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Simulating an uncertain world: using qualitative reasoning to model a plant-resource system

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Uncertainty is part of everyday life both for scientists and for decision makers. Nevertheless, such professionals build up theories, develop technological applications, and (try to) make informed decisions. According to Pielke (2001), uncertainty means that more than one outcome is consistent with our expectations. As such, uncertainty is not just some feature of the natural world waiting to be revealed but is instead a fundamental characteristic of how human perceptions and understandings shape expectations.

Much ecological knowledge is incomplete, qualitative and fuzzy, often expressed verbally and diagrammatically. More specifically, these characteristics are often related to the following aspects of uncertainty:

- *structural uncertainty* related to the system structure, which includes knowledge about objects, relations between entities, and what quantities should be included in the model;
- *uncertainty in explanation*, which refers to lack of knowledge to explain why a certain result or behavior appears;
- *vagueness* of the value of a quantity, a reference to the lack of knowledge about possible values of relevant quantities;
- *unknown functional relations* involving quantities included in the model;
- lack of knowledge about *exogenous processes*—those that can affect the system, but are not affected by it;
- uncertainty about the *range of possible behaviors* of the system given a particular set of conditions.

Such kinds of uncertainty associated with incomplete knowledge of a phenomenon—and incomplete knowledge of the limits of one's knowledge—are referred to as epistemic uncertainty (Pielke 2003). In contrast, aleatory uncertainty describes the kind of uncertainty that results from natural variation or stochasticity. Here, we focus on describing ways to deal with epistemic uncertainty in modeling ecological systems.

The characteristics of ecological data just described can make analytical or numerical solutions difficult or impossible to achieve, but nevertheless ecologists need ways to make their substantial qualitative knowledge explicit, well organized, computer processable (Rykiel 1989). In many cases ecologists, managers, and decision makers are interested primarily (or only) in qualitative aspects of ecological systems. For example, questions related to whether a set of conditions will improve a situation or make it worse, what happens if a system component is missing, whether certain outcomes are possible, or what combination of factors caused a given outcome to occur can all be addressed (to a certain degree) with qualitative answers and qualitative data.

In this paper we discuss the use of Qualitative Reasoning (QR) (Weld and de Kleer 1990, Bredeweg and Struss 2003) to cope with epistemic uncertainty in ecological modeling. To do this, we describe a model of a simple yet fundamental ecological process, uptake of resources by plants. The model is based on resource competition theory (Tilman 1982). Our goals are thus to build a qualitative model that (1) captures the mechanisms of plant growth based on extraction of resources from the environment and that (2) illustrates how epistemic uncertainty can be addressed in QR models. Furthermore, by describing this fundamental interaction in the QR ontology, we construct a building block for more complex QR models of related systems.

QR provides a useful framework for expressing uncertainty due to inexact knowledge about parameter values and for exploring the consequences of different understandings of system structure. Uncertainty in parameter values can be expressed and managed using different representations of and constraints on the parameter's quantity space. Compositional modeling supports the creation of alternative models representing different system structures. Finally, QR models allow the creation of a full envisionment of all possible outcomes given a set of causal processes, a particular system structure, and starting values.

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