Hybridization of System Dynamics and Individual-Based Modelling as Solution to Modelling Issues in Ecology

Christian Vincenot, D3

July 29, 2011

Abstract

Modeling could be summed up as the task of reproducing the structure and imitating the behavior of complex real-life systems with components interacting with one another at different scales. Such endeavour can become particularly challenging, especially in Natural Sciences like Ecology, in which systems are large, dynamic, interactive, and intricated.

This thesis starts by an analysis of the state and purposes of Ecological Modelling. Based on philosophical and technical considerations, a potential solution to the recent issues faced by this discipline is advanced in the form of a conceptual framework relying on the fusion of System Dynamics and Individual-Based Modelling. The latter techniques have usually been considered until now as exclusive alternatives instead of synergistic tools. A quick introduction and comparison of the two approaches is undertaken to identify their strong and weak points depending on the type of components constituting the system under consideration. By isolating a class of systems difficult or in some cases impossible to model dynamically using any traditional modelling approach, because of conceptual limitations, the usefulness of merging the two paradigms inside of a hybrid modeling framework is stressed. Relying on observations of real natural systems, elementary combination patterns of System Dynamics and Individual-Based modeling are then proposed and form a set of so-called "reference cases", which are used inside of the conceptual framework as building blocks to mirror and reproduce ecosystems.

Since the power of such a hybrid approach has been unexplored in Ecology, three models related to various fields of this science – an epidemic model, a foraging model, and a vegetation model – are described. Each model is structurally unique and is consequently based on a different combination of reference cases of the framework. Also, each modelling case aims at showing how technical restrictions engendering detrimental assumptions in traditional models can be waved by resorting to hybrid modelling. While the fitness and originality of the conceptual framework is demonstrated through these exercises, some valuable ecological results are also extracted to show to ecology specialists the practical usefulness and interest of the models.

Ultimately, a synthesis of the knowledge learned throughout this research project is proposed and leads to a preliminary conclusion on the validity of this original fusion of paradigms.

1 Thesis structure

1.1 Chapter 1

A short introduction to Ecology and Ecological Modelling is given. Then, current trends and issues surfacing in the latter field are pointed out and described.

1.2 Chapter 2

To propose a solution to the problems described in chapter 1, the situation of ecological modeling is analyzed. A contrastive analysis between the goals of this discipline, the type of systems faced in Ecology, and the properties of the current modeling approaches is undertaken and leads to the formulation of a hypothesis about the negative effects of present modeling paradigms and their links with the problems enumerated before. The requirements for a new more fitting modeling approach are then explicated. On the basis of these requirements, a tentative solution is advanced in the form of a framework relying on the fusion of System Dynamics and Individual-Based Modelling. This represents the core of this thesis. Lastly, theoretical discussions on the usefulness of such a paradigm shift are reported and possible applications are underlined.

1.3 Chapter 3

As illustration and to proof the concept, three models in theoretical ecology are presented in this thesis. The first model deals with the accurate representation of large-scale epidemics in fragmented metapopulations. After brief background information on epidemic models, the SD-IB hybrid model is presented. Results in terms of ecology and health science are then presented and show the significant effects of metapopulation properties (e.g. topology) on disease dynamics, indirectly stressing thereby the usefulness of the concurrent simulation of local outbreaks dynamics and metapopulation-scale spread, which the hybrid model is able to reproduce. From the standpoint of modeling, detrimental effects of the well-mixed assumption in epidemic models are also demonstrated and reinforce the value of the SD-IB hybrid approach.

1.4 Chapter 4

The second case demonstrates a use of the concept to propose a complete view of foraging by integrating a continuous metabolism submodel, a discrete foraging decisions submodel and a memory submodel inside of a single spatially-explicit model. This model is then used to study the impact on the health of a generic forager of spatial resource distribution. The latter proves to be at least as critical as resource heterogeneity, which was the only aspect considered in previous models due to technical limitations. Also, a strong mutual influence between memory capabilities and the disadvantageousness of spatial resource distribution is exposed. From the modeling point of view, hybrid modeling is concluded as being decisive for the accurate modeling of foraging by allowing for the integration of all these submodels in space and by supporting realistic and ecologically-sound time considerations for each of them.

1.5 Chapter 5

The third study case involves the creation of an unprecedented model of vegetation growth at the plant-scale integrating plant-soil interactions at the same time as realistic dispersal mechanisms. It is used to study the mechanisms of vegetation pattern formation, and verify the accuracy of one of the two leading theories on this subject. Interesting ecological results on the link between vegetation patterns and resistance to stochastic meteorological fluctuations and climate shifts are shown. From the modeling of view, the value of the hybrid approach is demonstrated through the capacity to fusion current theories on the subject of vegetation patterns, to represent plant biological mechanisms, and to collect individual-scale data.

1.6 Chapter 6

The last chapter synthesizes the knowledge learned throughout this thesis. For future reference, preliminary learning on methodological aspects is first reported. Then, as regards the initial hypothesis, a critique is made of the relative success of the hybrid approach advocated here to tackle the problems initially isolated in ecological modeling. As a conclusion, possible future research steps are proposed.