Ecosystems (2017) 20: 211–214
DOI: 10.1007/s10021-016-0076-x

ECOSYSTEMS

20th Anniversary Paper

Ecosystem Modeling for the 21st Century

Monica G. Turner[1]* and Stephen R. Carpenter[2]

[1]Department of Zoology, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA;
[2]Center for Limnology, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA

Why Focus on Ecosystem Modeling?

Models play crucial roles in science, and ecosystem ecology is no exception. Ecosystem modeling emerged in the 1970s as early analog and digital computers made it possible to simulate system dynamics, and coordinated research programs like the International Biological Program (IBP) funded teams of scientists to study whole ecosystems. Quantitative ecosystem models were initially developed to mimic nature, generate questions, complement field experiments and observations, assimilate data, and conduct experiments that were not possible in nature (McIntosh 1985, p. 213; Golley 1993). Models continue to serve these key roles in ecosystem ecology, allowing consequences of assumptions to be explored quantitatively; identifying sensitive states, fluxes, and feedbacks in ecosystems; and identifying where current understanding is incomplete. Today, the need to anticipate consequences of rapid anthropogenic environmental changes (for example, climate and land use) and future conditions that have no prior analog requires that ecosystem ecologists increasingly rely on quantitative representations of complex systems. As we look toward the next two decades of challenges and opportunities to advance ecosystem science, how should modeling be balanced with other approaches? Are ecologists well prepared to deal wisely with the widespread use of models?

This second SF of our 20th Anniversary Special Features in Ecosystems tackles the role of ecosystem models now and in the future. We asked a diverse group of ecosystem modelers to write essays that addressed two questions: *What is the appropriate mix of empirical study vs. modeling/theory in ecosystem ecology? How should we be training ecosystem ecologists for the 21st century?* These issues were previously brought to the fore at the 2001 Cary Conference on models in ecosystem science (Canham and others 2003). We both offered presentations at this conference (Carpenter 2003; Turner 2003) and participated in spirited discussions along with several contributors to this Special Feature (Cottingham, Kinzig, Pastor, Peters, and Rastetter). Ecosystem science and modeling have continued to evolve, and a reassessment of opportunities and needs is timely.

The Essays

The Special Feature begins with two papers that provide broad and insightful perspectives on the role of models. Rastetter (2017) considers why ecosystem ecologists use models and places this discussion in the context of the earlier literature. Seidl (2017) offers rationales for using models in ecosystem ecology based on both practical and philosophical considerations. Both authors recognize that models are used sometimes for understanding and sometimes for prediction, and that these goals are different but complementary. Both

Received 1 November 2016; accepted 1 November 2016;
published online 14 November 2016
*Corresponding author; e-mail: turnermg@wisc.edu

authors also emphasize the value of models being wrong; models are extremely useful for identifying limits of current understanding.

Many questions in contemporary ecosystem ecology lie at its interface with other disciplines, and the next three papers argue eloquently for an increase in interdisciplinarity in ecosystem ecology and modeling. Many opportunities remain for strengthening bridges between ecosystem science and other subdisciplines, including community (Grimm and others 2017) and evolutionary ecology (Pastor 2017). Subdisciplines often develop along parallel trajectories that do not intersect, and both papers identify new areas of research intersection that are ripe for development. Individual-based models (IBMs) in ecology have offered powerful approaches for integrating organisms and ecosystem processes (Grimm and others 2017); yet understanding of biodiversity–ecosystem function relationships remains incomplete. How evolutionary processes intersect with ecosystem dynamics remains little explored (Pastor 2017). Essington and others (2017) call for greater integration of social and natural science while exploring empiricism and modeling in marine fisheries science. The trend toward integration of social and natural sciences is occurring in all areas of applied ecosystem science (Turner and Carpenter 1999; Weathers and others 2016), and ecosystem approaches to fisheries have led the way in quantitative approaches.

The next two papers consider broad-scale trends that are sweeping through science. The culture of science has been evolving along with changes in society, technology, and expectations of ecologists (Turner 2015). Amidst such change, Kinzig (2017) argues that some form of model is and will continue to be required in every scientific endeavor. She then offers thought-provoking ideas on how scales, incentives, and culture in ecology can foster a balance between modeling and empirical study at all levels of professional development given evolving roles of scientists. The use of ''big data'' in science is also ever growing. Peters and Okin (2017) provide a provocative view of big data, models, and theories in ecology. Trends toward big shared databases are expanding the uses of modeling both for synthesizing data and using it to test broad expectations about ecosystem functioning. These trends are further explored by LaDeau and colleagues in a stand-alone paper recruited for the 20th anniversary (LaDeau and others 2017).

Of tremendous importance to the future of ecosystem ecology in a world of big data is retention of the extensive, empirical knowledge of scientists who are deeply familiar with field sites and measurements, and who understand dynamics of the system. To ensure quality science, such scientists must be involved in teams using big data, and students must be trained properly in how to use datasets that were collected by others. The final paper by Cottingham and others (2017) offers a valuable roadmap for training the next generation of graduate students on theory, modeling, and empiricism in ways that prepare them to confidently tackle pressing environmental problems. Use of shared databases will increasingly augment individual field studies driven by site-specific questions. Future ecosystem scientists will attempt to build understanding using data from large collaborative field programs devoted to long-term or regionalized observations. New questions will be broad, and modeling will be a central activity for the next generation of ecosystem scientists.

Modeling *and* (not *or*) Empirical Study

Common themes abound within this set of papers. There is clear consensus that empirical study and theory/modeling should be inextricably intertwined. This does not mean that every paper or every ecosystem ecologist does everything, but the interaction between these two ways of knowing is critical to both and more powerful than either alone. Misperceptions about each camp by the other were past impediments to scientific progress (McIntosh 1985), and such barriers have no place in ecosystem science. Rather, ecosystem ecologists should have well-rounded training in observation, experiment, and quantitative models, and all scientists should appreciate these different approaches and understand their strengths and limitations (Cottingham and others 2017). As Seidl (2017) notes, ''Understanding models can help people become better field ecologists, and extensive exposure to the field makes for a better modeler.''

Another clear message across the set of papers is that healthy skepticism is required when using readily available models or datasets (Seidl 2017; Peters and Okin 2017). Models built for one purpose may be poor tools for another, and deciding whether to use an existing model or develop a new one requires careful thought. Ease of access is not a sufficient reason to apply any given model. Models must be matched to their purpose, and ultimately, we must know how the systems we study work. The quality of big data also must be assessed critically and understood; easy availability does not equate to usefulness. An especially critical eye is needed on open access data, and many online data sources are modeled—so users should be aware of models hiding in plain sight (Peters and Okin 2017).

The essays also recognize the tradeoffs inherent in the simple-to-complex gradient of models. Rastetter (2017) addresses this most explicitly, but all consider it to some degree in various contexts. These tradeoffs have challenged integration of population/community research (which is typically comfortable with more abstraction, and with models that are general but not predictive) and ecosystem/landscape research (which typically seeks more realism and greater predictive capability at the expense of generality.) These longstanding issues remain with us today (Kingsland 2005), and they apply also to applied modeling work. Spatially explicit models have facilitated integration across ecological levels of organization, and DeAngelis and Yurek (2017) review the rapid growth of spatial models in a stand-alone 20th Anniversary mini-review also in this issue of Ecosystems.

Perhaps the strongest common theme to emerge from this set of papers is the imperative to improve training in ecosystem modeling. There is a fundamental need to bolster modeling literacy overall and for students in ecosystem ecology to have rigorous training in both modeling and field study. Even if they are not coding models, ecosystem ecologists will be reading and digesting papers written by modelers and very often using the output of models (for example, GCMs). Next-generation ecologists simply *must* be familiar with *both* empirical and theory/modeling, understanding the basic principles of modeling, and how to use models appropriately. Most universities are not providing the strong foundation in modeling that will be needed by up-and-coming ecosystem ecologists. Modeling courses have diminished across the US (Canham and others 2003) as the generation of ecologists influenced by the IBP and rise of ecosystem ecology (McIntosh 1985) have retired. It is time to make a concerted effort to address that weakness. Each and every author also recognized that modelers must have first-hand field experience of their system and all have provided concrete recommendations for educating students and advancing the use of modeling within the field.

As we look to the future, the need to represent ecosystem responses to novel conditions will only grow in importance. Process-based models are critical because models built on past empirical relationships of the past may not hold in the future (Gustafson 2013), and the use of such models in ecosystem ecology must be strengthened. Collectively, these papers offer excellent fodder for discussion of ecology curricula and strong justifications for having empirically based ecosystem ecologists involved in modeling, and taking modelers out to the field. These essays call for renewed commitment to training next-generation ecosystem scientists who integrate rigorous modeling skills with a deep understanding and appreciation for nature. The future of our science depends on sustained excellence in both.

REFERENCES

Canham CD, Cole JJ, Lauenroth WK, Eds. 2003. Models in ecosystem science. Princeton: Princeton University Press.

Carpenter SR. 2003. The need for fast and frugal models. In: Canham CD, Cole JJ, Lauenroth WK, Eds. Models in ecosystem science. Princeton: Princeton University Press. p 455–60.

Cottingham KL, Fey SB, Firtschie KJ, Trout-Haney, JV. 2017. Advancing ecosystem science by promoting greater use of theory and multiple research approaches in graduate education. Ecosystems. doi:10.1007/s10021-016-0070-3.

DeAngelis D, Yurek S. 2017. Spatially explicit modeling in ecology: a review. Ecosystems. doi:10.1007/s10021-016-0066-z.

Essington TE, Ciannelli L, Heppell SS, Levin PS, McClanahan TF, Michelli F, Plagányi EE, van Putten IE. 2017. Empiricism and modeling for marine fisheries—advancing an interdisciplinary science. Ecosystems. doi:10.1007/s10021-016-0073-0.

Golley FB. 1993. A history of the ecosystem concept in ecology. New Haven: Yale University Press.

Grimm V, Akyllon D, Railsback SF. 2017. Next-generation individual based models integrate biodiversity and ecosystems: yes we can, and yes we must. Ecosystems. doi:10.1007/s10021-016-0071-2.

Gustafson EJ. 2013. When relationships estimated in the past cannot be used to predict the future: using mechanistic models to predict landscape ecological dynamics in a changing world. Landscape Ecol 28:1429–37.

Kingsland SE. 2005. The evolution of American ecology, 1890-2000. Baltimore: The Johns Hopkins University Press.

Kinzig AP. 2017. On achieving balance. Ecosystems. doi:10.1007/s10021-016-0074-z.

LaDeau S, Han B, Rosi-Marshall E, Weathers K. 2017. The next decade of big data in ecosystem science. Ecosystems 20. doi:10.1007/s10021-016-0075-y.

McIntosh RP. 1985. The background of ecology. Cambridge: Cambridge University Press.

Pastor J. 2017. Ecosystems ecology and evolutionary biology, a new frontier for experiments and models. Ecosystems. doi:10.1007/s10021-016-0069-9.

Peters DPC, Okin GS. 2017. A toolkit for ecosystem ecologists in the time of big science. Ecosystems. doi:10.1007/s10021-016-0072-1.

Rastetter EB. 2017. Modeling for understanding v. modeling for numbers. Ecosystems. doi:10.1007/s10021-016-0067-y.

Seidl R. 2017. To model or not to model, that is no longer the question for ecologists. Ecosystems. doi:10.1007/s10021-016-0068-x.

Turner MG. 2003. Modeling for synthesis and integration: forests, people, and riparian coarse woody debris. In: Canham

CD, Cole JJ, Lauenroth WK, Eds. Models in ecosystem science. Princeton: Princeton University Press. p 83–110.

Turner MG. 2015. Celebrating the past, embracing the future. Front Ecol Environ 13:291.

Turner MG, Carpenter SR. 1999. Tips and traps in interdisciplinary research. Ecosystems 2:275–6.

Weathers KC, Groffman PM, van Dolah E, Bernhardt E, Grimm NB, McMahon K, Schimel J, Paolisso M, Maranter R, Brauman K, Baer S, Hinckley E. 2016. Frontiers in ecosystem ecology from a community perspective: the future is boundless and bright. Ecosystems 19:753–70.