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Selection of scenarios for landscape-level risk assessment of chemicals: case studies for mammals

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Abstract

Background: For landscape-level risk assessments of pesticides, the choice of the scenario is a key question, since it determines the outcome of a risk assessment. Typically, the aim is to select a realistic worst-case scenario. In the present study, landscapes from an area with a high proportion of cereal fields in France were analysed and simulations with population models for wood mouse, common vole, brown hare and European rabbit were conducted to understand if the worst-case character regarding pesticide exposure and population survival can be determined based on landscape features alone. Furthermore, it was analysed which landscape features relate with population survival and the magnitude of effects due to pesticide application. Answers to these question may help to decide whether landscape scenarios can be selected based on expert decision and whether the same scenarios may be used for different species or not.

Results: There were species-specific landscape features relating to long-term population survival. A landscape that is worst-case for one species, was not necessarily worst-case for another. Furthermore, landscapes that were worst-case regarding population survival were often not worst-case regarding the magnitude of effects resulting from pesticide application. We also found that small landscapes were sometimes, but not always worst-case compared to larger landscapes. When small landscapes were worst-case, this was typical because of the artificial borders of the digitised landscape.

Conclusions: Landscape analyses can help to obtain an approximate impression of the worst-case character of a landscape scenario. However, since it was difficult to consistently and reliably do this for single landscapes, it may be advisable to use a set of different landscapes for each risk assessment, which covers the natural variability. Depending on whether population survival shall be ensured or the magnitude of effects due to pesticides, different landscape structure and composition needs to be considered to establish a worst-case landscape scenario.

Keywords: Landscape scenario, Landscape configuration, Landscape structure, Risk assessment, Population modelling, Pesticide, Common vole, Wood mouse, Brown hare, European rabbit

Background

In the ecotoxicological risk assessment of pesticides, ecological models are increasingly used as tools that provide an ecologically comprehensive understanding of risk [16, 20]. More comprehensive ecological models, such as population models, can combine ecological data, behavioural traits and life cycle in order to simulate entire populations on the landscape level. Population models are also able to translate laboratory-derived toxicity values causing individual effects to population-level effects in order to assess the risk on a landscape level. Furthermore, such models can also be used to address and reduce uncertainty, define trigger values for the risk assessment or to quantify specific protection goals [10,

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20]. Particularly the analysis and reduction of uncertainty represents a very powerful tool, which can help to obtain a much more comprehensive view of risk and to identify high risk situations or scenarios [16, 28].

In addition to the growing importance of ecological models for the risk assessment, also the focus on landscape-level approaches has increased, either with the general aim to determine realistic worst-case scenarios [10, 14, 47, 48, 53] or to address specific organisms such as bees, arthropod and mammals [45, 60, 66].

A landscape-level approach is important not only because of the pesticide exposure to the landscape, but also because of the dispersal movements and habitat preference, which is linked with landscape structure [18, 65]. The dispersal between exposed and unexposed areas has been shown to be affected by the structures of the landscape [18, 24].

Taking account of a landscape context is considered to generally provide a broader perspective in the understanding of ecological processes [10, 24, 36], and without the comprehensive view of landscape structure, the biological patterns can be undetected or misinterpreted [18]. This statement has been supported by a case study by Hermann et al. [19], who have reported that the landscape composition elements such as field margins were significantly correlated to the wireworm pest suppression, but only on a certain spatial scale (25 ha).

Landscape structure and patterns that may affect the population in agricultural areas are commonly referred to as landscape composition and landscape configuration [12, 19, 65]. To describe landscape composition and configuration in agricultural areas, several metrics quantifying the landscape have been suggested and developed, such as landscape scale, percentage of habitat area, connectivity, patch size, and shape complexity and grain size [18, 19, 49, 53, 57, 65, 66].

In the EFSA scientific opinion on good modelling practice, which describes criteria for the use of mechanistic effect models in the context of the risk assessment of pesticides [9], the consideration of such landscape characteristics is still rudimentary, therefore, further research on the relevance of landscape structure on the outcome of risk assessments is needed [47, 66]. Several studies suggested that various landscape elements can influence the outcome of landscape-based risk assessments of pesticides, such as the spatial scale and the landscape structure [27, 53, 57–60, 63, 66]. Topping and Odderskaer [57] demonstrated that changing the landscape structure had a stronger impact than pesticide application for the skylarks (*Alauda arvensis*) population. Kleinmann and Wang [27] compared field use predicted by a population model for brown hare (*Lepus europaeus*) with empirical data in several landscapes in the UK. They found that landscape structure had a strong impact on field use. Unexpectedly, areas with the highest field use (in the proportion of time) were not the ones with the highest proportion of crop, but the location of offcrop habitats determined field use.

Previous studies on the landscape context in environmental risk assessment using simulations focussed, however, mainly on a particular species like carabid beetles, skylarks or brown hare and not on the question of how realistic landscape scenarios can be developed. For the risk assessment, the choice of a suitable landscape scenario is a key question. Usually, risk assessors request to use worst-case landscape scenarios. Following a naïve approach, this could be done by conducting model simulations using many different landscape scenarios, which—hopefully—include a worst-case. However, even when using many landscapes, uncertainty remains whether the set of landscapes was sufficiently large or representative. It would hence be beneficial if the worst-case character of landscapes could be determined a priori based on landscape composition and structure alone (without conducting model simulations). Therefore, the objective of this study is to evaluate the impact of landscape composition and configuration on population development, in order to reveal if it is possible to estimate the worst-case character of a landscape scenario prior to conducting model simulations. This was done exemplarily for a model for common vole (*Microtus arvalis),* brown hare (*Lepus europaeus*), European rabbit (*Oryctolagus cuniculus*), and wood mouse (*Apodemus sylvaticus*) by parameterising the landscape composition and configuration in different spatial scales (5, 10, 25, 50, and 100 ha). For the objective, POLARIS, a modelling software framework that was designed for population-level risk assessment, was used to investigate the population-level effects resulting from individual behaviour of each species, both with and without pesticide application scenarios.

Methods

Selection of the study area

The selection of scenarios was exemplarily conducted for the crop cereals in France. To reflect a worst-case situation with intense cereal cultivation, the region Haut-Rhin in Grand Est was chosen as a study area. Haut-Rhin is characterised by a fertile plain with a high proportion of cereal cultivation (76% of all arable land; [11]; Fig. 1). In the next step, several grids (with a cell area of either 5, 10, 25, 50 and 100 ha) were generated using QGIS (version 3.10.1) to cut out landscape squares of different sizes. Vectorised agricultural field data from the Institut National de l'Information Géographique et Forestière [21] were used to estimate the proportion of arable land and cereal fields in each landscape square. Target

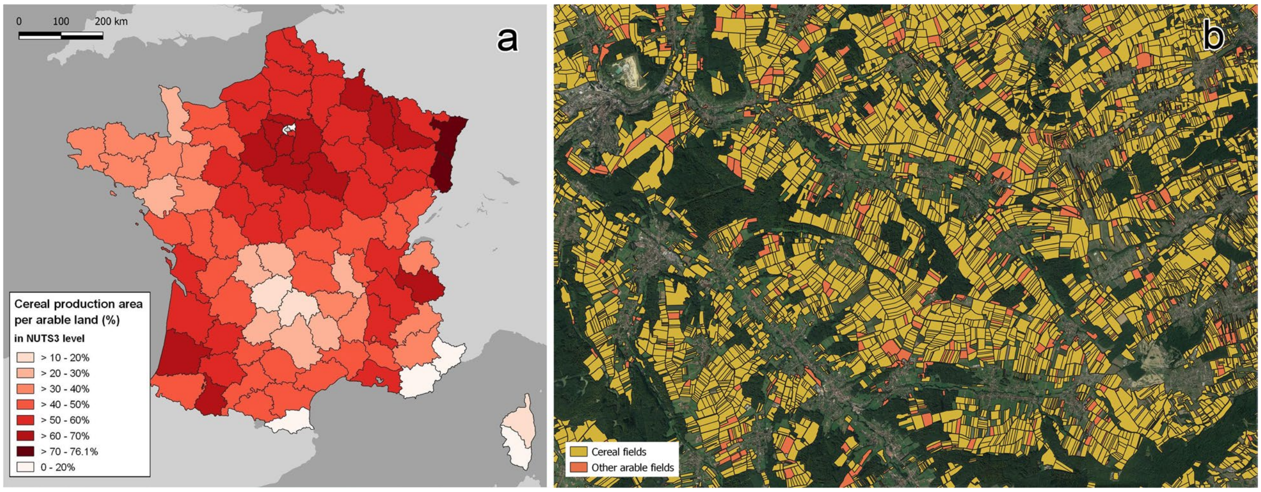

Fig. 1 Proportion of cereal production in France (**a**) and example of the distribution of cereal fields in the region Haut-Rhin (**b**)

landscapes were selected with at least 80% of arable land and at least 70% of the cereal field area. Finally, 51 landscapes were used (13 landscapes for 5, 10, 25 ha, 6 landscapes for 50 and 100 ha). The selection was in principle random, however, landscapes with a large fraction of settlements were excluded.

To further study the impact of landscape size on population survival some landscapes were analysed not only using their original landscape size, but also larger landscape sizes were used by including the surroundings. This was done for landscapes with 5 ha (expanded to 10 ha for testing) and 10 ha (expanded to 25 ha for testing).

Finally, simulations were conducted in artificial landscapes considering one offcrop patch within cereals in order to understand the impact of the shape of the offcrop. Three shapes (each of the same total area of 0.8 ha) were considered: 1. square, 2. thick cross and 3. thin cross. These shapes were placed in 10, 25 and 50 ha landscapes composed of cereals (Fig. 2).

A total of 61 landscapes were mapped and analysed for this study.

Spatial data

Landscapes were mapped based on the individual crop field data with polygons and detailed crop information from the National Institute of Geographic and Forest Information of France [21] and OpenStreetMap [37]. Landscapes were classified into crop area (arable land), offcrop vegetation area (grassland, woodland, hedges and orchards) and other areas (roads, buildings and waterbody). Landscapes were then cross-referenced with high-resolution Google Earth satellite imagery.

Analyses of landscape structure and composition

To analyse landscape structure and composition a number of spatial indices were calculated (see Table 1). Landscape composition parameters such as landscape area, proportion of offcrop area, total offcrop area, size

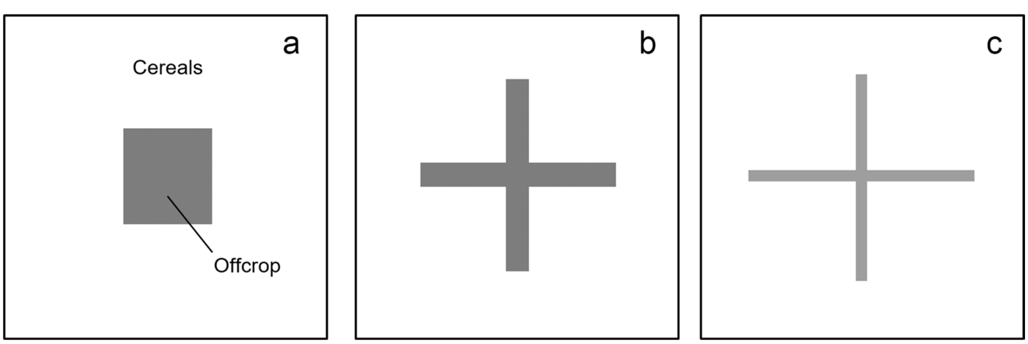

Fig. 2 Illustration of the shape of offcrop to analyse the effect on common vole population survival and the effect due to hypothetical pesticide application. Three shapes were considered: a square-shaped offcrop (**a** 90 m edge length), a cross-shaped offcrop (**b**) of the same area and a thinner cross-shaped offcrop (**c** also of the same size). All offcrop was assumed to be surrounded by fields

Table 1 Spatial indices describing the structure and composition of landscapes used in the present study

Category	Parameter	Abbreviation	Unit
Size and density	Total landscape area	Area	m^2
	Total offcrop area	TotalOC	m^2
	Size of the largest offcrop patch	SizeLarOC	m^2
	Proportion of total offcrop area per landscape	PropOC	NA [0..1]
Shape	Compactness of the largest offcrop area	CompLarOC	NA [0..1]
Patch distance	Distance index	DI	NA
Patch distance	Distance index × number of offcrop	DImultOCN	NA
Patch distance	Distance index × number of offcrop/landscape size	DImultOCNpLS	NA
Connectivity	Integral index of connectivity (species specific)	IIC	NA [0..1]
Connectivity	Equivalent connectivity	EC	m^2
Structure	Shannon index	SI	NA [0..1]
Structure	Overall resilience index (species specific)	OvResilInd	NA
Configuration	Border length between crop and offcrop area	BorLenCOC	m
Configuration	Border length between crop and offcrop area per total offcrop area perimeter	BorLenCOCpOC	m
Configuration	Border area between crop and offcrop area within 10 m distance from the border	BorArCOC	m^2

of the largest offcrop area, border length between crop and offcrop areas and compactness [42] of offcrop areas were calculated using the python library PyQGIS in QGIS 3.10.1 with the land cover maps.

An integral index of connectivity [38] was computed with ecological landscape software Graphab 2.6 [15] and Shannon index of landscape [34, 50] was computed using QGIS landscape ecology statistics plugin LecoS [25].

Furthermore, an index expressing the expected average annual population density was calculated for common vole in each landscape. This was done using average measured population abundance from published field studies. For common vole the following densities were considered [54], [22]: 288 N/ha in grassland, 133 N/ha in pasture (used as surrogate for orchards), 38 N/ha in woodland (also used as surrogate for hedges) and 50 N/ha in arable land. For wood mouse [56], Fig. 2) densities were: 8.3 N/ha in field edges (used as surrogate for grassland and orchards), 45.6 N/ha in woodland, 18.2 N/ha in hedges and 11.5 N/ha in arable land. For brown hare [1, 4, 13, 30, 39, 41, 46, 51, 52], [26] a mean density of 0.31 N/ha was considered in the whole landscape. For European rabbit [32] the following densities were considered: 3.4 N/ha in pasture or grassland (La Chevallerais), 1.3 N/ha in woodland (Lalinde), 15.8 N/ha for hedges (Donzère-Mondragon) and 3.9 N/ha in arable land (Cerizay).

In addition to that, a distance index (DI) was used, which was defined as the distance between all pairs or offcrop habitat patches weighted by the size of patches:

$$\text{DistanceIndex} = \sum_{i=1}^{N}\sum_{j=1}^{N}\frac{D_{ij}(A_i + A_j)}{N(N-1)},$$

with N = number of offcrop habitat areas; A_i = area extent of offcrop habitat area i; A_j = area extent of offcrop habitat area j, and D_{ij} = minimum distance between offcrop area i and j.

Furthermore, an overall resilience index (OvResilInd) was developed. This index describes the average population size expected in an area by taking connectivity via offcrop corridors into account. Offcrop corridors were considered small, linear offcrop areas with less than 10 m widths, which connect larger offcrop areas. The index was calculated based on the expected average annual population density in each offcrop patch and the number of animals being able to supply a patch by immigration. This number was calculated by the multiplication of the dispersal probability and the population size of the connected patch. Assuming that in corridors dispersal will likely occur in either of two directions (along the corridor) the probability was calculated by $p = 2^{-\text{corridor length/dispersal distance}}$. Hence the resilience index also reflects the recolonization potential of a local population:

$$\text{OvResilInd} = \sum_{i=1}^{N-1}\sum_{j=i+1}^{N} P_i + P_j p,$$

with N = number of offcrop patches; P_i = expected population size in patch i (calculated by patch size × density); P_j = expected population size in patch j (calculated by patch size × density), and p = probability to disperse between patches separated by an offcrop corridor.

Some indices use dispersal distance (resilience index and integral index of connectivity). Regarding dispersal distance, typical species-specific dispersal distances were used (common vole: 537 m, Boyce and Boyce, 1988; wood mouse: about 1000 m, Hacker and Pearson, 1951, and Wolton, 1985; brown hare: on average 3.67 km (range: 1.34–6.00 km), [40]; European rabbit: 1025 m, [7]).

Simulations with population models

Twenty years of simulations were conducted in each landscape for common vole (*Microtus arvalis*), wood mouse (*Apodemus sylvaticus*), brown hare (*Lepus europaeus*) and European rabbit (*Oryctolagus cuniculus*) using the commercial software POLARIS 3.6 [64], a modelling framework software that is designed for population-level risk assessment of pesticides. These species have been selected since they represent representative species for the mammalian risk assessment according to EFSA [8]. The modelling software POLARIS has been chosen as it is frequently used for population modelling for the risk assessment of pesticides. The models are spatially explicit individual based models, which have been parameterised based on public literature (see [27, 61, 62]), models are summarised in the Additional file 1). Monte Carlo simulation is used to capture the variability of model parameters. Models were run with default settings using 50 iterations. Simulations were conducted for all species to measure population survival in different landscapes. In addition, simulations were also conducted assuming the application of a hypothetical pesticide. This was done exemplarily for common vole and European rabbit. Toxicity was included by using a dose–response curve (a log-logistic 2-parameter curve with an ED_{50} of 25 mg/kg bw/day and a slope of 3.1: $y = 1 - 1/[1 + (x/25)^{3.1})]$. The application was assumed to start on 15th June (three applications with a 14-day interval, applied simultaneously in all fields) and exposure was calculated according to EFSA ([8]; in this document values are provided to estimate exposure regarding food intake, food energy, body weight). An application rate of 1 kg of the active substance was considered. It was assumed that the substance causes a reduction of litter size. With the dose–response curve given above, an effect of > 90% reduced litter size is expected when animals feed entirely in fields. Regarding population-level effects, the mean effect strength due to the hypothetical pesticide was measured as the mean difference of population density at the end of the year and the pesticide was assumed to be applied from year 6 (in order to let populations stabilise during the first 5 years) to year 15 (in order to see whether populations recover; [48].

Statistical analyses

The outcome of simulations with the population models, i.e., the population survival (evaluated for all species) and effect strength (differences of population density between control and treatment simulations; evaluated exemplarily only for common vole and European rabbit), was analysed using Generalized Linear Models (GLM), which were generated in *R* [44]. Population survival and treatment-related effect strength can be described as a function of spatial indices, such as the Shannon index 'SI' or the proportion of offcrop 'PropOC' (see list of indices given in Table 2). To evaluate the impact of these indices, GLM were compared based on AICc (AIC correction for small sample sizes) and R^2 after McFadden [33]. Since the dependent variable 'population survival' with or without effects is the result of a Bernoulli process (i.e., the number of survived populations in all 50 iterations), logistic regressions were performed assuming a binomial distribution.

The mean effect strength for common vole or European rabbit is defined as the mean ratio of treatment and control population density within 10 years of continuous application. Since this endpoint tends to range from 0 to 100% but values > 100% may still occur (i.e., the control may show lower mean population density than the treatment), a gamma distribution was assumed for this endpoint.

The comparison of model parameter coefficients corresponding to the impact of the single indices can be difficult if their scale differs significantly. Therefore, the predictor variables were all normalised to the interval [0, 1] prior to the analysis scaling their minima to 0 and their maxima to 1. This normalisation has no impact on the model performance or the results except on the scale and comparability of the resulting coefficients.

Results

Landscape indices affecting population survival

In a first step the relationship between landscape structure, measured by a series of spatial indices, and population survival was assessed to verify the suitability of the applied models and indices (for an illustration see Fig. 3). Results from the GLM analyses are summarised in Table 2. In these GLM a maximum of four variables had been selected to predict each endpoint, since the R^2 could be improved by only 1.2% on average when using one additional variable.

Common vole

The population survival of common vole was mainly explained by the presence of offcrop in the landscape: the size of the largest offcrop patch (SizeLarOC) was

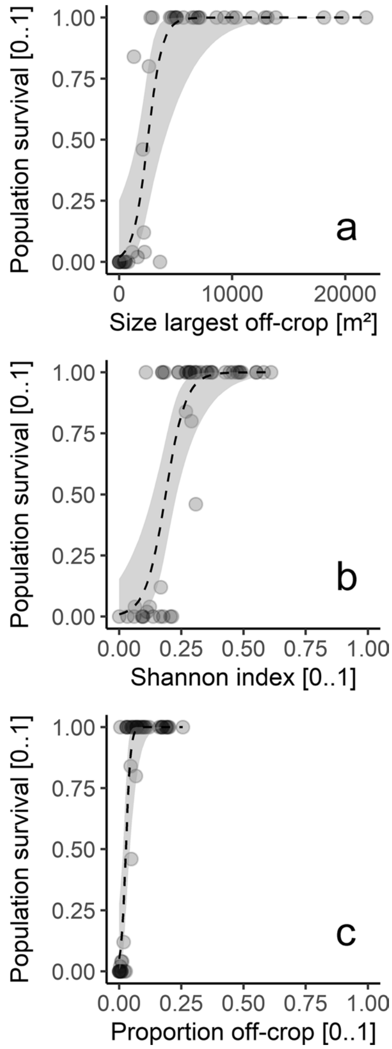

Fig. 3 Relation of three important landscape indices (**a** SizeLarOC, **b** SI, **c** PropOC) on population survival of common voles obtained from GLM (logistic regression model with 95% confidence band)

the most important parameter explaining population survival when considering only one- and two-parameter models (SI + SizeLarOC and PropOC + SizeLarOC) and explained more than 80% of the variability (Table 2). When regarding three- and four-parameter models, a combination of the offcrop proportion (PropOC) and the total offcrop area (TotalOC) in the landscape explained population survival best. Furthermore, also the compactness of the largest offcrop (CompLarOC) and the distance between offcrop patches (DI) positively contributed to population survival.

European rabbit

The population survival of the European rabbit was mainly driven by the size of offcrop area (TotalOC, explaining 69% of the variability, Table 2). When considering two to three parameters, also the landscape size (Area), proportion of offcrop (PropOC) and the size of the largest offcrop (SizeLarOC) was important for the survival of this medium-sized lagomorph. Finally, when adding further parameters, the size of the landscape (Area), the size of the largest offcrop (SizeLarOC), the size of all offcrop (TotalOC) and Shannon Index (SI) best explained population survival.

Brown hare

Brown hares have very large home ranges and were not affected by small-scale landscape characteristics such as the compactness of an offcrop patch. Landscape size (Area) was the single most important parameter explaining population survival (explaining 98% of the variability). Adding further variables to the model only marginally improved the model prediction (i.e., the R^2 difference is very small) and finally lead to over-parameterisation indicated by increasing AICc.

Wood mouse

Wood mouse population survival was explained by the availability of offcrop area (SizeLarOC, TotalOC, PropOC) but also on landscape connectivity (OvResilInd, DImultOCN, DI), diversity (SI) and size (Area). The use of few parameters did not explain population survival well (see R^2 in Table 2). The sharply increasing R^2, when considering an increasing number of parameters (see Table 2) indicates that the influence of landscape structure on population survival is more complex. Hence the survival of this species was linked much more to landscape structure than in the other species.

The results over all four species indicate that population survival of the species is linked to different landscape indices. Hence it may not be advisable to consider using the same landscape scenarios in a risk assessment for different species.

Effects by a pesticide

Apart from the analysis of population survival for all species, it was analysed how the application of a hypothetical pesticide may affect population survival. This was done exemplarily for common vole and European rabbit. Exposure and toxicity had been chosen in a way that more than 90% reduction of litter size would be

Table 2 Best GLM (lowest AICc among all parameter combinations marked in bold) for modelling the population survival of four species in different landscapes with one to four predictor variables

Species	Parameter no.	Model	AICc	R^b (McFadden)
Common vole (*N* = 51)	1	SizeLarOC	574.37	0.8114
	2	SI + SizeLarOC	339.54	0.8930
		PropOC + SizeLarOC[a]	340.20	0.8928
	3	CompLarOC + PropOC + TotalOC	233.35	0.9304
	4	CompLarOC + DI + PropOC + TotalOC	**150.85**	0.9595
		DI − OvResilInd + SI + SizeLarOC[a]	151.64	0.9593
European rabbit (*N* = 51)	1	TotalOC	875.93	0.6865
	2	− PropOC + TotalOC	654.09	0.7739
	3	Area − SizeLarOC + TotalOC	561.79	0.8107
	4	Area + SI − SizeLarOC + TotalOC	**512.72**	0.8307
Brown hare (*N* = 41)	1	Area	**37.02**	0.9833
	2	Area + CompLarOC[b]	38.06	0.9865
	3	Area + CompLarOC − PropOC[b]	39.50	0.9887
	4	Area + CompLarOC − PropOC + TotalOC[b]	41.52	0.9894
Wood mouse (*N* = 51)	1	SizeLarOC	832.78	0.5414
	2	− DI + TotalOC	603.82	0.6746
	3	EC − IIC + SI	290.10	0.8568
	4	− DImultOCN + EC − IIC + SI	**197.99**	0.9112
		Area − DI + PropOC + SI[a]	199.63	0.9102

The signs of the parameters represent positive or negative influence on the endpoint

[a] This model is within an AICc range of 2 and is therefore considered to be comparable to the model with the lowest AICc

[b] There were 10, 55 and 131 additional 2-, 3- and 4-parameter models within an AICc range of 2, respectively, all of which had 'Area' as the dominant parameter

expected in animals feeding entirely in treated field (see "Methods"). Again GLM were applied using a maximum of four variables. Results from the GLM analyses are summarised in Table 3.

Impact on population survival

As in the above analysis on population survival, in common vole also the effects of a hypothetical pesticide largely depended on the size (SizeLarOC, TotalOC) of offcrop. However, now also the border length to the treated area (BorArCOC), which determines exposure risk, had an impact. Adding more parameters to the model also revealed landscape connectivity (IIC, OvResilInd) as an important parameter. Hence, factors associated with exposure and with the capability for recolonization gain in importance when a pesticide treatment was applied (compare with model parameters from models on population survival without effects).

Results were similar for European rabbit. Regarding population survival offcrop-related parameters (e.g., PropOC, TotalOC or SizeLarOC) were important parameters in all models. Also border length to the treated area (BorArCOC) or indices regarding connectivity (e.g., IIC, OvResilInd) played a role.

Effect strength

The mean effect strength due to the hypothetical pesticide was measured as the mean difference of population density in control and treatment simulations at the end of the year. In common vole, this mean effect was clearly driven by the proportion of offcrop area (PropOC) and landscape diversity (SI). Adding more than these two variables to the model slightly improves the model prediction (i.e., small increase of R^2) but leads to over-parameterisation indicated by increasing AICc. In European rabbit, the proportion of offcrop (PropOC), offcrop connectivity (IIC) and border length between crop and offcrop area per total offcrop area perimeter (BorLenCOCpOC) were important parameters relating to effect strength.

Effect by the expansion of landscapes

In the previous analyses landscape squares were used that had been cut out from a region in France. Hence the size of these landscapes was artificially determined and in reality landscapes would not be confined as those used for modelling. We therefore also studied the effect of slightly increasing the smaller landscapes (i.e., from 5 to 10 ha or from 10 to 25 ha) on the outcome of the simulations. This was in particular interesting

Table 3 Best GLM (lowest AICc among all parameter combinations marked in bold) for modelling the population survival with effect and the treatment-related effect strength for common vole and European rabbit in different landscapes with one to four predictor variables

Species	Endpoint	Parameter no.	Model	AICc	R^b
Common vole	Survival with effect (effect magnitude ~ 25%, $N=40$)	1	SizeLarOC	1172.56	0.4682
		2	− BorArCOC + TotalOC	771.87	0.6595
		3	− BorArCOC + IIC + TotalOC	625.73	0.7299
		4	− BorArCOC + IIC − OvResilInd + TotalOC	**556.90**	0.7636
	Effect strength (treatment/control, mean of year 6–15, $N=40$)	1	− PropOC	− 14.59	0.3844
		2	− PropOC − SI	**− 20.34**	0.4917
		3	BorLenCOCpOC – PropOC − SI[a]	− 20.21	0.5192
		4	EC – PropOC – SI − TotalOC[a]	− 18.61	0.5309
European rabbit	Survival with effect (effect magnitude ~ 25%, $N=28$)	1	TotalOC	141.74	0.9369
		2	− IIC + TotalOC DImultOCN + TotalOC BorArCOC + TotalOC OvResilInd + TotalOC	137.62 138.63 139.16 139.21	0.9429 0.9419 0.9410 0.9417
		3	DImultOCN + OvResilInd + TotalOC	131.49	0.9513
		4	DI − IIC + PropOC + TotalOC DImultOCN − IIC + PropOC + TotalOC − IIC + PropOC − SizeLarOC + TotalOC	**127.41** 127.81 128.85	0.9575 0.9573 0.9565
	Effect strength (treatment/control, mean of year 6–15, $N=27$)	1	− IIC − PropOC BorLenCOCpOC	**− 46.55** − 45.84 − 44.93	0.1015 0.0775 0.0461
		2	CompLarOC − IIC[c] CompLarOC − PropOC[c]	− 46.02 − 45.48	0.1659 0.1491
		3	BorLenCOCpOC + CompLarOC − IIC[c] BorLenCOCpOC + CompLarOC − PropOC[c]	− 44.59 − 44.38	0.2064 0.2002
		4	BorLenCOCpOC + CompLarOC + OvResilInd − PropOC[c] BorLenCOCpOC + CompLarOC – DImultOCNpLS − IIC[c]	− 41.73 − 41.66	0.2117 0.2098

The signs of the parameters represent positive or negative influence on the endpoint

[a] There were 8 and 54 additional 3- and 4-parameter models within an AICc range of 2, respectively, all of which had 'PropOC' and 'SI' as the dominant parameters

[b] This model is within an AICc range of 2 and is therefore considered to be comparable to the model with the lowest AICc

[c] There were 9, 23 and 141 additional 2-, 3- and 4-parameter models within an AICc range of 2, respectively, all of which had 'IIC' or 'PropOC' included

Table 4 Effect of increasing landscape size for locations where populations showed a reduced survival after application of a hypothetical pesticide and 100% without pesticide application

Landscape ID	Size (ha)	Population survival without pesticide in original landscape (%)	Population survival with pesticide in original landscape (%)	Population survival with pesticide in enlarged landscape (%)
88,068	5–10	100.0	32.0	100.0
43,527	10–25 ha	100.0	34.0	6.0
44,379	10–25 ha	100.0	92.0	100.0
47,695	10–25 ha	100.0	0.0	92.0
49,352	10–25 ha	100.0	18.0	100.0

for those landscapes, where survival was reduced from 100% to less than 100% due to pesticide application (this was the case in five landscapes).

While we expected that increasing landscapes would always enhance survival as more offcrop areas would be included, this was not always the case (see Table 4): an increased survival was observed in four of the landscapes. In one landscape, population survival was reduced from 32 to only 6%. In this landscape, a very small offcrop was located within a large area with fields (Fig. 2). The reason for the reduction of survival when increasing this landscape was that animals dispersing from fields when the crop attractive to voles (triggered by increasing vegetation cover protecting against predation and food becoming more available) had a lower likelihood to find back to the small offcrop when fields became unattractive. This illustrated that small landscapes do not necessarily represent a worst-case and that it depends on landscape structure whether they are or not. In the other landscape, where an increase of the landscape improved survival, satellite images showed that offcrop had been limited artificially only by the borders of the landscape cell grid; i.e. larger offcrop was always available, but landscapes only contained a fraction of this offcrop. Increasing the landscape size increased the fraction of the offcrop that had been dissected (see Fig. 4).

Effect of the shape of offcrop

Finally, simulations were conducted for common vole in artificial landscapes considering one offcrop patch within cereals in order to understand the impact of the shape of the offcrop. The result from simulations using three different offcrop shapes covering the same area (square, thick cross and thin cross, see Fig. 2) and different landscape sizes are presented in Table 5.

Results demonstrate that the shape of offcrop had a marked impact on population survival, which additionally depended on landscape size. For example, while 54% of common vole populations survived in the 10 ha landscape with a square-shaped offcrop when a hypothetical pesticide was applied only 4% survived when using a thick cross-shaped offcrop. Considering the thin-cross

Fig. 4 Illustration of how the proportion of offcrop changes when landscape squares are increased. **a** In this landscape a small offcrop was included in the middle of the landscape, when increasing landscape size population survival deteriorated, since when retreating in the offcrop in winter (when vegetation cover was lacking in fields) animals had more difficulties finding offcrop. **b** In most landscapes, the size of offcrop in landscape squares was restricted by the spatial limits of the landscape square. In reality, offcrop was usually much larger and when increasing landscape size population survival increased due to more offcrop being available

Table 5 Common vole population survival in landscapes with differently shaped offcrop (0.8 ha; square, cross or thin cross) and different landscape sizes

Landscape size (ha)	10	10	25	25	50	50
Pesticide application	No	Yes	No	Yes	No	Yes
Square (%)	100	54	100	40	98	8
Thick cross (%)	100	4	100	2	98	0
Thin cross (%)	100	0	100	0	96	0

The remaining area was assumed to be covered entirely by cereal fields offcrop, none of the populations survived. Furthermore, in the larger landscapes, in which the same 0.8 ha offcrop was located, population survival was lower than in the smaller landscapes. This was due to the fact that animals dispersing after the harvest had more difficulties finding the offcrop where they could establish new home ranges.

Discussion

For the risk assessment of chemicals, such as pesticides, a key question of landscape-level analyses is the choice of the scenario, which ideally reflects a representative worst-case [10, 14, 47, 48, 53]. The aim of the present study was to evaluate if the worst-case character of a landscape scenario can be determined a priori, i.e., based on landscape features alone. The study has shown that there are landscape features that correlate with population survival, such as the amount of offcrop area for common vole or a mix of offcrop area, connectivity, and other features for wood mouse. These features were clearly species specific, which means that it is not possible to define a generic worst-case landscape for different species, but the worst-case character of a landscape has to be determined for each species separately. The reasons for the species-specific differences are different spatial behaviour and habitat preference: for example, for wood mice hedges and woodland are important habitats, where high abundance is reached [55]. Wood mouse population survival was explained best by a combination of many different spatial indices, which take the size of offcrop (SizeLarOC, TotalOC, PropOC), the distance between offcrop patches and the connectivity (OvResilInd, DImultOCN, DI) and diversity (SI) into account. This indicated that landscape structure plays a more prominent role for wood mouse compared to all other tested species and it may be an indicator for the vulnerability of the species. Habitat connectivity contributed to population survival since corridors between offcrop habitats reduce the risk of wood mice to become extinct when habitat patches are small (such as small woodland or isolated hedges). Notably, wood mice have rather large home ranges [2, 17], which can reach 1 ha in arable land in males [43] and hence population density is much lower (8–45 N/ha, [56] than the population density of other small rodents, such as common vole (about 200–600 N/ha, [22]. A low density increases the risk of local population extinction, in particular in small, isolated habitat patches [31]. Common voles in turn have very small home ranges and hence density is much higher [22]. As a consequence, they can persist much better even in small habitat patches (e.g., grassland). Hence connectivity was less important for voles and the size of offcrop (SizeLarOC, PropOC) or habitat diversity (SI) was more relevant. Also for lagomorphs, spatial behaviour determined which landscape features related to population survival: for brown hare, the single most relevant landscape feature was the size of a landscape. Brown hares are much less selective regarding habitat use compared to small mammals. They prefer to forage in habitats with low vegetation where predators can easily be seen ([3]; this is contrary to rodents, which prefer to forage in habitats with high vegetation cover to avoid avian predators; [5, 23] and they prefer areas with high vegetation for resting [35]. Furthermore, hares have very large home ranges and population density is very low (around 20 N/100 ha, [26]. Since practically all habitats are used, in particular arable land, landscape size was the most relevant parameter regarding population survival since larger landscapes related to larger populations.

However, although some landscape features or indices correlated with population survival (in a species-specific way), it was still not easy to select a worst-case based on landscape indices alone, since there was considerable variability (see Fig. 3). This implies that an a priori definition of a worst-case landscape scenario based on landscape indices alone is difficult in practice. It may instead be advisable to use a set of different landscapes to ensure that the variability of landscape composition and structure is fully considered.

Another important observation was that landscapes can be worst-case regarding population survival, but not worst-case regarding the magnitude of effect regarding population survival (compare Table 2 with 3). Landscapes in which populations survive well can be landscapes in which strong effects after pesticide application are found and vice versa. When addressing the effect by pesticides additional landscape parameters gained importance: as expected, these include landscape features affecting the likelihood of exposure. This was expected, since landscape features can significantly influence exposure [29]. Hence prior to answering the question which landscape represents a worst-case one would need to ask the question "a worst-case regarding what (population survival or magnitude of effect)?". The protection goals currently considered in the pesticide risk assessment in Europe (i.e., no long-term repercussions for abundance and diversity, see EFSA [8]) may apply to both population survival and the magnitude of effects. The magnitude of effect would probably reflect short-term differences of abundance in most cases, while population survival or the potential for recovery would focus on long-term abundance. In the past, most landscape analyses of effects by pesticides focused on the magnitude of effect. Dalkvist et al. [6] studied effects in voles after application of a hypothetical endocrine disruptor using a population model. They observed smaller effects in landscapes containing more unmanaged grassland or in areas with fewer treated areas. The authors concluded that an accurate prediction of population impacts cannot be achieved without taking landscape structure into account.

A third important finding of the present study was that small landscapes are not necessarily worst-case compared to larger ones. It may seem intuitive that small landscapes, including only a small 'population' may represent a worst case, because it is more likely that small populations become extinct after pesticide application than large ones [63]. However, in the present study we found that it again depended on landscape structure whether small or large landscapes are worst-case (see the comparison of square vs. cross-shaped offcrop in landscapes of different sizes). Furthermore, in many small landscapes, in which populations did not consistently survive this was due to the arbitrary limits of the landscapes. Offcrop close to the border often only seemed to be small, while in reality (i.e., when considering the real landscape outside of the artificially selected borders of the landscape) they extended outside of the selected landscape grid cell. Hence, the size of these offcrop areas only seemed to be small due to the artificial borders of the landscape. When increasing the size of the landscapes and therefore including more of the offcrop, populations consistently survived. That means that apart from not always being worst-case, small landscapes may also only seem worst-case due to the artificial cutting-off of offcrop habitats. Two conditions regarding offcrop can distinguished: 1. When offcrop is present within landscapes, not cut off by borders of the landscape, then large landscapes are worst-case. 2. When offcrop is located at the border of landscapes and artificially cut off by the landscape borders, then small landscapes are worst-case. However, this is an artificial creation of a worst-case, since in reality offcrop is larger. If one desires to focus on real-world worst-case situations the approach of selecting a small landscape out of a larger landscape context may not be adequate.

Overall, the present study offered new insights which can help to define landscape scenarios for landscape or population-level risk assessments in the future. This may also help to address criticism of the present risk assessment approach, which does not routinely consider a landscape context and may result in inaccurate predictions of exposure and effects [47]. Apart from findings demonstrating that the definition of a worst-case needs to be species specific and that it may be difficult to define a worst-case scenario a priori based on expert judgement or landscape analysis alone, it was also shown that it may be helpful to clarify the protection goals in future risk assessments and guidance documents [10]: depending on whether population survival or the magnitude of potential effects shall be addressed, not only different scenarios may need to be selected, but adverse effects may also be prevented using different mitigation measures may be used to ensure that these goals are met. Populations may be better protected in the long term when focusing on population viability instead of focusing on the magnitude of effects. However, if this would be the goal then the availability of offcrop and its management would be a key aspect to ensure this goal. On the other hand, when focusing on the magnitude of effects, then mitigation measures ensuring minimal exposure may be more relevant and edge length (between fields and offcrop) may be more important than the size of offcrop.

Conclusions

The present study revealed important findings which are relevant for the development of landscape scenarios for the risk assessment of pesticides. The worst-case character of landscapes is very species specific. Hence for each of the studied species, different landscape features relate to population survival. Although there are some landscape indices, which relate to high or low population survival of effect size after application of a pesticide, it is difficult to anticipate the worst-case character for individual landscapes. For the risk assessment it seems preferable to include a variety of landscapes. Furthermore, small landscape size is not necessarily more worst-case than large landscape size. In small landscapes it is also more likely to create artificial situations when habitats are not completely included due to the arbitrary selection of landscape borders during digitization. Finally, it was found that landscapes can be worst-case regarding population survival, but not regarding the effects size after application of a pesticide and vice versa. Hence, when assessing the worst-case character of a landscape, it needs to be defined regarding which parameter a landscape shall be worst-case.

Abbreviations

AICc: Akaike information criterion with correction for small samples; EFSA: European Food Safety Authority; GLM: Generalized linear models; IIC: Integral Index of Connectivity.

Supplementary Information

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Additional file 1: Figure S1. Concept of the update of the reproductive stage for female common voles. **Figure S2.** Conceptual representation of the process for updating the home range. **Figure S3.** Concept of the update of the reproductive stage for female wood mice. **Table S1.** Criteria for the evaluation of landscape cells for the common vole in a descending ranking order. **Table S2.** List of model parameters for the common vole. **Table S3.** Criteria for the evaluation of landscape cells for the wood mouse in a descending ranking order. **Table S4.** List of model parameters for the wood mouse. **Table S5.** List of model parameters. **Table S6.** Species-independent landscape parameters used for GLM analysis (Table 1 of 2). **Table S7.** Species-independent landscape parameters used for GLM analysis (Table 2 of 2). **Table S8.** Species-dependent landscape parameters used for GLM analysis for common vole. The population survival with and without effects (EffPopSurv and PopSurv) and the mean population density compared to the control (MeanPopDensCtrl) represent response parameters. **Table S9.** Species-dependent landscape parameters used for GLM analysis for European rabbit. The population survival (PopSurv) represents the response parameter. **Table S10.** Species-dependent landscape parameters used for GLM analysis for brown hare. The population survival (PopSurv) represents the response parameter. **Table S11.** Species-dependent landscape parameters used for GLM analysis for wood mouse. The population survival (PopSurv) represents the response parameter.

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Authors' contributions
MW designed and directed the study and was a major contributor in writing the manuscript. SP, JK and CD contributed in writing the manuscript. Furthermore, SP processed the spatial data and CD provided the statistical analysis. All authors read and approved the final manuscript.

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