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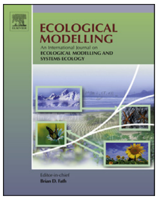

Robustness analysis: Deconstructing computational models for ecological theory and applications

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ABSTRACT

The design of computational models is path-dependent: the choices made in each step during model development constrain the choices that are available in the subsequent steps. The actual path of model development can be extremely different, even for the same system, because the path depends on the question addressed, the availability of data, and the consideration of specific expert knowledge, in addition to the experience, background, and modelling preferences of the modellers. Thus, insights from different models are practically impossible to integrate, which hinders the development of general theory. We therefore suggest augmenting the current culture of communicating models as working just fine with a culture of presenting analyses in which we try to break models, i.e., model mechanisms explaining certain observations break down. We refer to the systematic attempts to break a model as “robustness analysis” (RA). RA is the systematic deconstruction of a model by forcefully changing the model’s parameters, structure, and representation of processes. We discuss the nature and elements of RA and provide brief examples. RA cannot be completely formalized into specific techniques and instead corresponds to detective work that is driven by general questions and specific hypotheses, with strong attention focused on unusual behaviours. Both individual modellers and ecological modelling in general will benefit from RA because RA helps with understanding models and identifying “robust theories”, which are general principles that are independent of the idiosyncrasies of specific models. Integrating the results of RAs from different models to address certain systems or questions will then provide a comprehensive overview of when certain mechanisms control system behaviour and when and why this control ceases. This approach can provide insights into the mechanisms that lead to regime shifts in actual ecological systems.

1. Introduction

Computational models in ecology incorporate factors that are often key to understanding and predicting system-level dynamics and responses to changes in drivers (e.g., Stillman et al., 2015), such as local interactions, variability among individuals, spatial and temporal heterogeneity in resource availability and habitat quality, and adaptive behaviours. Thus, computational models are indispensable tools in theoretical and applied ecology.

However, important limitations remain when using these models to develop general, predictive theory and for the support and management of actual ecological systems under changing conditions. A major and often bemoaned limitation is the complexity of models, but in this study, we focused on a related limitation that has not received much previous discussion: the path-dependence of model development. Path dependence means that the choices that are made in each step during model development constrain the choices that are available in subsequent steps.

For example, if we decide to not include belowground processes in vegetation models, we will find model assumptions and parameter combinations for the aboveground model that explain the observed dynamics sufficiently well, although those dynamics may be largely caused by belowground processes. Thus, we must tweak our model to appear correct with the assumptions

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that certain model mechanisms are either more or less important than they actually are in real ecosystems. To some degree, this type of tweaking is inherent to any type of modelling, and the art of modelling that focuses on a mechanistic understanding of systems requires limiting such tweaking as much as possible.

However, even for the same system, the pathways taken in modelling can be extremely different because the development of models is influenced by differences in the questions, availability of data, and consideration of specific expert knowledge, in addition to the experience, background, and modelling preferences of the modellers (Thiele and Grimm, 2015). As a result, for almost any class of ecological system, we have a multitude of different models, all of which claim to be useful but are often so different in basic assumptions and structure that they are more difficult to compare than apples and oranges. For example, the models that were developed to describe the vegetation dynamics of savannas typically focus on different key processes, including tree-tree interactions (Wiegand et al., 2006; Calabrese et al., 2011), belowground competition between trees and grass for water (Jeltsch et al., 1996), ecophysiology (Higgins and Scheiter, 2012), interactions between the plants and hydrological processes (Tietjen et al., 2010), and various combinations of these processes. This situation is a major impediment to the development of a coherent, generic theory that would represent our understanding of when and why a particular set of factors is required to explain the dynamics of ecological systems. This impediment also contradicts the claim that computational modelling captures the mechanistic functioning of ecological systems.

Overcoming this impediment requires a new culture of analysis and presentation of computational models. Instead of solely focussing on making sure that a model appears correct, inferring from that appearance that it represents the correct set of processes to explain certain observations, we should demonstrate more often when and why a particular model does not work, i.e., when the model mechanisms that explain a certain phenomenon break down. This approach would provide a better understanding of the essential parameters in a given model and the conditions under which certain mechanisms control or cease to control overall system behaviour. Therefore, in this study, we propose systematic attempts to break a model mechanism as an integral element of ecological modelling, which is no less important than, for example, sensitivity analysis (SA hereafter). We refer to this element as the "robustness analysis of computational models".

2. Robustness analysis

The term "robustness analysis" (RA hereafter) is not new and was introduced to ecological modelling by Levins (1966), who suggests examining a set of similar models to determine whether models that are based on different assumptions lead to similar results. When these models do produce similar results, "we have what we can call a robust theorem that is relatively free of the details of the model" (Levins, 1966, p. 423). Thus, the "robust theorem" refers to a general principle that holds independent of the idiosyncrasies of specific models. In the following, we refer to this outcome as "robust theory" because the word "theorem" refers to something that has been proven to be true, as in mathematics, which is not possible in the real world. As an example of a "robust theory", Zinck and Grimm (2009), regarding forest fires, found that two apparently exclusive classes of models that were developed in forest ecology and in statistical physics produced essentially the same outcome. Both models included the "robust theory" that ecological memory, i.e., the susceptibility of a site to burning again as a function of recovery since the last fire, determined the shape of the fire size distributions. Similarly, Weisberg and Reisman (2008) used RA to extract another robust theory from a suite of mathematical and individual-based models that was based on the effects of biocides on predator-prey systems.

The concept of RA has been discussed by epistemologists (e.g., Wimsatt, 1981; Orzack and Sober, 1993;Wimsatt, 2007; Weisberg and Reisman, 2008) but never became a routine part of ecological modelling. More recently, Weisberg (2012) summarized Wimsatt's (1981) characterization of RA: "robustness analysis' aim is to separate the scientifically important parts and predictions of our models from the illusory ones which are accidents of representations. These reliable parts are what Levins called robust theorems". We adopted this notion, particularly the idea that robustness analysis should help discriminate the "accidents of representation", which all models contain because of path dependence, from the mechanisms that actually operate under defined conditions.

Our concept of robustness analysis is complementary to the original idea of Levins (1966). Levins emphasized the similarities in which models point in the same direction, whereas we emphasized pushing models to the breaking point. These points of emphasis are often two sides of the same analysis, but they are not the same and do not provide the same information. Levins attempted to extract general mechanisms, which were the same across different models, whereas we attempt to determine the robustness of the mechanisms within a given model. We suggest a focus not only on the different models that were developed by different modellers but also on individual computational models by systematically creating many different versions of the same model. This approach corresponds to the practice that all skilful modellers routinely use during model construction: try to test many different versions of a model. Our objective was to formalize the inverse process and systematically deconstruct a model and then to trace and document the subsequent comparison of the descriptions of the systems to identify the robust mechanisms.

Robustness analysis is more in-depth than sensitivity analysis. Almost 30 years ago, Mollison (1986) wrote that "a traditional 'sensitivity analysis', in which numerical parameters are varied, is not really adequate; we also need to know whether our result is sensitive to the form of components (e.g., the shape of a dispersal distribution) or indeed to the inclusion of some further component in our model" (Mollison, 1986, p. 677). Certainly, many experienced computational modellers are familiar with the concerns of Mollison and actually perform elements of a robustness analysis, but in most modelling studies, the structure of a model remains as a given, and the model analysis is restricted to sensitivity experiments and analyses or to uncertainty analysis.

Grimm (1999) suggests that a psychological barrier might be responsible for this: making a computational model produce realistic output can be a time-consuming and complex task. A switch then, for model analysis, from construction to deconstruction apparently contradicts the purpose of modelling, which is to produce realistic representations. Therefore, in an attempt to overcome this psychological barrier, we suggest the following: summarize the elements of the structural model analysis under a common name, robustness analysis (RA); suggest that path dependence is the primary reason for RA; summarize the elements of the RA into a more coherent framework; and discuss the benefits of RA both for the individual modeller and for ecology in general.

Ultimately, the goal is to have "robustness analysis" routinely and no less often presented than, for example, "sensitivity analysis", in the Methods and Results sections of future modelling publications. We believe that RA should be a key element of model analysis because RA improves the understanding of the control mechanisms of models and, therefore, the actual counterparts in nature, which contributes to the development of general ecological theory.

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