Summary

Ecological risk assessment of chemicals aims to predict adverse effects of chemicals on natural populations by comparing the predicted environmental concentration with the no-effect concentration level. The information on the ecotoxicity is derived from laboratory bioassays in which individual-level effects of toxic chemicals on survival, fecundity, or body growth rate are determined. These bioassays are standardized and usually conducted under constant environmental conditions, which neglects potential influences of all other environmental factors. What is more, the experimental conditions are presumably optimal for the test organisms. However, in their natural environment, organisms rarely experience optimal or constant conditions. On the contrary, they have to cope with either suboptimal conditions or even severe environmental stress for most of their life spans. Thus, the relevance of results of standard toxicity tests for field situations is limited, and it is also economically prohibitive or just impossible to experimentally assess all possible interactions. To fill this gap, we need analytical tools that can take individual-level data as input and calculate measures of population-level performance, by considering important ecological factors that can influence the effects of toxicants at individual and population levels. This thesis is primarily aimed at developing population models to extrapolate the combined effects of
toxicants and natural environmental stressors (particularly temperature and density-dependence) from the individual to the population. The first step in this study was to implement an age–based matrix model to infer the consequences of toxicant effects observed on individuals to population end points. The primary focus of the modeling approach was to identify the extent to which individual-level responses influence the population-level effects. The results showed that the population level interpretation of the individual level experimental results requires information on the effect of the toxicant on the life stage under study and the demographic sensitivity of the population multiplication factor ($\lambda$) to changes in particular life stages. The demographic decomposition analysis presented in this part of the thesis was recommended as a tool to design short term experimental studies. In the rest of the thesis, the combined effects of natural environmental factors and cadmium on *Folsomia candida* was studied by applying different modelling approaches. *F. candida* is the most studied collembolan in ecology and ecotoxicology. Currently, the species is used as standard test organism for terrestrial invertebrates both in OECD and ISO guidelines. Initially, a stochastic density–dependence matrix model was developed and applied to investigate the combined effects of cadmium, seasonal temperature fluctuation and density–dependence on the population dynamics of *F. candida*. It was shown
that extrapolating individual-level effects of Cd to a higher level of biological organization without considering environmental variability underestimates effects of chemicals on the population growth rate. The study result showed that chemicals can also reduce the population size at its carrying capacity. The latter phenomenon arises from different effects of toxicants on different age/stage classes combined with natural demographic processes. Mean time to extinction (MTE) was applied as population–level index to combine all these effects (i.e., environmental variability, chemical-specific toxicity, and density dependence). From the model simulation, it was shown that the mean time to extinction of a *F. candida* population exposed to 1000 mg Cd/kg soil can be reduced by 40% compared to the control population. Nevertheless, this significant reduction will not lead to rapid extinction of the population as the estimated mean time to extinction is still over 3000 years. Based on these results, a population of *F. candida* exposed to this concentration of Cd may not be considered to be endangered. The population–level effects assessment presented in this study is one possible improvement in risk assessment, and an extension of the methodology applied, would be to add yet another end-point which can be calculated using the approach presented herein, namely the equilibrium size of a population under pollution pressure.
A more generic and mechanistic model was developed by linking an energetic based individual-level effect model with the Euler-Lotka equation. Formulating mechanistic effect models to interpret organism-level effects of chemicals helps to understand the interactions between individuals and the environment. It can also help to make an educated extrapolation to the population-level. Such mechanistic effect models can be derived from a general and comprehensive energetic theory: the Dynamic Energy Budget (DEB) theory. DEB theory provides a mechanistic interpretation of how organisms acquire and use energy. The development and implementation of this model framework for particular species requires, however, reasonable model parameters for the organism of interest. Thus, as first step a suitable experiment was designed using a simplified DEB model (“DEBkiss”), which was parameterized and calibrated for *F. candida*. The DEBkiss model successfully captured the growth and reproduction trends of the organism at different feeding and temperature conditions, but at the early juvenile stage, the growth of *F. candida* deviated from the von Bertalanffy curve. We assumed an age-dependent switch in feeding behavior of the juveniles, which resulted in a good fit to the body size data for all observed data sets. The model was linked with the Euler-Lotka equation to predict the combined effect of food density and temperature on the population growth rate of *F. candida*. We
conclude that the life history of *F. candida* is influenced by both food limitation and temperature in a predictable manner. We also showed that food limitation and temperature can have different forms of interactions on the dynamics of *F. candida*. In addition to this ecological application, the potential use of the model framework in the ERA process was presented. For this we applied the DEBkiss model to capture the combined effects of Cd and temperature on the growth and reproduction of *F. candida*, and then we applied the Euler-Lotka equation to extrapolate these individual-level effects to population-level. At the individual-level, the DEBkiss model was able to capture the effects of Cd on *F. candida* at 15 and 20 °C, but due to the higher mortality and low reproduction, we could not make reliable fit at 25 °C. Using the model outputs, we estimated EC$_{25}$ and EC$_{50}$ for growth and reproduction, respectively, at both at 15 and 20 °C. These estimates were lower at 15 °C, which indicates that the magnitude of the effects on vital rates of *F. candida* is higher at 15 °C than 20 °C. The response of *F. candida* population to increasing concentrations of Cd was predicted using the Euler-Lotka equation. We found that the population growth rate of *F. candida* decreases at a higher rate at 15 °C than at 20 °C with increased cadmium concentrations. We conclude that extrapolation of effects from the current 20 °C based standard toxicity tests to individuals and population living in different
temperature conditions might lead to erroneous conclusion. We show the great potential of energetic-based models, like DEBkiss, for the mechanistic interpretation of the combined effects of multiple stressors on individuals; and their advantages for developing population models to extrapolation effects to population-level. In recent time, a tendency has developed to integrate population models in risk assessment process, thus the model framework presented in this study can be one potential tool to address the objectives of this new paradigm in ERA.