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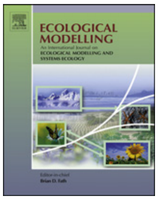

Review

The role of agent-based models in wildlife ecology and management

Adam J. McLane[a], Christina Semeniuk[b,*], Gregory J. McDermid[a], Danielle J. Marceau[b]

[a] Foothills Facility for Remote Sensing and GIScience, Department of Geography, University of Calgary, 2500 University Dr. NW, Calgary, AB, T2N 1N4 Canada
[b] Geocomputing Laboratory, Department of Geomatics Engineering, University of Calgary, 2500 University Dr. NW, Calgary, AB, T2N 1N4 Canada

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ABSTRACT

Conservation planning of critical habitats for wildlife species at risk is a priority topic that requires the knowledge of how animals select and use their habitat, and how they respond to future developmental changes in their environment. This paper explores the role of a habitat-modeling methodological approach, agent-based modeling, which we advocate as a promising approach for ecological research. Agent-based models (ABMs) are capable of simultaneously distinguishing animal densities from habitat quality, can explicitly represent the environment and its dynamism, can accommodate spatial patterns of inter- and intra-species mechanisms, and can explore feedbacks and adaptations inherent in these systems. ABMs comprise autonomous, individual entities; each with dynamic, adaptive behaviors and heterogeneous characteristics that interact with each other and with their environment. These interactions result in emergent outcomes that can be used to quantitatively examine critical habitats from the individual- to population-level. ABMs can also explore how wildlife will respond to potential changes in environmental conditions, since they can readily incorporate adaptive animal-movement ecology in a changing landscape. This paper describes the necessary elements of an ABM developed specifically for understanding wildlife habitat selection, reviews the current empirical literature on ABMs in wildlife ecology and management, and evaluates the current and future roles these ABMs can play, specifically with regards to scenario planning of designated critical habitats.

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* Corresponding author. Tel.: +1 403 220 4916; fax: +1 403 284 1980.
E-mail addresses: ajmclane@ucalgary.ca (A.J. McLane), semeniuc@ucalgary.ca (C. Semeniuk), mcdermid@ucalgary.ca (G.J. McDermid), dmarceau@ucalgary.ca (D.J. Marceau).

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1. Introduction

Wildlife species are under tremendous pressure from both natural and anthropogenic influences, including climate change, pollution, and habitat loss and fragmentation. Identification and protection of critical habitats is central to the management of species at risk, and the need to designate habitats as critical for species persistence is universally recognized by scientists, resource managers, and the general public. However, critical habitat designations will be challenged if they affect stakeholders who bear the lost opportunity costs of economic activity (Rosenfeld and Hatfield, 2006). As a result, political decision-makers involved in conservation planning of critical habitats face difficult challenges when it comes to balancing economic development and the maintenance of a healthy environment.

Conservation planning is the process of locating, configuring, implementing and maintaining areas that are managed to promote the persistence of biodiversity (Margules and Pressey, 2000). Effective conservation planning also acknowledges the complexity imposed by dynamic updating of priorities for both biodiversity patterns and processes as decisions are made. For instance, anticipated changes to species distributions in response to environmental and/or landscape change will influence decisions about conservation design (Pressey et al., 2007). Scenario planning is one important component of conservation planning, and is necessary for assisting the development of knowledge and planning tools required by managers and decision makers. A technique for making decisions in the face of uncontrollable, irreducible uncertainty, scenario planning offers managers a method for creating more resilient conservation policies by considering multiple possible futures, both socio-economic and ecological (Peterson et al., 2003). Benefits of using scenario planning include increased understanding of key uncertainties, the incorporation of alternative perspectives into conservation planning, and greater resilience of decisions to surprise. This approach has direct implication for the process of delineating critical habitats for species at risk, since in addition to determining wildlife habitat space and usage, conservation planning of wildlife habitats also involves the analysis of future habitat-linked population demographics under various land-use development scenarios.

To better inform management in the determination of critical habitat, wildlife research has long focused on understanding wildlife use of habitats and, when combined with the availability of resources, what animals select and avoid on the landscape, and how, and why they select the features that they do (Morris et al., 2008). Specifically, information on the wildlife's adaptive behaviors of habitat selection, movement ecology, and its responses to a dynamic environment are integral to successful conservation and scenario planning. For instance, an examination of the underlying processes and mechanisms of habitat-selection by the individual will provide the ability to distinguish habitat use based on adaptive preferences, maladaptive preferences (ecological traps), or non-ideal habitat selection (i.e., the fitness consequences of habitat selection; for an example see Arlt and Pärt, 2007). This distinction is of considerable value in the ranking of habitat types for conservation planning. Next, the movement ecology of the organism, which includes the internal state, motion capacity, and navigation capacity of the individual, provides insight into how wildlife are affected by matrix heterogeneity, and can generate emergent properties that improve our understanding of the demographics of stochastic, spatially structured populations (Revilla and Wiegand, 2008). Because the dynamic nature of the environment plays such an influential role in affecting organism state, behavioral decisions, and motion, a representation of the animal's actual environment in a spatially explicit manner in habitat modeling can improve the effectiveness of conservation planning, since it can highlight the causal links between organism movement and environmental change (Nathan et al., 2008). Finally, the capacity to accommodate the dynamism of the environment, the spatial patterns of inter- and intra-species mechanisms, and the feedbacks and adaptations inherent in these systems can allow one to explore how animals will respond to and be affected by future and novel changes in their landscape, which is an essential criterion for scenario planning.

Management of wildlife therefore requires the stewardship and/or conservation of cognizant and adaptive individuals that interact with one another and their environment, the combination of which comprises very diverse and dynamic populations. It is this diversity and dynamic nature that makes populations robust and capable of handling perturbations in environmental conditions, and therefore this information should not be overlooked. What is needed is a thorough understanding of the individual behaviors and motivations of wildlife involved in habitat selection and use, and the ability to utilize and project these fitness-maximizing decision and movement rules in a spatio-temporal context to assess how animals will respond to future changes in their environment. A range of habitat models are available and are capable of addressing one or more of these issues independently or in concert; for instance, resource-selection models (e.g., Johnson et al., 2004), dynamic optimization models (e.g., Chubaty et al., 2009), and population-level land-use change models (e.g., Copeland et al., 2009), to name but a few. Our intent is not to conduct a systematic comparison of each approach as they often complement, as opposed to supersede one another. Rather, we review here a further methodology that can accommodate spatio-ecological information, and which links detailed knowledge of animal behavior and movement with explicit and dynamic environment variables: agent-based modeling.

Agent-based models (ABMs) are computational simulation tools cable of incorporating intelligence, by combining elements of learning, adaptation, evolution, and fuzzy logic. Specifically, ABMs rely on a bottom-up approach that begins by explicitly considering the components of a system (i.e., individual agents) and tries to understand how the system's properties emerge from the interactions among these components (Grimm, 1999; Grimm et al., 2005). A community of agents acts independently of any controlling intelligence, they are goal-driven and try to fulfill specific objectives, they are aware of and can respond to changes in their environment, they can move within that environment, and they can be designed to learn and adapt their state and behavior in response to stimuli from other agents and their environment. This emphasis on interactions between agents and their environment is what distinguishes agent-based modeling (also referred to as individual-based models) from other systemic modeling approaches (Marceau, 2008).

Over the past fifteen years, ABMs have been applied to address a broad range of issues related to environmental resource management, such as water, forest, and agro-ecosystem management