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ECOSYSTEMS

20th Anniversary Paper

Twenty Years of *Ecosystems*: Emerging Questions and Challenges

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This issue opens the 20th volume of *Ecosystems*. Prior to the launch of *Ecosystems*, there was no flagship journal devoted to ecosystem-level science. *Ecosystems* was intended to fill that void and provide a forum for cutting-edge ecosystem science that would lead to new ways of thinking and creative, insightful integration (Carpenter and Turner 1998). After 20 years, we are pleased to be part of a thriving journal and grateful to the many people—authors, reviewers, past and current editorial board members, our managing editor, and the publisher—whose efforts have contributed to *Ecosystems*' success.

Milestones provoke reflection, and as our 20th year of publication approached, we reflected on the state of ecosystem science, especially on emerging research directions and areas that seemed ripe for synthesis. To mark this milestone for *Ecosystems*, we invited a wide range of authors to contribute to two Special Features and a series of mini-reviews that will appear throughout 2017. Here, we introduce the first special feature (below) and the first two mini-reviews. Offering perspectives from historical ecology, Bürgi and others (2016) reviewed effects of land-use history on contemporary ecosystems, a topic that was prominent in Volume 1 of *Ecosystems* (for example, Foster and others 1998; Fuller and others 1998) and important today. They argue for more nuanced and comprehensive consideration of human activities and their long-term legacies, much as the complexity of natural disturbances, and their ecosystem roles are treated. Schindler and Smits (2016) synthesize insights on cross-ecosystem transfers of matter and energy derived from current understanding of fluxes from aquatic to terrestrial systems. Early research emphasized fluxes from land to water, but floods, complex hydrological linkages, and animal movements transport significant amounts of nutrients and organic energy to land from water. Forthcoming 20th anniversary articles will address a wide range of interesting subjects, and we encourage readers to watch for these papers as they are published throughout the year.

The Next 20 Years

Our first Special Feature in Volume 20 looks to the future of our field. Emerging issues and challenges for ecosystem science were addressed from time to time in the past two decades of *Ecosystems*. For our 20th anniversary, we invited nine papers from a diverse group of ecosystem scientists to examine two questions:

- What are the most important challenges for ecosystem science in the next 20 years?
- What are the provocative questions in ecosystem science?

The resulting essays explore opportunities in specific areas that together represent a diverse sampling of modern ecosystem science. They complement a synthesis by Weathers and others

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(2016) published recently in *Ecosystems*. Weathers and colleagues identified research frontiers through a broad survey of ecosystem scientists in the U.S. Their survey identified critical needs under four themes: (1) new drivers of ecosystem change, (2) deeper analysis of ecosystem processes, (3) human dimensions of ecosystem ecology, and (4) expanded application of ecosystem ecology in solving societal problems. It is not surprising that all four of these themes emerge in this Special Feature. The discipline has evolved from the four frontier themes we identified in the inaugural issue of *Ecosystems*: people and ecosystems, spatial scale shifts, cross-disciplinary linkages, and temporal scale shifts (Carpenter and Turner 1998). Yet, scale, human dimensions, and the need for interdisciplinarity remain as important frontiers for ecosystem science.

About 20 years ago, a Cary Conference on *Successes, Limitations, and Frontiers in Ecosystem Science* (Pace and Groffman 1998a) foreshadowed these themes. Writing on the pages of *Ecosystems*, Pace and Groffman (1998b) illuminated debates that underpinned the book. Ecosystems are complex, but simplification is needed for effective research. The tension between real-world complexity and simplification for understanding creates intellectual turbulence that drives ecosystem science. It also complicates the linkages of science and management. The latter needs answers that account for the complexity of human–environment interactions at broad spatial scales; the necessary understanding is often not available on the time frame of decision making. These issues are unresolved and even more urgent in a time of rapid global change (Higgins 2017). Certainly they shaped the intellectual agenda of *Ecosystems* from the early years to the present (Turner and Carpenter 1999a, b; Carpenter and Turner 2007). What themes will shape the field in years ahead?

Engagement with the Anthropocene is an urgent priority for ecosystem science, according to papers in this Special Feature. Österblom and others (2016) argue that understanding social-ecological thresholds to manage marine ecosystems for resilience will require new skills in modeling the Anthropocene. Such research will require an explicitly transdisciplinary approach to understanding ecosystem features of high relevance to stakeholders, according to Bennett (2017). We cannot understand ecosystems without considering how humans have shaped them. For example, human preferences for open landscapes have altered terrestrial ecosystems for centuries, as shown in the historical perspective from Holmgren and Scheffer (2017). In modern times of globalized highly connected markets, trade has become a key driver of ecosystem change as well as a research opportunity for ecosystem analysis (Pace and Gephart 2017). Cities are foci of consumption and waste generation by people and are where most people encounter nature; thus cities are ground zero for ecology in the Anthropocene (Groffman and others 2017). These papers bring the Anthropocene front and center.

Concepts and controversies of ecosystem services were emerging at the inception of *Ecosystems*, and they quickly became a topic for many papers in the journal (Carpenter and Turner 2000). In the Special Feature, Bennett (2017) explicitly addresses ecosystem services, and the concept is implicit in many of the papers. Other essays also touch on ecosystem services in estuaries (Testa and others 2017) and forests (Holmgren and Scheffer 2017). As drivers of global change continue to alter ecosystem structure and function, the importance of understanding the benefits to people provided by nature will continue to grow. The essays in this Special Feature underscore research priorities that are critical to sustaining ecosystem services in our lands, waters, oceans, and cities. Not surprisingly, climate change is also mentioned in several of these essays (for example, Higgins 2017; Scholes 2017; Testa and others 2017). Temperature and water are fundamental to ecosystem function, and changes in mean values as well as the frequency, duration, and intensity of extreme events are already underway. Anticipating the impacts of these changes for biotic communities, ecosystem processes, and ecosystem services and how to mitigate undesirable outcomes or adapt to inevitable ones will remain research priorities for coming decades.

Scale issues are either the bane of ecosystem science or fertile ground for intellectual advances, depending on your point of view. Certainly scale considerations are unavoidable in ecosystem research. *Ecosystems* has published several collections of papers on this topic (Turner and Dale 1998; Turner and Carpenter 1999a; Peters and others 2007; Carpenter and Turner 2000a). The papers in this Special Feature reflect ecologists' increasing sophistication in organizing processes and feedbacks across multiple scales. Scholes (2017) calls explicitly for integration of multi-scale data, empirical models, and theory to build a more robust approach to problems of scale. Such an approach is needed to address the growing probability of regime shifts as climate and human use of the biosphere trend upward over coming decades (Higgins 2017; Österblom and others 2016). Turetsky and others (Turetsky et al. 2017) develop

a specific example for boreal ecosystems where feedbacks are strong between global and regional processes. Global trade creates new opportunities for cross-scale interactions (Pace and Gephart 2017). Cross-scale connections always involve multiple drivers as highlighted by Testa and others (2017), for example, in the interactive effects of climate change and sea-level rise on estuaries.

Ecosystem science is an intellectual crossroads. Every paper in the Special Feature highlights connections of ecosystem science with other disciplines of the natural sciences, often the social sciences, and sometimes the arts and humanities. Interdisciplinarity has always been prominent in *Ecosystems* (Levin 1998; Turner and Carpenter 1999c; Holling 2001; Carpenter and Turner 2001, 2007; Carpenter and others 2005). This Special Feature suggests that interdisciplinary research will become even more prominent in the future. Yet interdisciplinarity continues to pose multiple challenges for ecosystem science (Turner and Carpenter 1999b). If the boundaries of the discipline are porous, how stable is the core? Fundamental concepts of boundaries, scale, flux, stability, mass balance, and ecosystem energetics have formed the core of ecosystem science (Pace and Groffman 1998a). These powerful ideas will remain central in the future. In other aspects, the evolution of ecosystem science is fluid and unpredictable. The questions that are inspiring cutting-edge work in ecosystem science emerge at the boundaries between disciplines, and as these questions are answered ecosystem science that develops and changes. Therefore, we expect the next two decades of *Ecosystems* to be as exciting and productive as the first 20 years.

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