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Modelling long-term ecotoxicological effects on an algal population under dynamic nutrient stress

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ABSTRACT

We study the effects of toxicants on the functioning of phototrophic unicellular organism (an algae) in a simple aquatic microcosm by applying a parameter-sparse model. The model allows us to study the interaction between ecological and toxicological effects. Nutrient stress and toxicant stress, together or alone, can cause extinction of the algal population. The modelled algae consume dissolved inorganic nitrogen (DIN) under surplus light and use it for growth and maintenance. Dead algal biomass is mineralized by bacterial activity, leading to nutrient recycling. The ecological model is coupled with a toxicity-module that describes the dependency of the algal growth and death rate on the toxicant concentration. Model parameter fitting is performed on experimental data from Liebig, M., Schmidt, G., Bontje, D., Kooi, B.W., Streck, G., Traunspurger, W., Knacker, T. [2008. Direct and indirect effects of pollutants on algae and algivorous ciliates in an aquatic indoor microcosm. Aquatic Toxicology 88, 102–110]. These experiments were especially designed to include nutrient limitation, nutrient recycling and long-term exposure to toxicants. The flagellate species *Cryptomonas* sp. was exposed to the herbicide prometryn and insecticide methyl parathion in semi-closed Erlenmeyers. Given the total limiting amount of nitrogen in the system, the estimated toxicant concentration at which a long-term steady population of algae goes extinct will be derived. We intend to use the results of this study to investigate the effects of ecological (environmental) and toxicological stresses on more realistic ecosystem structure and functioning.

1. Introduction

When assessing the ecological status of a river, the effects of both toxicant and environmental stresses on multiple species have to be accounted for (Brack et al., 2005). Laboratory toxicity tests, on the other hand, generally concern a single stress and a single species. The use of population models for extrapolation from single species ecotoxicological observations to the relevant effects on an ecosystem is discussed in Forbes and Callow (2002) and in Forbes et al. (2008). Here for modelling purposes, an aquatic ecosystem contains a limiting nutrient and functional groups: producers, predators and decomposers to ensure nutrient recycling.

In order to study direct and indirect effect of toxicants, the bottom trophic levels of this system have been exposed and studied by Liebig et al. (2008) in these microcosm experiments. In these Erlenmeyer experiments the flagellate *Cryptomonas* sp. represents the producers, the ciliate *Urotricha furcata* represents the predators and undetermined bacteria are the decomposers. The system is exposed to either a herbicide or

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a pesticide for 14 days. The nutrient level is maximum at the onset and is reduced by the algae. Therefore, the nutrient concentration declines dynamically during the batch experiments and becomes limiting after the first days. In Liebig et al. (2008), the data sets were analysed using the traditional toxicity test procedures (OECD, 2006). These procedures may only be applied under exponential growth conditions, which holds true for the first days of the algal data sets when nutrients are abundant and thus no interactive effects of nutrient limitation and toxic stress occur.

In this paper, we perform an analysis of the limiting nutrient-*Cryptomonas* sp. subsystem using the full duration of the experiment. Consequently, the analysis is extended outside the exponential growth phase and includes nutrient limitation. To perform this extended analysis, we apply a process-based eco-toxicological model in which the growth and death of the species is simulated using a deterministic Marr-Pirt model (Kooijman, 2000; Kooi, 2003). Dead algal biomass is mineralized by bacterial activity. The model considers recycling of the limiting nutrient. To incorporate the toxicant effect the DEBtox approach (Bedaux and Kooijman, 1994; Kooijman et al., 1996) is applied where two parameters are needed per affected process such as growth or mortality. One of the toxicity parameters is the no-effect concentration (NEC). Below this threshold the toxicant has no effect on an individual. The other is the tolerance concentration (TC) which represents the strength of the toxic effect. Parameter values, standard deviations and their covariance are estimated by fitting the resulting model on the experimental data from Liebig et al. (2008) with a least-sum-of-squares method. This provides simultaneously the toxicological parameters, NEC and TC, and the biological parameters, such as growth rate, hazard rate and nutrient half-saturation constant.

The algal growth dynamics, including steady-state biomass, depends on these biological parameters. Toxicants affect biological processes and thus the dynamics. Dynamic behaviour is also affected by nutrient availability. Hence, the effects of a toxicant and a nutrient on the dynamics, which are difficult to separate in nature, are taken into account in the model formulation simultaneously.

Hallam et al. (1993) introduced the Population Extinction Threshold (PET): defined as the highest ambient chemical concentration at which the population could persist during long-term exposure. Extinction of a population can be caused by a too low nutrient availability (starvation) but also because of toxic effects causing increased death rate or reduced growth efficiency. From the deterministic model the expressions for the PET are derived. In the Appendix, the stochastic formulation of the PET which respects covariance between parameters is given. The estimated toxicological and biological parameters are used to study the dependence of both extinction and persistence of the algae on toxicant concentration and nutrient load.

2. Material and methods

2.1. *Experimental data of system with nitrogen,* Cryptomonas *sp. and toxicant*

Liebig et al. (2008) performed in Erlenmeyers 14-day exposure experiments with the flagellated algae *Cryptomonas* sp. and the herbicide prometryn (CAS 7287-19-6), which inhibits photosystem II, and the insecticide methyl parathion (CAS 298-00-0). In these experiments chemical stress and nutrient limitation occur simultaneously. Fig. 1 (Liebig et al., 2008, Fig. 1A) shows the growth curves for cell numbers affected by each toxicant. The measured number of cells ($V(t)$) is converted into algal biomass (A) expressed in mol N L^{-1} by using

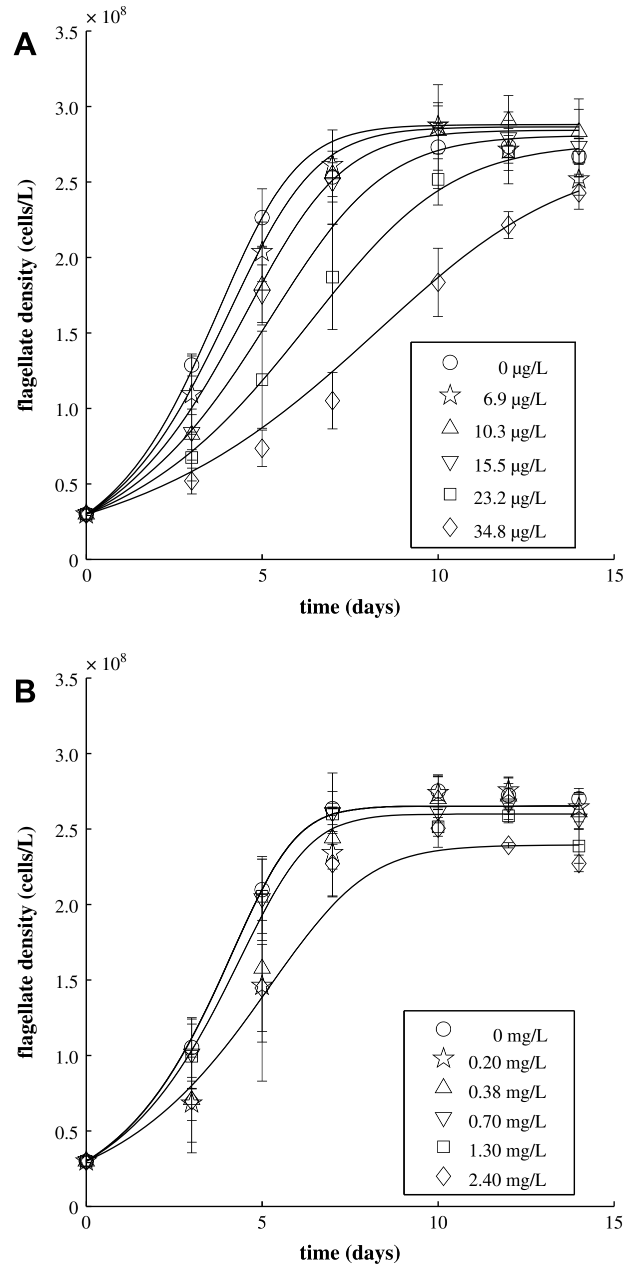

Fig. 1 – Calculated and measured algal densities are affected by prometryn and methyl parathion. See Table 2 for parameter values of the fit for each data set. Averages and variances are based on four replicates. A: Prometryn was modelled to affect the growth rate. B: Methyl parathion was modelled to affect the hazard rate. The NEC is above the first three exposure concentrations. Therefore only the simulations with the highest two exposure concentrations differ from the control.