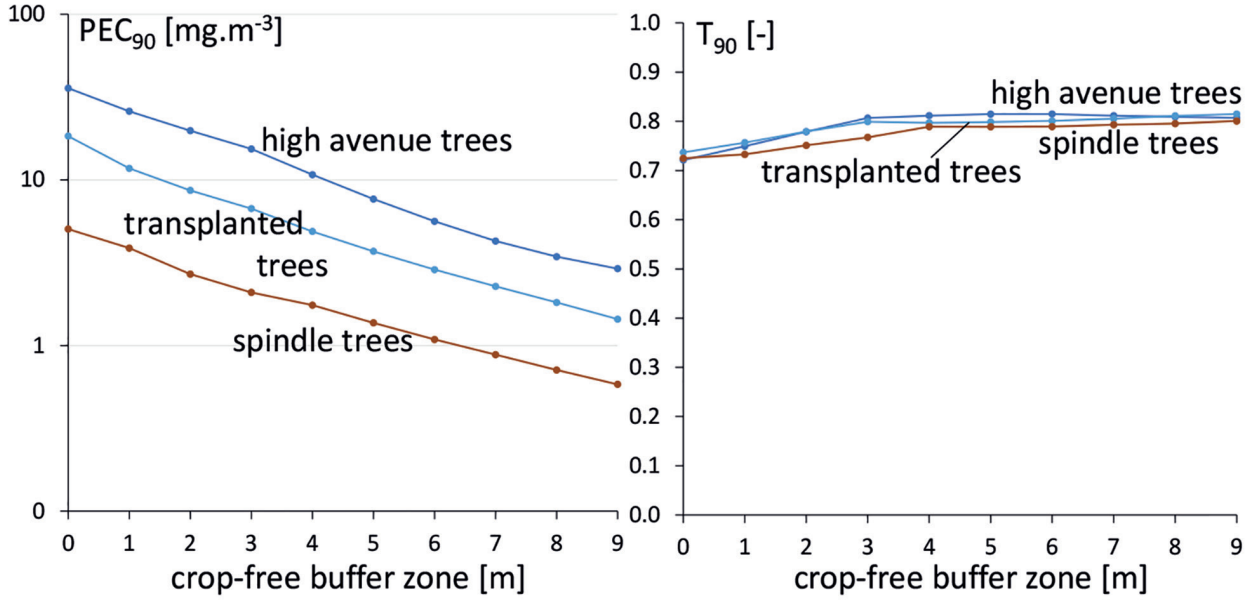

Fig. 5. Some results of countrywide simulations for avenue-US, for 1 conventional application and crop-free buffer zones. *Left*: countrywide PEC_{90} values (applied in-field dosage 1 kg·m^{-2}); *right*: local T_{90} values.

Discussion

Different spray drift models have been developed to evaluate the countrywide exposure of edge-of-field watercourses to spray drift deposition. The locally selected spatial configuration can be used as a monitoring situation. The countrywide 90th percentile PEC value is found for the local situation at a different (temporal) percentile, T_{90}, PEC_{90} and T_{90} values have been determined from simulation studies for upward and sideways spray applications in fruit orchards and avenue tree nurseries, and for downward spray applications to the ground below these fruit and avenue trees. Effects of application techniques from different DRT classes, a range of crop-free buffer zones and one or more treatments per year were determined as well. For fruit-US the model approach

has a high level of realism. For the other scenarios various simplifications had to be implemented since the limited variation in of experimental conditions did not allow to develop models with the same level of realism there. Still, the approach offers a considerable improvement compared to simpler worst-case studies. The spray drift models are combined with the TOXSWA fate model and were built together into the DRAINBOW model. A certain scenario situation is run using the DRAINBOW model for a limited number of years for the locally selected watercourse, producing exposure concentrations in the watercourse for each year, considering both spray drift and drainage as entry routes. The years are ranked regarding increasing annual maximum PEC, assuming the exposure risk for aquatic organisms is caused by acute toxic effects. Then the T_{90} corresponding to the given scenario also reflects the temporal percentile of the simulated years. As an example, say T_{90} is 0.6 and 10 years are simulated, then the 6th ranked year of the local simulation represents the countrywide 90% exposure risk. In fact, this is only true when spray drift is the dominant route for exposure. The evaluation procedure was adjusted slightly when the drainage route becomes significant. The latter procedure is discussed in detail by Boesten *et al*. (2021).

In this way, the chosen probabilistic approach as shortly described in this paper offers a realistic possibility to evaluate the exposure to and fate of pesticides in surface waters to quantify exposure risk levels for aquatic organisms. This serves higher-tier assessment studies for the authorization of plant protection products.

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