Research Article

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A simple approach for a spatial terrestrial exposure assessment of the insecticide fenoxycarb, based on a high-resolution landscape analysis

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Abstract

BACKGROUND: The objective was to refine the standard regulatory exposure scenario used in plant protection product authorisations by developing a more realistic landscape-related GIS-based exposure assessment for terrestrial non-target arthropods. We quantified the proportion of adjacent off-target area in agricultural landscapes potentially exposed to insecticide drift from applications of the active substance fenoxycarb. High-resolution imagery, landscape classification and subsequent stepwise analysis of a whole landscape using drift and interception functions were applied to selected areas in representative fruit-producing regions in Germany.

RESULTS: Even under worst-case assumptions regarding treated area, use rate and drift, less than 12% of the non-agricultural habitat area would potentially be exposed to fenoxycarb drift above regulatory acceptable concentrations. Additionally, if the filtering effect of tall vegetation were taken into account, this number would decrease to 6.6%. Further refinements to landscape elements and application conditions indicate that less than 5% of the habitat area might be exposed above regulatory acceptable concentrations, meaning that 95% of the non-agricultural habitat area will be unimpacted (i.e. no unacceptable effects) and can serve as refuge for recolonisation.

CONCLUSION: Approaches and tools are proposed for standardisable and transparent refinements in regulatory risk assessments on the landscape level.

Supporting information may be found in the online version of this article.

Keywords: fenoxycarb; higher tier; exposure assessment; landscape analysis

1 INTRODUCTION

One of the many requirements underlying the authorisation of plant protection products is for an ecotoxicological risk assessment based on ecotoxicological studies and exposure scenarios.

The initial risk assessment is based upon simple but conservative ecotoxicity test designs and exposure scenarios. According to the regulations in Germany, the assessment should predict no unacceptable effects to terrestrial non-target arthropods (NTAs) in the immediate vicinity of the treated crop. 'Immediate vicinity' in this case is equivalent to a distance of ≥3 m in all directions around tall crops (orchards, viticulture, hops) and a distance of ≥1 m for arable crops. A product may only be authorised if there is a sufficiently high safety margin between the predicted exposure levels and the laboratory measured effect thresholds. If this margin of safety is not met, the applicant may refine the risk assessment using more sophisticated ecotoxicological test designs or more realistic exposure scenarios.

The toxicity of the active substance fenoxycarb (cf. EFSA[1]), used for control of insect pests (tortricids) on apples and pears, means that the standard risk assessment for NTAs is failed and that the introduction of typical risk mitigation measures to the assessment still does not achieve a pass. Therefore, this paper presents the outcome of refining the standard risk assessment for NTAs using a landscape-based approach. Specifically, this involved quantifying the portion of the non-cropped areas in an agricultural landscape

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in which the required margin of safety would not be met, as this defines the level of protection for NTAs in this landscape. The standard regulatory risk assessment scenario is clearly unrealistic on the landscape level, because its default assumption is that the wind blows simultaneously in all directions at high speed during every application event. This assumption will generate unrealistically protective results when considered at the landscape scale. Conversely, if real-world landscape data are used to refine the exposure assessment, it is more likely that the predicted exposure will not exceed toxic thresholds.

The advantages of the refined exposure assessment approach proposed here are (i) to show the area where the regulatory acceptable concentration is not predicted to be exceeded (under conditions that are worse case but still on the realistic side) and (ii) to provide a more transparent basis for a regulatory decision, including, for example, a risk benefit analysis by balancing remaining areas of concern versus the relevance of the evaluated pesticide for the growers, to maintain regional fruit production.

Several studies have shown that the precise mapping of the landscape depends upon the area scale being mapped, the desired scale of analysis and the method selected for feature extraction and classification.[2–7] Consequently, as we wished to examine proximity at the single metre scale in a buffer of up to 20 m around the orchard in this study, we used (very) high-resolution imagery (resolution between 0.25 and 1 m) and object-based image analysis (OBIA) as a basis for estimating the potential exposure of non-agricultural habitats (subsequently called 'biotopes'; cf. Enzian[8] and Gutsche[9]) to spray drift during applications of fenoxycarb.

The aim of this geodata-based landscape classification and analysis study was to generate an approach for refined and more realistic exposure assessment, as required for the reauthorisation of the insecticidal formulation INSEGAR (250 g kg^{-1} fenoxycarb) in Germany. This was achieved by using geodata at various scales in accordance with concepts developed and summarised during a workshop on 'Probabilistic Assessment Methods for Risk Analysis in the Framework of Plant Protection Product Authorisation' at the German Environment Agency (UBA) in 2003.[10] The integration of the procedures described in this paper into a higher-tier risk assessment should be considered as a 'straw man' proposal for how such refinements might be performed. If adopted, the quality of the resulting risk assessments and the reliability of their conclusions might be improved by processing additional orchard regions and developing a broader database on drift processes in tall vegetation.

2 MATERIALS AND METHODS

2.1 Selection of the regions of interest and areas under investigation

2.1.1 Overview of the procedure

As fenoxycarb is an insecticide for pest control in pome fruit, the landscape analysis focused on typical orchard regions in Germany, comparable with the concepts reported by Verro *et al.*[11] as 'stepwise zooming'. Such regions with a substantial coincidence of pome fruits and biotopes were designated 'regions of interest' (ROI). The identification of ROI and subsequent analysis of their representativeness were conducted using Germany-wide available coarse-level data (one dataset with a resolution of 100 m and one dataset based on municipality level; cf. next section).

Eventually, three ROI were selected for further detailed analysis. The three ROI were selected to represent low, medium and large orchard sizes and different degrees of scattering (low to high) of orchards in the landscape, as described in detail in the next section. This analysis was conducted for limited areas within each ROI, designated 'areas under investigation' (AUI). (Very) high-resolution (hr) remote sensing images (spatial resolution 0.25–1 m) were obtained for the refined landscape analysis of the AUI. Medium-resolution vector data (scale range 1:10.000 to 1:50.000) were used only to identify and exclude areas that were not relevant in the context of this study, e.g. urban areas, roads, etc.

2.1.2 Geodata used

2.1.2.1 Coarse geodata for selection of the ROI. Identification of the ROI was based on two Germany-wide available geodatasets, the CORINE (http://www.corine.dfd.dlr.de/intro_de.html) dataset with a pixel resolution of 100 m and the so-called 'biotope index' (BI)[8,9] coverage based on the municipality level. The BI is calculated by the following formula:

$$BI = \frac{\text{sum of biotope structure area}}{\text{sum of biotope structure area} + \text{sum of agricultural area without grassland}} \times 100$$

Consequently, a high BI value implies a high amount of biotope structures in the respective community, whereas a low BI value corresponds to a lower biotope percentage. The median BI of the ~680 fruit-producing municipalities in Germany is 23, with a tenth percentile of 9 and a 90th percentile of 40.

Predominant orchard types within the CORINE orchard regions were identified on the basis of statistical reports issued by the federal states of Rhineland-Palatinate and Baden-Württemberg and information from the official agricultural authorities.[12]

Based upon a spatial merging of both datasets (CORINE and biotope index), the following three ROI were identified, which were deemed to cover a broad spectrum of German pome fruit growing with regard to potential fenoxycarb use, pome orchard density/scattering and BI range (see supporting information Fig. S1):

- Rhine-Hesse (several small, scattered orchards, mean BI = 15) close to the city of Ingelheim in the centre of the federal state of Rhineland-Palatinate, as representative of orchard regions with a mixture of areas of intensive orchard production (e.g. large orchard plantations, high density of plants, also with espalier fruit) and more scattered cultivation.
- Eastern part of the Lake Constance region (many large orchards, mean BI = 34) close to the city of Friedrichshafen in the south of the federal state of Baden-Württemberg, as representative of intensive orchard cultivation.
- Middle Rhine Valley close to the city of Koblenz (a few orchards in a very diverse landscape, mean BI = 31) in the north of the federal state of Rhineland-Palatinate, as representative of a diverse landscape with low intensity of orchards.

The three ROI selected for this study encompass an orchard production area of about 184 km^2, based on CORINE, which is equivalent to 15% of the entire orchard area in Germany.

Detailed results are only presented here for Rhine-Hesse, because the analysis showed that this region represents a worst case in terms of potentially affected 'biotope' area.

In this paper, the word 'biotope' is applied to non-agricultural habitats for NTAs, in order to use the same idiom as in the 'biotope index',[8,9] which is of specific regulatory relevance in Germany.

The ROI Rhine-Hesse is the largest fruit-growing region in Rhineland-Palatinate and covers about 2880 ha, which represents

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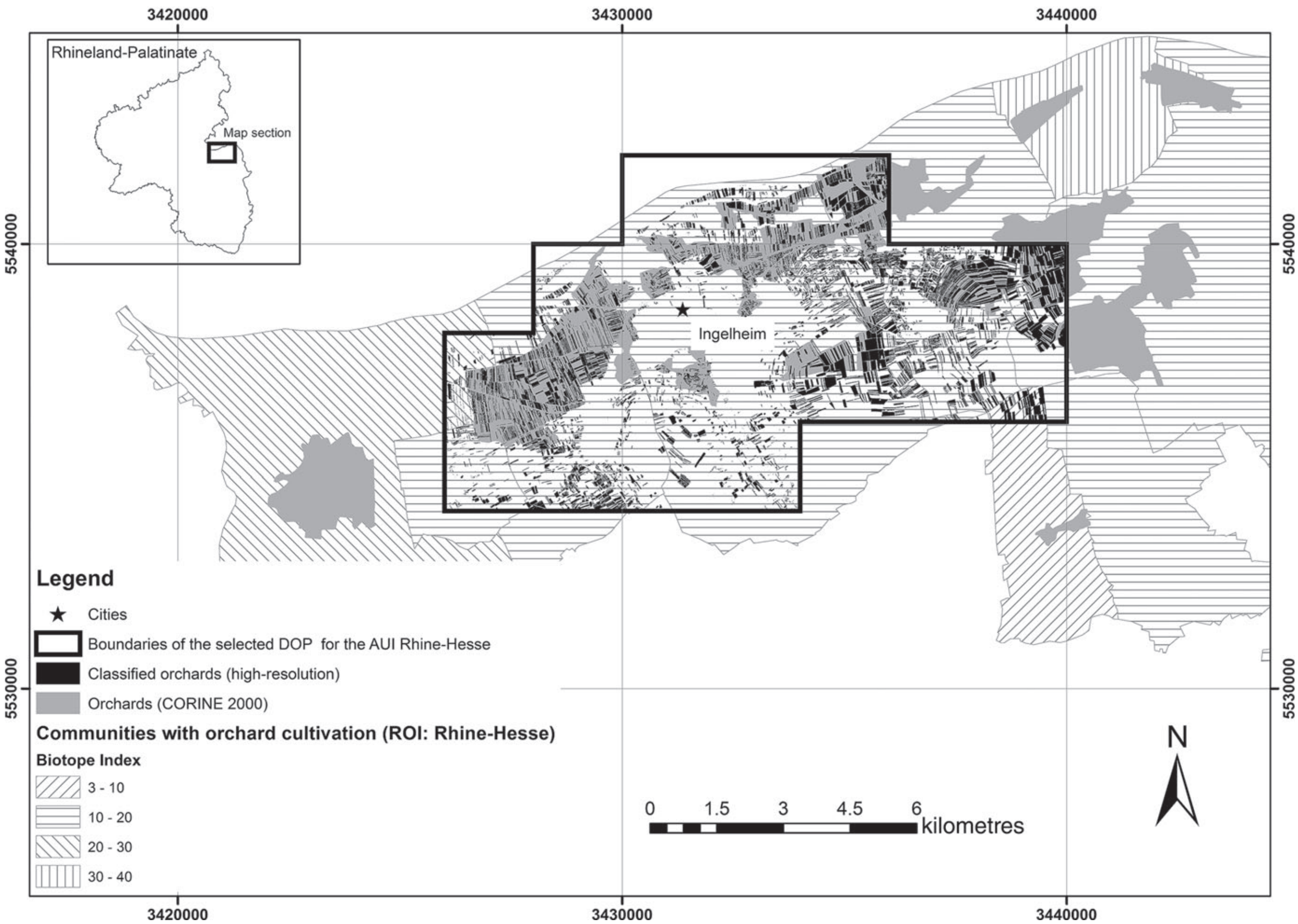

Figure 1. Overview of the location of the ROI and AUI in Rhine-Hesse.[8,9]

31% of the whole growing region in Rhineland-Palatinate. A 1400 ha orchard area was analysed in high resolution.

The AUI was located in the centre of the ROI Rhine-Hesse. The included orchard areas were distributed rather regularly over the whole AUI (see Fig. 1).

Details of fenoxycarb use were supplied by local experts from the Chambers for Agriculture of the federal states.

2.1.2.2 High-resolution geodata within the AUI. According to the method of Enzian[8] and Gutsche,[9] a 500 m buffer was drawn around the orchards identified by the high-resolution analysis, and the area covered by this buffer was defined as the AUI.

Digital orthorectified aerial photographs (DOPs)[13] and satellite images (IKONOS2 mission, http://www.euspaceimaging.com/) were used for the refined landscape analysis in the selected AUI.

- DOPs were used for the AUI Rhine-Hesse and Middle Rhine Valley. These RGB-DOPs have a pixel size of 0.25×0.25 m. The spatial accuracy of the images is ± 3 m. The DOPs were mostly taken in the year preceding the analysis. Neither four-channel DOPs with near-infrared nor photogrammetric-based surface models were available for this project.
- Multispectral remote sensing images from the IKONOS2 mission were used for the Lake Constance (Bodensee) region. The scene covers an area of about 165 km^2. The data have a spatial resolution of 1 m panchromatic (PAN) and 4 m multispectral (MS) and were orthorectified and preprocessed.

2.2 Landscape classification

The process of high-resolution landscape classification covers two distinct steps:

- The definition of landscape features that are relevant to the objective of the study, i.e. the development of a 'classification scheme'.
- The identification and classification of these defined landscape features in the (very) high-resolution (hr) images to which individual objects (e.g. single fruit trees, orchards, forests, bushes) belong. This step was principally conducted using the object-based software package eCognition (http://www.trimble.com). The segmentation process performed with eCognition results in objects as a geometric basis to differentiate, for example, bushes and (individual) trees from meadows or arable fields. Surface model data to capture three-dimensional (3D) features were not available for this study. The differentiation between 3D non-agricultural habitat vegetation (which normally is heterogeneous and of irregular shape) and tall arable crops such as maize fields (which have a homogeneous and symmetrical stand) was done by using shape parameters such as compactness and asymmetry from the segmentation process in eCognition, as well as by on-screen digitising and correction of the semi-automated generated objects. The raw IKONOS scene was preprocessed using ERDAS Imagine software (http://www.hexagongeospatial.com/products/producer-suite/erdas-imagine). Post-processing

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of the classification results and all additional landscape analysis were conducted using ArcGIS (http://www.esri.com/software/arcgis), VBA and Python scripting.

2.2.1 *Classification scheme*

Two relevant parent landscape classes were defined, the parent class 'treated' and the parent class 'to be protected':

- 'Treated' comprised orchards that were potentially treated with the product (espalier trained as well as (more) standard orchards with individual fruit tree planting).
- 'To be protected' comprised 3D non-target biotope areas, such as bushes, hedgerows, trees, etc.

The 'to be protected' class was restricted to 3D biotopes because the available data and tools could not distinguish two-dimensional (2D) biotopes (such as extensively used grassland) from other vegetated, agriculturally used, 2D structures. However, the error resulting from this classification constraint was comparatively small, because 2D biotopes only constituted 6.2% of the overall biotope area. This percentage derived from a spatial merging of official biotope cadastre information from the LANIS portal (Landschaftsinformationssystem der Naturschutzverwaltung Rheinland-Pfalz, http://map1.naturschutz.rlp.de/mapserver_lanis/) with the classification results derived within this project. This merging identified 139.8 ha of grassland within the 20 m buffer around orchard areas. During the 'step 2' analysis (cf. Section 2.3.1), this area was shown to include 122.3 ha that was characterised as 'impacted by agricultural activity' (e.g. by fertilisation, occasional tillage, livestock farming or treatments with plant protection products) according to the official biotope cadastre. This meant that this 122.3 ha did not fall under the definition of 'biotope'. The remaining 17.5 ha of grassland was equivalent to 6.2% of the total biotope area (i.e. the sum of 265.9 ha of 3D biotopes identified at step 2 plus 17.5 ha of 2D biotopes from the biotope cadastre).

Other landscape features (e.g. arable fields, urban areas, roads, etc.), derived from the dataset ATKIS (Authorised Topographical Cartographical Information System, http://www.lvermgeo.rlp.de, http://www.lgl-bw.de), were not regarded as relevant for the purpose of the analysis and therefore were not considered in subsequent processing.

2.3 Landscape analysis

The risk assessment was based upon a georeferenced proximity analysis of the 'treated' orchards and the 'to be protected' biotopes based on the high-resolution landscape classification.

A first assessment, identified here as the 'default approach', was based on default regulatory assumption; i.e. where applicable, it was assumed that fenoxycarb would be applied once at the full rate of 150 g ha^{-1} to every orchard identified in the AUI, and that worst-case drift conditions would prevail at each application (i.e. drift calculated as described in Rautmann *et al.*[14] for the regulatory assessment).

This default approach was then 'refined' in order to generate a more realistic estimate of the potentially impacted biotope area, e.g. by making more realistic assumptions concerning the number of applications, the use rate, drift processes, etc., as will be explained further below. The resulting 'refined approach' comprised various elements, some of which increased the regulatory conservativeness (e.g. two applications instead of just one) while others decreased the regulatory conservativeness (e.g. assuming the application of fenoxycarb only on crops where it was authorised).

A flow diagram comparing the analysis steps of the default and refined approach is shown in Fig. 2.

The following assumptions were made for the default approach:

- All orchards are treated with the product at the same time.
- Treatments are conducted by applying equipment and measures to achieve 90% drift reduction.
- Applications of fenoxycarb start in the spring before full foliage is reached, and therefore the Rautmann *et al.*[14] drift scenario 'orchards early' is used to estimate potential off-target movement.
- Detrimental effects on non-target arthropods may occur where the predicted exposure from drift exceeds the lowest toxicity endpoint from laboratory studies. Therefore, this proportion of the biotope area is regarded as a 'potentially drift-impacted area' (PDIA).

2.3.1 *Stepwise landscape analysis*

The GIS-based landscape analysis and exposure assessment were conducted stepwise with increasing levels of realism. An overview of the steps in the default approach is given below.

Step 1: Identification of all biotopes that might (in part or to their full extent) be exposed to drift concentrations above the regulatory threshold. These are all biotopes that are partially or fully located within a 20 m distance from any orchard (buffer distance based on product toxicity, use rate and selected drift scenario tables).

Step 2: Calculation of theoretical maximum PDIA. Under the unrealistic assumption that wind blows from all directions simultaneously during all application events, the theoretical maximum PDIA is equivalent to the sum of the biotope area within a 20 m distance from all orchards.

Step 3: Calculation of realistic worst-case PDIA. Under the assumption that the wind only blows from one of the eight cardinal wind quadrant directions during the application period, individual PDIAs were calculated (one for each cardinal wind direction).[15–17] The realistic worst-case PDIA is the largest of these eight individual PDIAs.

Step 4: Calculation of realistic PDIA. The realistic worst-case PDIA from step 3 was refined through consideration of potential interception by tall vegetation (hedges, bushes, etc.) based on the width of such vegetation elements. This was achieved by applying a specific drift curve based on drift measurements in hedges, using published data from Gove[18] and Koch *et al.*[19]

In Fig. 3, an example for steps 1 to 3 is shown for two wind directions. In this example, the largest PDIA is in the north-west direction, i.e. wind blowing from the south-east is the worst case. An aerial image showing more details of the directional exposure analysis is presented in supporting information Fig. S2.

The worst-case PDIA from step 3 (i.e. the largest PDIA from the eight cardinal wind directions) is a conservative estimate because it is based on the unrealistic assumption that the drift events will always be directed in the worst-case wind directions. In reality, along with wind speeds, the frequency of the wind direction determines the probability of a biotope being affected by drift.[15,17,20–22] Therefore, a more realistic estimate of the PDIA was achieved by weighting the calculated eight PDIAs with the probability of the corresponding wind direction. Statistics on the distribution of directions for winds with speeds of <5 m s^{-1} (i.e. according to good agricultural practice, also the basic assumption in regulatory calculations)[14] for Rhine-Hesse in the

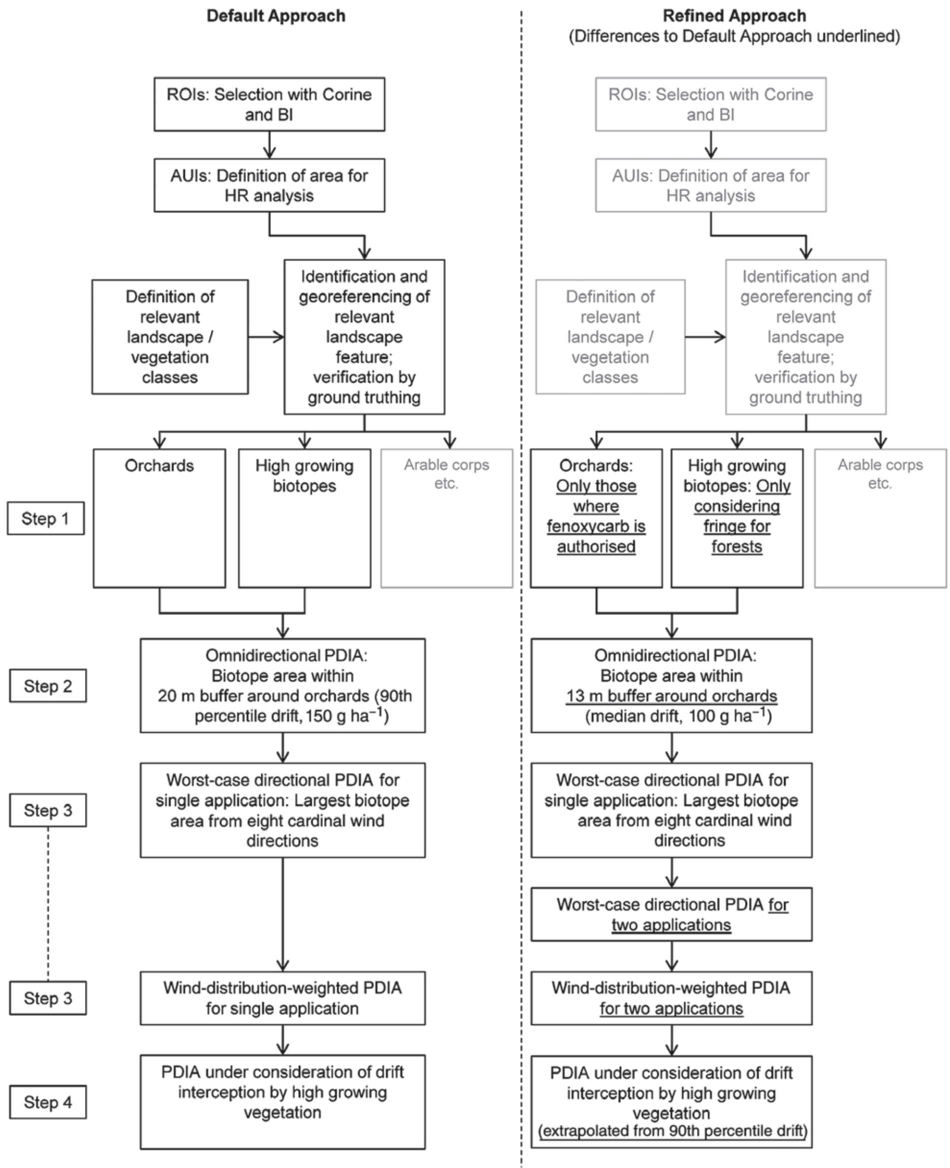

Figure 2. Flow diagram showing the analysis steps of the default and refined approaches.

months of March to May (when fenoxycarb was being applied), provided by the DWD (German Weather Service), are listed in Table 1.

The step 3 PDIA does not account for interception of drift by tall (3D) vegetation in the biotopes. This reduction was applied in step 4 to the PDIA resulting from step 3, to account for the filtering effect of tall vegetation structures (e.g. hedges, bushes, trees). The filtering effect was calculated by means of a first-order multicompartment function fitted to data points derived from deposited residues measured on leaves after drift experiments in hedges.[18,19] This approach is described in more detail in the supporting information.

As step 4 required a large amount of computing time, it was only calculated once for the default approach in the AUI Rhine-Hesse. The resulting filtering factor for Rhine Hesse (a reduction in the PDIA by a factor of 1.75 from step 3 to step 4) was then used to extrapolate the step 4 PDIA in the refined approach.

The refined approach (steps 1 to 4) is explained in detail below.

2.4 Refined approach

2.4.1 Refinement of the drift scenario

For the default approach, the 90th percentile value of the regulatory drift tables was applied in order to provide a realistic worse case. However, to simulate various applications at various sites and with wind from several directions (directing off-target drift directly towards, at an angle to or directly away from the biotope), the use of the median (i.e. the 50th percentile) is more representative of a realistic exposure (Rautmann D, private communication, 2007). The AUI in the landscape analysis comprise several thousand individual orchards to which fenoxycarb is applied over a period of several days. It can be assumed that essentially independent and different drift conditions will prevail for each individual application.[15,17,21,22] The most probable drift deposition from off-target drift in a multitude of independent application events is the median measured value, and by definition this is the value with the lowest associated measurement uncertainty. Therefore, the median deposition data from spray drift studies conducted by the Julius Kühn-Institut were used.[24]

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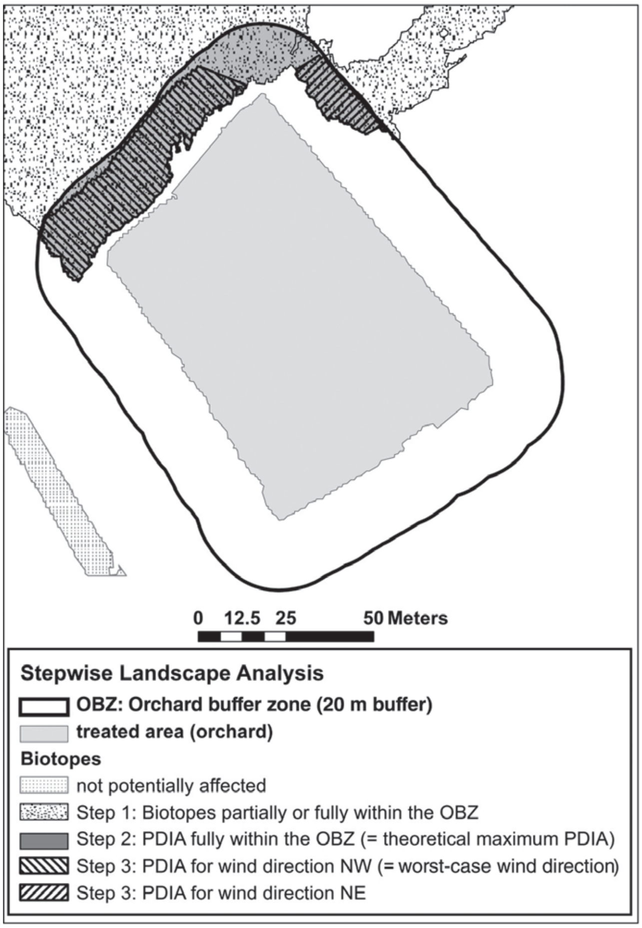

Figure 3. Directional exposure analysis (step 1 to step 3) example for two selected wind directions (north-west and north-east).

Table 1. Frequency of the cardinal wind directions calculated for the Ingelheim area (Rhine-Hesse) for the months of March to May and for wind speeds below 5 m s^{-1} [23]

Cardinal wind direction (direction the blowing wind comes from)	Frequency (%)	Resulting direction of the impacted biotope (direction of the flowing-off wind) (deg)
NE	24	225
E	10	270
SE	5	315
S	13	360
SW	21	45
W	7	90
NW	8	135
N	11	180

Assuming the 90th percentile of the spray drift tables and the full fenoxycarb use rate of 150 g ha^{-1}, the PDIA would extend up to a distance of 20 m from the treated orchards. In a refined approach, using the more realistic median (see the supporting information), the PDIA would extend only up to a distance of 15 m from the treated area.

2.4.2 *Refinement of the use rate*

The PDIA can be further refined with more realistic assumptions concerning the use rate of fenoxycarb. The maximum label rate of 150 g ha^{-1} is the rate foreseen for large fruit trees with a tree height of 3 m. However, in practice, fruit tree height in commercial orchards rarely exceeds 2 m in order to facilitate maintenance measures and harvest. Furthermore, the full use rate is only used where there is a heavy pest infestation. According to information from the Federal State Extension Service, the typical use rate of fenoxycarb in Rhine-Hesse does not exceed 100 g ha^{-1} (because commercial orchards with tree heights of $\leq$2 m are the rule). With this use rate and the 50th percentile drift values, the PDIA would only extend to 13 m from the treated crop.

2.4.3 *Refinement of the proportion of orchard area actually treated with fenoxycarb*

This region of Rhine-Hesse is known to be a typical cherry-growing area. The proportion of pome and other fruit (pears, plums/damsons, mirabelles, greengages) where fenoxycarb use is authorised there amounts to 62%.[12]

It was therefore assumed that only 62% of the orchard area of Rhine-Hesse was treated with fenoxycarb. As it was not possible to distinguish different fruit tree species in the DOPs, a statistical allocation of orchard objects to fruit types was conducted by randomly selecting a proportion of the individual orchard area objects and assigning them either to 'fenoxycarb treated' or 'not fenoxycarb treated'. When the total area of the 'not treated' objects corresponded sufficiently precisely to the desired proportion (38 ± 1%) of the whole orchard area, the selected orchards were excluded from the 'orchards' database. All subsequent calculations based on this selection of 62% of the total orchard area, defined as 'treated', required significant computing resources, and therefore this analysis was only conducted once. Repeated Monte Carlo style runs, each one excluding a different randomly selected set of orchards, were not performed, because it was assumed that a repetition would render very similar results owing to the very high number of orchards (ca 20 000).

2.4.4 *Consideration of forest fringe structures*

In the default approach, the whole forest area in the AUI was classified as potential habitat for NTAs. However, arthropod biodiversity in agricultural landscapes is influenced much more by forest fringes than by inner forest areas.[25] For this reason, in the refined approach, only the forest fringes (rather than the whole forest area) were classified as biotopes. The forest fringe was defined as a 20 m deep strip along the forest edge.

Technically, this was achieved by subjecting the biotopes classified as forest areas to a further two-tiered analysis. Firstly, areas of forest smaller than 1200 m^2 (i.e. the approximate area of a circle of 20 m radius) were identified. The remaining areas were rechecked via the aerial image to ensure that they really were enclosed forest areas. If large glades, windfalls, etc., were perceptible, they were eliminated from the area classified as forest. The outer 20 m of these forest areas was then delineated, and only those margins plus the forests of <1200 m^2 were included in the calculation of the whole biotope area.

2.4.5 *Relevance of repeat applications*

As fenoxycarb may be used to control different insect pests occurring at different times of the year, having the option of applying

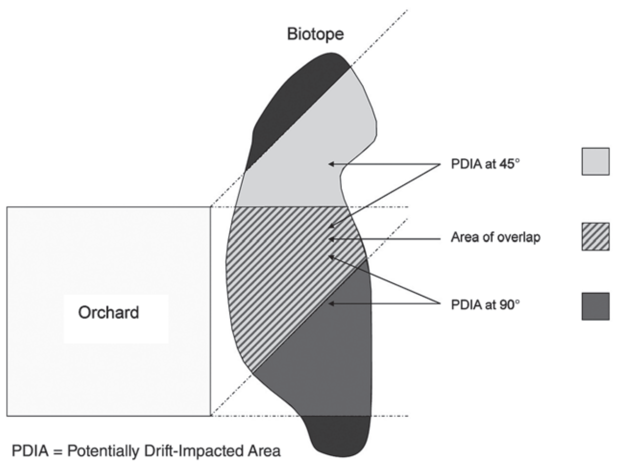

Figure 4. Schematic portrayal for the calculation of the potentially drift-impacted biotope area with two applications and different wind directions.

it more than once to a given orchard would offer increased flexibility to the farmer. Therefore, the default approach with only one application per year was refined by calculating the PDIA after two applications.

For step 3, the PDIA was first determined separately for each cardinal wind direction. The PDIA for two consecutive applications was calculated by adding the PDIAs for each of the two applications and then subtracting the overlap area, as schematically indicated for the wind directions north-east and east in Fig. 4.

As fenoxycarb is a contact insecticide, potential toxicity will depend on the amount of chemical present on the leaf surfaces. To assess whether the assessment should investigate the potential for residue accumulation from multiple applications, available data from foliar dislodgable residue studies (designed to assess worker safety) were used. These showed that surface residues have a half-life of <2 days. Because fenoxycarb repeat applications must be at least 10 days apart, there is no significant potential for residue accumulation, and consequently this was not considered further.

2.4.6 Influence of the wind direction distribution

Analogous to the default approach, the largest PDIA resulting from the above analyses remains a conservative estimate because it is based on the unrealistic assumption that the drift events will always be directed in the worst-case pair of the eight cardinal wind directions. In reality, together with wind speed, the frequency of the wind direction determines the probability of a biotope being affected by drift. Therefore, all 64 PDIAs calculated for the duplicate application scenario were weighted with the probability of wind blowing in their respective directions. A worked example is provided in the supporting information.

3 RESULTS

3.1 Ground truthing

To validate the results of this semi-automated classification process, the whole area was divided into 100 m by 100 m grid subsets. From these grids, nearly 13% was randomly selected. Once border effects were eliminated, a net area of 11% of the whole area remained for cross-checks by ground truthing. This was done in each of the three ROI. In Rhine-Hesse, 94.9% of the classified objects of these randomised selected subsets were found to be classified correctly by comparison with ground truthing data. The most significant misclassifications were incorrect discrimination between biotopes and orchards owing to land cover change, as well as misclassifications regarding the differentiation between vineyards and espalier orchards based on the specific espalier growing methods. In the Middle Rhine Valley and the Lake Constance area, 99 and 98%, respectively, of the relevant areas were classified correctly. Ground truthing is described in more detail in the supporting information. It was felt that ground truthing indicated that the classification had been effective and produced a high-quality dataset for further analysis.

The orchard region Rhine-Hesse demonstrated a more scattered landscape structure and the lowest biotope indices of the three investigated regions. The BI of the investigated area in Rhine-Hesse averaged 15. The comparable values for the Middle Rhine Valley and Lake Constance were 31 and 34 respectively.

The landscape analyses in the default approach revealed that a much larger proportion of the biotope areas was potentially impacted by drift in Rhine-Hesse than in the AUI Lake Constance or Middle Rhine Valley. Therefore, the refined approach with interception (step 4) was only calculated for the AUI Rhine Hesse, and only the results for Rhine-Hesse (default approach and refined approach) are shown here in detail. Results for the other two AUI are available in the supporting information.

Table 2 summarises the results of the stepwise landscape analysis for Rhine-Hesse for the default approach and all potential refinements. The level of realism increases as the analysis progresses from step 1 to step 4 of the basic approach, and then improves further with the refinements of the basic approach.

3.2 Default approach

Over 1400 ha of orchard areas and over 767 ha of 3D biotope areas (wood, bushes, hedges, trees) were identified within an area of 80 km^2 of the orchard region Rhine-Hesse.

In step 1, the total area of all the biotopes in the AUI was determined. This area amounted to 767 ha. Furthermore, biotopes at a distance of ≤20 m from orchard areas were identified. This distance was chosen because the predicted environmental concentration was computed to fall below the regulatory threshold for non-target arthropods (drift scenario 'orchard early', 90% loss reduction) at a distance of approximately 20 m.

In step 2, the biotope area contained completely within the 20 m buffer zone around the orchard areas was determined. Under the unrealistic assumption that the wind blows in all directions at the same time, this would be the maximum possible area of off-target vegetation potentially experiencing exposure above the regulatory threshold for NTAs. This area comprised 266 ha or 34.7% of the total biotope area.

In step 3, this omnidirectional preliminary analysis was extended by determining the potentially impacted biotope area for each of the eight main wind directions.

The propagation of the drift was modelled using the regulatory drift values (scenario 'orchard early'),[14] i.e. interception by vegetation was not taken into consideration. Depending on the wind direction, at this level the potentially impacted biotope area was between 78 and 88 ha. The worst-case direction was 45° (wind from the south-west to the north-east). In this direction, 88 ha of the biotope area (11.5% of the total area) was potentially impacted by drift.

This worst-case PDIA (i.e. the largest PDIA for the eight cardinal wind directions) is a conservative estimate because it is based on the unrealistic assumption that the wind direction will always

Table 2. Rhine-Hesse – comparison of the results of the basic approach with the results of the refined landscape analysis. The default approach results are based on a maximum use rate of 150 g ha^{-1}, a 20 m buffer and one application. The refined approach results are based on an average use rate of 100 g ha^{-1}, a 13 m buffer and two applications

Description	Results of default approach		Results of refined approach	
	Area (absolute)	Biotope area to be protected (%)	Area (absolute)	Biotope area to be protected (%)
Area under investigation (AUI)	80 km^2		80 km^2	
Orchard areas (all orchards) within the AUI (100% of all fruit tree plantings)	1400 ha			
Orchard areas (fenoxycarb orchards) within the AUI (62% of all fruit tree plantings)			863 ha	
Biotope area within the AUI:				
with whole forest area	766.8 ha	100.0		
only with forest fringe (20 m)			644.6 ha	100.0
Biotope area fully within the OBZ (step 2)	265.9 ha	34.7	117.0 ha	18.2
PDIA without interception (step 3)				
in worst-case direction after one treatment	88.4 ha	11.5	34.0 ha	5.3
maximum (worst-case directions) after two treatments (fenoxycarb orchards)			61.2 ha	9.5
wind-direction-distribution-weighted maximum after one treatment (all orchards)	84.0 ha	11.0		
wind-direction-distribution-weighted maximum after two treatments (fenoxycarb orchards)			50.8 ha	7.9
PDIA with interception (step 4)	50.4 ha	6.6	29.0 ha[a]	4.5[b]

[a] Extrapolated from the wind-direction-distribution-weighted PDIA under consideration for an area ratio of step 3 to step 4 in the standard approach for Rhine-Hesse of 1.753.
[b] PDIA: potentially drift-impacted area of biotopes (non-agricultural habitats defined by DE regulations).

be in the direction of the highest PDIA. In reality, the occurrence frequency of each wind direction (as well as the wind speed) determines the probability of a biotope being affected by drift. A more realistic estimate of the PDIA can therefore be achieved by weighting the calculated eight PDIAs with the probability of the wind blowing in their direction. The PDIA sum resulting from this approach is 84 ha or 11% of the total biotope area, and hence similar to the worst-case number. This similarity is presumably a consequence of the homogeneous dispersion of biotope areas in the AUI Rhine-Hesse.

For step 4, the filtering of the drift by mitigating tall vegetation was taken into consideration. This higher-tier exposure assessment yielded a potentially impacted biotope area of 50 ha in the north-east direction, corresponding to 6.6% of the total biotope area.

3.3 Refined exposure calculations

In the refined approach, the use rate of fenoxycarb was adjusted according to the actual tree height in commercial orchards and limited to orchards with fruit types where fenoxycarb was authorised. Additionally, the median (50th percentile) of the basic spray drift values (justified by the multitude of application events) was used for modelling of off-target drift. As expected, these refinements led to a considerable decrease in the step 2 PDIA (i.e. the total biotope area in the vicinity of the orchards that may potentially be impacted by drift, under the unrealistic assumption that the wind blows simultaneously from all directions). In the default approach this area was 266 ha. In the refined approach, only 117 ha of biotope was close enough to orchards to receive critical drift (cf. Table 2).

In the course of the refinement, the definition of a biotope was further modified to assume that only the outer 20 m fringe of a forest area was biotope. As a result, the total area of all biotopes in the AUI decreased from 767 ha (all of the forest area included) to 645 ha (only the forest fringe included).

The proportion of the biotopes that encroached within 20 m (default approach) or 13 m (refined approach) of the orchard areas decreased from 34.7 to 18.2%, i.e. only 18.2% of the biotope area was at all at risk of being affected by spray drift.

The PDIAs discussed above were calculated using an omnidirectional buffer. This is an unrealistic scenario because the wind does not blow from all directions at the same time when the product is applied. For this reason, the PDIAs for the eight cardinal wind directions were calculated, and then the worst-case direction(s) were identified. In the event of a single application, a maximum of 11.5% of the biotope area was potentially drift impacted in the default approach, whereas only 5.3% was potentially impacted in the refined approach. The worst-case direction in the default approach was 45° (south-west wind; cf. Table 3) and 90° (west wind) in the refined approach (owing to the divergent area selection).

Repeat applications were not simulated in the default approach. In the refined approach, assuming two applications, the maximum PDIA increased from 34.0 ha (5.3%, one application) to 61.2 ha (9.5%, two applications). This 61.2 ha represents the worst case, i.e. is based on the dual assumptions that the wind blows in the worst-case direction during the first application and in the direction leading to the greatest proportion of additional PDIA during the second application.

If a real wind direction distribution for the AUI is taken into consideration instead of these 'worst-case' assumptions, the

Table 3. Rhine-Hesse – PDIA for the eight cardinal wind directions from the default approach

Direction from orchard to biotope (deg)	Potentially drift-impacted area (PDIA) (ha)
45	88.43
90	87.96
135	85.17
180	78.42
225	83.89
270	83.95
315	80.67
360	80.17

potentially maximum drift-impacted area decreases further to 50.8 ha. This is 7.9% of the total biotope area.

As in the default approach, the drift filtering effect from tall vegetation was taken into consideration at step 4. Using the refined approach, the maximum impacted area after two applications amounted to 29.0 ha (4.5%).

If the above refinements were conducted assuming the maximum label rate of 150 g ha^{-1} (intended for trees with a maximum height of 3 m, which are no longer planted in commercial orchards), the step 4 PDIA would be only slightly higher (33.4 ha or 5.2% of the biotope area, see the supporting information).

This means that, under realistic assumptions, i.e. disregarding the inner forest area beyond the 20 m fringe and accounting for interception, approximately 95% of the biotope area in Rhine-Hesse will not be exposed above regulatory acceptable concentrations by the use of fenoxycarb with two repeat applications, and therefore no unacceptable effects would be expected.

4 DISCUSSION

The study presented here aimed to refine the standard drift exposure scenario for terrestrial non-target arthropods used in the German plant protection product authorisation process by using a more realistic, georeferenced exposure assessment.

High-resolution geodata inputs to a landscape classification permit a more realistic characterisation of the percentage of affected biotope area adjacent to treated orchards. The accuracy of the landscape classification conducted with the object-based approach in the eCognition software package and additional GIS-functionalities was confirmed to be high by ground truthing in the AUI.

The novelty of this study was the combination of standard terrestrial exposure and risk assessment based on the use pattern and intrinsic properties of fenoxycarb together with the proximity estimates from three representative real-world high-resolution landscape classifications. Using the approaches exemplified in the study, the calculation of the PDIA areas could easily be adapted according to individual requirements, taking into account (for example) different use rates, off-target drift behaviour and/or additional interception by tall vegetation, etc.

The method of defining, analysing and mapping AUI has been automated to provide georeferenced spatial data that have been incorporated into the workflow of a higher-tier risk assessment for fenoxycarb which follows the recommendations of the first workshop on Probabilistic Risk Assessment in Germany in 2003.[10] The methods of preprocessing and classification of high-resolution geodata described above follow the proposals by, for example, Lang,[5] Pfleger[26] and Yu[27] for the use of remote sensing data, adapted to the specific requirements of this spatial terrestrial exposure assessment of the insecticide fenoxycarb.

Schad *et al.*[21] proposed to use DOPs for higher-tier aquatic risk assessment, based on earlier use of GIS in risk assessments by Hendley *et al.*[16] The effects of the actual distance between treated orchards, vineyards or hopyards and small streams, as well as the filtering effect of 3D vegetation adjacent to the streams, on the reduction in drift deposits reaching surface water were reported in Schad *et al.*[21] These results were discussed within the regulatory community, and this approach, along with some proposals for simplification of drift reduction aspects, was partially integrated into a larger scientific project conducted by Kubiak *et al.*[17] Both research groups, however, used fixed discrete filtering values for different width classes of the filtering vegetation. A different concept was proposed by Otto *et al.*,[20] who used mathematical functions for estimating drift interception by hedgerows in standardised scenarios and applied this methodology in a risk assessment of numerous pesticides. The present authors propose the use of continuous functions to simulate distribution ranges for drift deposition (as well as reduction in deposition by intervening vegetation) depending on real-world measurements of the width of adjacent natural vegetation in relevant cropping landscapes. This offers more flexibility and a higher degree of realism for regulatory risk assessments.

For future risk assessments, it would be helpful to have more robust data available on the filtering effect of hedges and other 3D structures, as well as on the frequency of occurrence of such structures in the landscape. Currently, data are still scarce, and there is some variability in the results for measured depositions, leading to some uncertainty in predicting potential interception. However, even given this uncertainty, to ignore the filtering effect of 3D structures (which unequivocally occur in the real world) would make overall risk assessment less realistic and unreasonably conservative. Therefore, the higher-tier exposure assessment presented here, making use of high-resolution (and partially government-provided) geodata and integrating drift and drift interception, demonstrates how refinements can be applied for realistic characterisation of the distributions of potential exposure and risk that may occur across cropping landscapes.

To make better use of the proposed approach in a regulatory context, it would be valuable thoroughly to characterise the spatial heterogeneity of various types of agricultural landscape, as this is specific to the crop/type of crop concerned rather than any specific PPP. As a first step, a larger number of regions could be investigated for various crop types for which high variation in habitat structure is anticipated between various agricultural regions. This would ensure that the full distribution of potential crop/habitat interactions is understood.

5 CONCLUSION

With the methods described in this paper (e.g. high-resolution landscape analysis and classification, refined assumptions on drift reduction by intervening vegetation), we were able to identify and quantify landscape elements with higher potential exposure of NTAs for EU pesticide regulatory decision-making. A combination of mathematical functions enabled us to estimate the potential for drift deposition from orchard applications into the margins of adjacent biotopes, while taking account of the interception of this drift by taller vegetation. By combining this with regional data characterising the proximity and directional orientation of orchard and nearby biotopes, we generated distributions of potential refined exposure concentrations for key orchard crop regions in Germany. Moreover, these approaches also provide data that can potentially reflect the extent to which potential biotope exposure depends upon wind direction.

Using fenoxycarb as an example chemical, the results of this refined approach show that, in contrast to the lower-tier default methodology, >95% of the biotope area in the investigated orchard regions can be regarded as being of no regulatory concern, i.e. exposure there will remain below the toxicity threshold from laboratory studies with NTAs. Most procedures used in the landscape analysis are transparent and can be standardised, permitting a high degree of process automation in a geographic information system and facilitating communication of the outcome. We therefore regard these more realistic distributional exposure characterisations as valuable steps towards higher-tier risk assessment methodologies, which will allow regulators to make judgements based on an understanding of the real-world frequency of occurrence of default scenario conditions. These estimated exposure distributions can serve as critical input data for non-target insect population models, which are becoming more established in international regulatory frameworks.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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6 GLOSSARY

ATKIS	*Authoritative Topographic Cartographic Information System.* A GIS-based vector dataset with a scale range of 1:10 000 to 1:25 000
AUI	*Area under investigation.* An area subject to landscape analysis by means of aerial or satellite images
BI	*Biotope index* (a 'biotope' in this context means a non-agricultural habitat, e.g. woods): biotope index = total area of small structures*100/(total area of small structures + total agricultural area excluding grassland) (following Enzian and Gutsche[8]). See http://www.jki.bund.de/fileadmin/dam_uploads/_SF/kleinstrukturen/Beschreibung%20der%20Methode%20zur%20Ermittlung%20der%20Kleinstrukturen.pdf and http://www.jki.bund.de/no_cache/de/startseite/fachinformationen/pflanzenschutz/pflanzenschutzverfahren/kleinstrukturen/verzeichnis-der-regionalisierten-kleinstrukturanteile-stand-2004.html
CORINE	*Coordinated information on the environment.* The aim of the pan-European programme CORINE Land Cover (CLC) is to provide standardised and therefore comparable data regarding land cover for Europe, focusing on the environment. Mapping is carried out in the Member States on a scale of 1:100 000, with a total of 44 land cover categories
DOP	*Digital orthophoto* orthorectified aerial image (in different spectral ranges, depending on the source)
OBZ	*Orchard buffer zone.* The area of a 20 m wide buffer strip around all orchard areas
PDIA	*Potentially drift-impacted area.* The area of a biotope where the drift exceeds the acceptable exposure level
ROI	*Region of interest.* The fruit-growing area in Germany, defined using the information in CORINE (CLC 2000) and the biotope index

