MASTEP – an individual based model to predict recovery of aquatic invertebrates following pesticide stress

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Summary

For the ecological risk assessment of pesticides, recovery of affected aquatic populations is an important aspect. Due to spatial and temporal constraints, recovery cannot be studied experimentally for all species. For instance, species that lack a resistant life-stage and also lack areal dispersal cannot recover after becoming extinct in microcosms or mesocosms. It is, therefore, proposed to estimate recovery using ecological modelling.

In this paper we present an individual-based population model (MASTEP, Metapopulation model for Assessing Spatial and Temporal Effects of Pesticides) describing the effects on and recovery of the waterlouse *Asellus aquaticus* after exposure to a fast acting, non-persistent insecticide as a result of spray drift in pond, ditch and stream scenarios. The model used the spatial and temporal distribution of the exposure in different treatment conditions as an input parameter. A dose–response relation derived from a hypothetical mesocosm study was used to link the exposure with the effects. The modelled landscape was represented as a lattice of 1 by 1 m cells. The model included processes of mortality of *A. aquaticus*, life history, random walk between cells, density dependence of population regulation and, in the case of the stream scenario, medium-distance drift of *A. aquaticus* due to flow. All parameter estimates were based on expert judgment and the results of a thorough review of published information on the ecology of *A. aquaticus*.

Introduction

One of the major issues in the environmental risk assessment of pesticides in Europe is to estimate recovery of affected (aquatic) organisms after pesticide induced stress (EU, 1997). For organisms with resistant life stages or an flying life-phase and multiple life-cycles per year, like *Daphnia* and *Chaoborus*, recovery can be estimated experimentally using outdoor microcosms or mesocosms (Van den Brink et al., 1996). For non-flying organisms with no insensitive life-stages like *Gammarus* and *Asellus*, however, the isolated nature of the mesocosms and the limited duration of the experiment prevent the study of recovery of these species.

In this paper we, therefore, describe a spatially-explicit model for waterlouse *Asellus aquaticus* populations and their recovery after pesticide stress. The model can be used to estimate combined autogenic and allogenic recovery after a spray drift event involving an insecticide in a stream in North-West Europe. *Asellus aquaticus* is a widely distributed freshwater crustacean common in both standing water (ponds, lakes) and flowing water (streams, rivers). Population dynamics vary according to temperature: typically, there is one breeding peak in summer in Northern Europe, two peaks (one in spring and one in autumn) in North-West and Central Europe, and either year-round reproduction or winter breeding in Southern Europe. Since this paper focuses on North-West Europe, only life-cycle characteristics representative of this region were used.

The waterlouse *A. aquaticus* was used as an example for invertebrates because it is relatively sensitive to insecticides and has a presumed low capacity for allogenic and autogenic recovery because it does not have the possibility to recolonise affected patches or stretches of a water body via terrestrial life-stages and was believed to have a relatively low population growth rate. The decision to use *A. aquaticus* meant that there was no need to model multiple non-connected watercourses, because exchange of individuals between these watercourses would not occur directly without interference of other agents like man and waterfowl. We therefore only modelled connected watercourses, though the model concept easily allows for the inclusion of non-connected watercourses in the future. The model is described in full by Van den Brink et al. (2007).

Materials and Methods

This section describes the MASTEP model (Metapopulation model for Assessing Spatial and Temporal Effects of Pesticides) and its application for *Asellus aquaticus*. We follow the standard protocol for describing individual-based models as proposed by Grimm et al. (2006). We chose an individual-based approach because the individual level is easily linked to the population level, the level we are interested in from a risk assessment point of view, and allows us to use available data both at the individual and the population level. It is a natural approach because it describes the very entities comprising a population and their behaviour. MASTEP was developed in VisualWorks Smalltalk (smalltalk.cincom.com) using the EcoTalk modelling framework (Baveco and Smeulders, 1994).

Purpose

The purpose of the model is to quantify population effects and recovery after pesticide exposure.

State variables and scales

The model included two types of entities: female individuals and quadratic grid cells comprising the habitat. The individuals were characterized by the state variables: identity number, generation number, location (coordinates of a grid cell), and an array of experienced local densities (density history). The time unit is a day and simulations usually lasted for one year (365 days). A grid cell's size represented 1 by 1 m and the habitat contained a number of grid cells depending on the spatial scenario (e.g., an array of 600 cells for a ditch scenario).

Process overview and scheduling

State changes are scheduled as discrete events (see Fig. 1). When appearing in the simulation (at individual "birth") the events of reproduction and of death due to aging are scheduled. If the individual is still alive at the time of the reproduction event, it will reproduce. At the time of the mortality event it will be removed from the simulation. Also movement is scheduled as a sequence of discrete events in continuous time. The timing of movement events is determined by the residence time probability density function (PDF). The timing of reproduction and mortality due to aging are determined by the age at reproduction PDF and lifespan PDF, respectively. The check on local (within cell) density and the effectuation of density-dependent mortality is scheduled with a fixed delay of 1 day, equivalent to what would happen in a time-step based model with a one day time-step.

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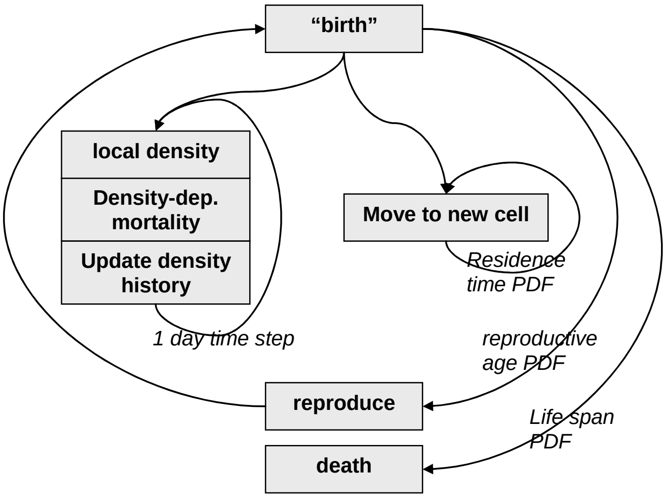

Fig. 1. Overview of the scheduling of state-change for an Asellus individual in the Metapopulation model for Assessing Spatial and Temporal Effects of Pesticides (MASTEP) model. In boxes the different events in its life-history are shown. In italics the origin of the time delay after which the event takes place. Arrows without text point to events that take place 'immediately' (time delay of zero). The main loops are the one occurring with a one day time delay checking for density-dependent mortality, and the movement loop. Pesticide application was scheduled as a separate event.

Design concepts

The model does so far not include any kind of adaptive behaviour or individual decision making, but is, similar to matrix models, based on demographic rates and further empirical parameters.

The representation of the processes reproduction, mortality and movement or dispersal included stochasticity. As figure 1 shows, the timing of most events is stochastic. In addition, some vital rates are interpreted as probabilities, e.g. density-dependent mortality and the number of offspring. Stochasticity is included in order to incorporate individual variability in a natural way, and to avoid artefacts due to unrealistic synchronization (e.g., all offspring appearing at the same day).

The observation variables were density of individuals, either in the 100 m sprayed part of the scenario or the whole modelled water body (600 m). All individuals of the different generations were summed. The 95% confidence intervals of the results were obtained from at least five replicate runs.

Initialization

Initial population size amounted to 1000 individuals, randomly distributed over the 600 cells.

Input

The model did not include any driving environmental variable, i.e. the environment was assumed to be constant.

Submodels

For details, see Van den Brink et al. (2007).

Lifecycle: The model focused on a single annual cycle, comprising several generations. The first generation (1) consisted of individuals born in the previous year. These individuals reproduced around day 120 (day 1 is 1 January), causing the first population peak. The next generation of individuals (2) reproduced 70 days later (around day 190), leading to the second population peak.

Reproduction: Clutch size was set to be depending on age at reproduction and mean local density encountered by the individual. Mean local density was calculated as the mean of all the within grid cell densities encountered by the individual. The number of offspring could never exceed twice the default clutch size.
Mortality: The model set the lifespan of each individual at birth in a probabilistic way.
Density dependence: Density-dependent mortality rate is assumed to be linearly related to actual local density. Density-dependent reproduction is incorporated by decreasing the number of offspring with average experienced density for each individual.
Dispersal and movement: Individual movement by walking was modelled as a jump from one cell to a randomly selected neighbouring cell at a time set by the (probabilistic) residence time. The probability density function was obtained from a simulation of a random walk process with parameters derived from experimental work (Englund and Hambäck, 2004). The model incorporates passive movement downstream by implying that 1% of the movement to other cells was long-distance movement (drift) in a downstream direction. Drift distance was incorporated as an exponential distribution, with an assumed average of 10 m.
Pesticide mortality: Survival at a given initial (peak) concentration in the water was defined by a dose–response curve using a logistic model, with mortality occurring directly after exposure. The parameters of this curve are obtained from the results of a hypothetical mesocosm experiment. The numbers of *A. aquaticus* collected one week after application of the chemical was regressed on the peak concentrations of the chemical, occurring directly after application.

Scenarios
Landscape: the structure of the stream scenario was 600 by 1 m^2 cells. To obtain more realistic boundary conditions the first cell was connected to the last one (periodic boundary conditions): the individuals that migrated out of the system downstream, entered it on the upstream side The pesticide could be transported downstream, but no further than 600 m. Periodic boundary conditions simulated a simultaneous treatment 600 m upstream of the system (and 1200, 1800 etc m).
Exposure: Since this paper focuses on the effect-side of the model no justification will be provided for the peak exposures that are used to calculate the pesticide-induced mortality. The four concentration profiles used are, however, representative for a normal agricultural use of a fast-acting, fast dissipating insecticide, using a 10, 12.5, 15 and 17.5 m buffer zone.

Results

The untreated population density showed the expected trend of a spring peak and a (higher) summer peak (Fig. 2A, B). Figure 2C shows the results with the 95% confidence intervals for the control and the 17.5 and 10 m buffer zone treatment levels. All buffer zone treatment levels were chosen to result in insecticide PECs at or above the EC50 and thus leading to a clear decrease in densities. Spatially, the application of the insecticide lead to a drop in densities in the first 100 m stretch (Fig. 2A). There were many cells from which all individuals disappeared, although a rapid recovery after treatment was observed, i.e. all treatment conditions returned to control levels within 50 d (Fig. 2A).

This shows that the long-distance movement of *Asellus* was a very important factor determining its population recovery. After 75 d, the effect became apparent again, as a result of the periodic boundary conditions. When the numbers in the entire 600 m stretch are taken into account, differences persisted longer (Fig. 2B). This means that effects were “exported” to untreated cells due to a reduced influx either by walking or by drift from the treated cells. This is clearly visualised in Figure 3. In the figure time runs from top to bottom and the stream from left to right. The left part of the stream is sprayed with the insecticide on day 130 and causes a complete die off (black denotes absence of *Asellus*, blue high abundance values). Although only 1/6th of the stream is sprayed with the insecticide, in more than half of the 600m stretch of the stream *Asellus* dies because of contamination by water movement (Fig. 3). Recovery is fast in the affected parts of the stream due to the movement by drift. Because of that the ‘empty patch’ travels through the stream in time. Eventually, no full recovery within a year was obtained in the three highest treatment levels, because of the periodic boundary conditions.

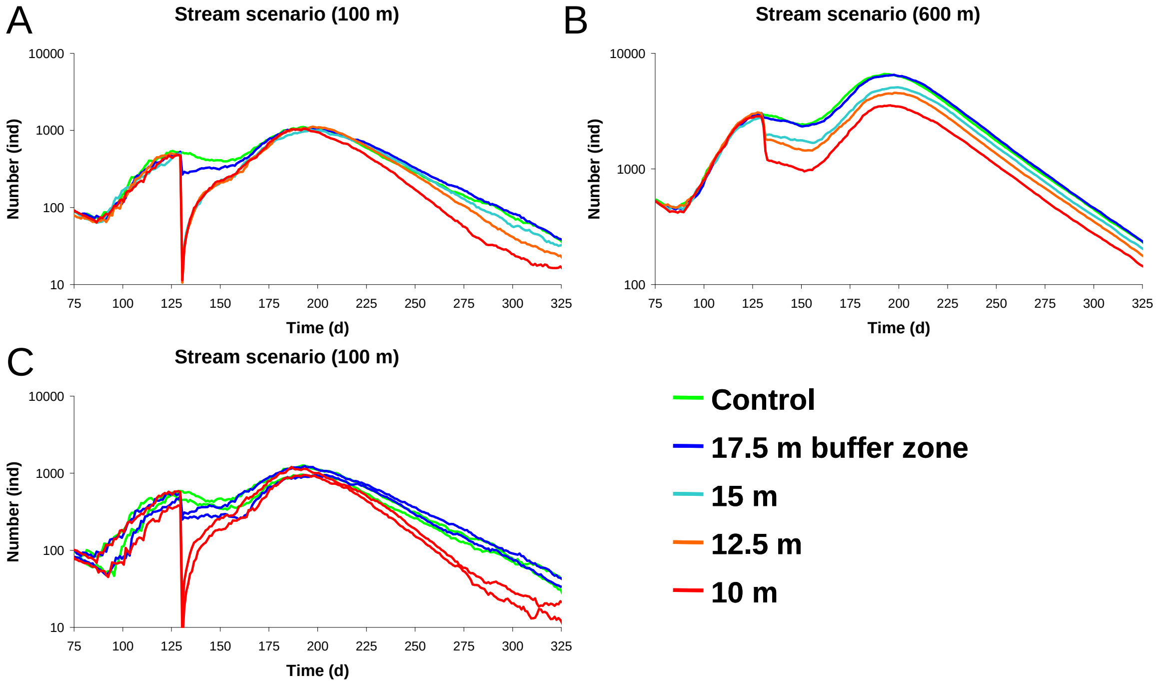

Fig. 2. Dynamics of numbers in all treatment levels for: (A), the treated 100 m stretch (B), the complete 600 m stretch and (C), 95% confidence intervals of the dynamics of numbers of the treated 100 m stretch. The application occurred on day 130.

Discussion

Assumptions of the model

Models are by definition a simplification of reality. The model presented here is detailed in terms of population age structure and spatial structure (and movement), but many other factors have been omitted or simplified. In the present study we implemented a simple link between the fate of a chemical and the effects on *Asellus* individuals in the model.

Uncertainty in the parameters

Some of the parameters of the model, such as mortality, age of breeding and number of young, have been accurately reported in the literature. The situation is completely different for parameters of movement and density-dependent processes. We know of only one experiment studying *Asellus* movement, and have derived the movement parameters for our model from this experiment, which was performed in an artificial environment without food and shelter.

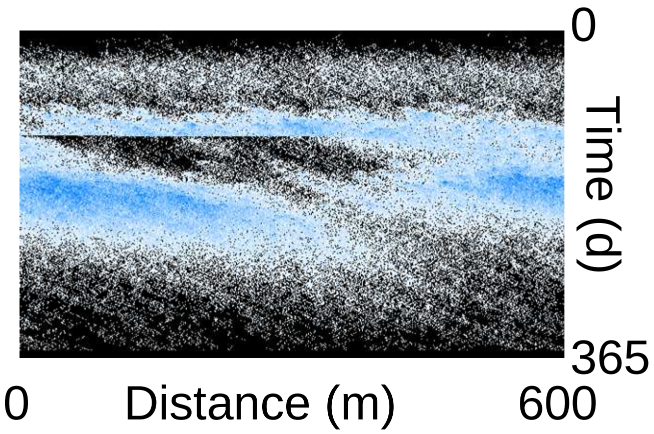

Fig. 3. Visual representation of the dynamics of abundance for one of the runs for the 10 m buffer zone treatment level. The x-axis shows the numbers over the complete 600 m stretch, while the y-axis represents the temporal dimension (each day adding a row). The results of the complete 600 m stretch are given; the first 100 m stretch is treated with an insecticide on Julian day130.

To assess /the sensitivity of the model to the invertebrate drift parameters, we conducted simulations with and without invertebrate drift (results without drift not shown). These showed that the outcome differed for the treated stretch of the stream, where densities in the absence of invertebrate drift failed to return to untreated levels, but not much for the entire population in the 600 m stretch. We are unsure what the real drift values are, although 1% does not seem unrealistically high (Peeters et al., 2002).

The parameters we use for density-dependent regulation cannot be underpinned with data from the literature; the main role of the density-dependence in the model is to keep populations at a desired density level without all too much affecting the population’s potential for recovery from very low densities.

Outlook

The model presented in this paper shows that theories on for instance density-dependence, life-cycles, movement patterns developed in the field of ecology can be applied in the risk assessment of chemicals. It therefore also offers an example of stress ecology, i.e. ecology, into which a stress element is integrated. Risk assessment of pesticides is currently merely based on determining the sensitivity of organisms, while the results of this model show that life-cycle characteristics might be equally important for determining the spatial and temporal magnitude of the effects. This raises the question what actual level of protection is achieved by the use of single-species tests in the first tier of the risk assessment, which is completely devoid of ecology (Van den Brink, 2006). This first tier may still provide a sufficient level of protection because of the use of safety factors.

In this paper we used the well-studied waterlouse *A. aquaticus* as an example. Although some life-cycle characteristics of this species, like age and number of offspring, are known from detailed studies, others, like density dependence and walking behaviour, are not. We therefore need more research concentrating on the life-cycle and movement patterns of invertebrates. If flying insects are included as well, non-connected water bodies should also be included, so the model becomes a metapopulation model in the classical sense. Adding more life-cycles and more complex landscape features will make MASTEP a tool that allows the results of microcosm and mesocosm experiments to be extrapolated to the landscape level. This would allow better regulatory decisions to be made on acceptability of effects, as a more realistic description of recovery is obtained than that provided by the microcosm and mesocosm experiments alone.

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