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ECOSYSTEMS

Frontiers in Ecosystem Ecology from a Community Perspective: The Future is Boundless and Bright

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ABSTRACT

In an era of increasingly multidisciplinary science, it is essential to identify the frontiers as well as the core of an inherently holistic discipline: ecosystem ecology. To achieve this, we led a series of town hall events at multiple scientific-society meetings over a two-year period followed by a workshop with a diverse set of ecosystem scientists to review and expand on those outcomes. For the society town hall events ~70 individuals were asked to give short, provocative (the so-called, soapbox) presentations and audience members (~250) filled out tailored surveys. Both presentations and surveys were transcribed and themes were extracted and analyzed before and during the follow-up workshop. Formal ethnographic analysis of the soapbox texts produced three major themes: "frontiers," "capacity building," and "barriers to implementation," including several subthemes. A workshop was held to analyze the ethnographic data where workshop participants further grouped key frontiers as (1) rethinking the drivers of ecosystem change, (2) new insights into ecosystem process and function, (3) evaluating human dimensions of ecosystem ecology, and (4) new angles on problem-solving/applied research. In addition, 13 experts were interviewed to cross-check interpretations. The survey data, workshop deliberations, and expert interviews suggest that the core of these frontiers defines the current state and provides the foundational knowledge that bounds ecosystem ecology as a discipline. In response to emerging complex environmental issues and ongoing socioecological challenges, the edges of these frontiers expand fundamental ecosystem ecology to engage and intersect with disciplinary realms to create new ways of making sense of complexity, and to develop an even more holistic understanding of ecological systems. In this paper,

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we present our synthesis of the frontier and core research themes with the goal of inspiring the next wave of studies in ecosystem ecology.

Key words: networks; ecological systems; thresholds; human dimensions; state changes; drivers of change.

INTRODUCTION

Ecosystem ecology has been a fundamental discipline in environmental science since it emerged in the 1960s as an integrative field. Ecosystems are studied as units that encompass not only the organisms within a defined boundary but also the physical environment with which they interact; flows of energy lead to trophic structure, biotic diversity, material, and information cycles (Odum 1969; Likens 1992; Golley 1996; Weathers and others 2013a). As science is becoming more interdisciplinary (for example, Uriarte and others 2007; Bechtold and others 2013; Cheruvelil and others 2014; Heffernan and others 2014), particularly surrounding the topical areas of global environmental change and sustainability, ecosystem ecology is often at the intellectual heart. Given the dynamic nature and wide scope of ecosystem ecology, there has been interest in defining its intellectual frontiers, core foci, and its central place within the broader fields of environmental science (Baron and Galvin 1990; Likens 1992; Pace and Groffman 1999).

Often efforts to define the frontiers of a field result either from a focused initiative by a small number of leaders (for example, an essay or a book; Likens 1992; Golley 1996), or from developing a ''science plan'' to help guide a specific research program (for example, Baron and Galvin 1990, National Ecological Observatory Network, or the Arctic System Science Program). To gain a sense of what the overall ecosystems research community identifies as the frontiers of the science, without a specific initiative as a target, and in the spirit of co-design, we led a series of workshops and discussion groups over a two-year period at multiple scientific-society meetings, convened a workshop to discuss and expand upon those data, and conducted expert interviews to crosscheck frontiers.

COMMUNITY INPUT: TOWN HALL MEETINGS AND SOAPBOX PRESENTATIONS

Community meetings and town halls were held at the Ecological Society of America (ESA), Association of the Sciences of Limnology and Oceanography (ASLO), International Symposium on Microbial Ecology (ISME), Long Term Ecological Research Network All Scientists Meeting (LTER ASM), Soil Science Society of America (SSSA) and American Geophysical Union (AGU), where soapbox presentations were made (Box 1) and surveys were administered (Supplement 1).

The contents for all the 69 soapbox presentation videos (Box 1) as well as 253 surveys (Supplement 1) were transcribed and analyzed using ethnographic techniques. More specifically, the transcription files were used to create hermeneutic units (groupings of files based on some underlying shared characteristics or meanings, such as career stage, discipline, professional affiliation) for stakeholder groups. We then deductively (applying relevant existing codes to the text) and inductively (apply-

Box 1. Soapbox Presentations

A Steering Committee (SC) guided this community assessment. At each of the workshops or town halls, the SC asked approximately eight people to give 1–3 min, engaging talks (hereafter referred to as ''soapbox''—a forum that provides an opportunity for a person to articulate his/her views publically) that were required to be short and pithy and that would be intentionally provocative about the questions they would pursue to press the frontiers in ecosystem ecology if resources of $10 million were available. In most cases, we were able to provide some type of actual ''box'' for speakers to stand on. Following the soapbox presentations, we invited volunteers to add their soapbox perspectives. About half of the presentations were invited and half were from volunteers. All presentations were recorded (video and audio) and analyzed for content.

Those in attendance at the workshops had the opportunity to contribute their own ideas and to react to the ideas of all soapbox speakers through surveys. At the beginning of the session, audience members filled out a survey with questions about demographic information, academic background, and research focus. The survey also included questions about preferred definitions and research areas in ecosystem ecology. After the presentations, participants filled out the final section of the survey where they expressed opinions and preferences about the soapbox presentations they had heard. Following the surveys, we organized discussions, either in small groups (~ 10 people, ~30 min) or as plenary discussions, that explored the common and missing elements and themes of the soapbox talks.

ing new codes that emerged from the text analysis) extracted themes from the presentations to identify and define frontiers of ecosystem ecology. These data and analyses formed the basis for discussions at a workshop held at the Socio-Environmental Synthesis Center (SESYNC). This workshop was composed of approximately 30 scientists, from a range of career stages, representing a diversity of subdisciplines in ecosystem ecology and the social sciences. It focused on: What are the research frontiers for ecosystem ecology? What limitations or barriers exist, and how do they complicate addressing these frontiers? What are the opportunities? After the workshop, we crosschecked our findings by comparing them to 13 individual interviews with expert (that is, practitioners with significant experience in a range of wet to dry ecosystems) ecosystem ecologists to explore both core and fringe frontiers topics in ecosystem ecology (Supplement 3).

Table 1. Frontiers in Ecosystem Ecology Survey Respondent Answer to the Question: How Would You Introduce Yourself to a Colleague?

How would you introduce yourself?

Title	Responses	
	N	Percent
Biogeochemist	99	16.4%
Community ecologist	25	4.2%
Ecologist	82	13.6%
Ecological modeler	13	2.2%
Ecosystem ecologist	104	17.3%
Ecosystem scientist	62	10.3%
Environmental scientist	39	6.5%
Plant ecologist	12	2.0%
Limnologist	36	6.0%
Microbial ecologist	42	7.0%
Stream ecologist	27	4.5%
Wetland ecologist	19	3.2%
Other	42	7.0%
Total	602	100.0%

THE SURVEY AND THE PARTICIPANTS

Our survey contained two distinct parts and began with questions about the respondent, including the question ''how would you introduce yourself to ecological colleagues?'' (Supplement 1, Table 1). We then presented six common definitions of the term ''ecosystem'' and asked participants to rank their most and least favorite of these definitions (Box 2). Survey participants were also given an opportunity to propose their own definition. The first part of the survey then ended with the question ''If you had 1 min to argue for a major new research funding initiative, what would you say is the most important question for ecosystem ecologists to explore in the coming decade?''

After the first part of the survey was completed, participants listened to the series of soapbox talks and then filled out the second part of the survey which asked them to rate the talks that they heard in terms of ''what topics were most interesting,'' ''what topics were most ''frontier'' to ecosystem ecology,'' and ''what topics were most ''core'' to ecosystem ecology.'' Participants were also asked if the soapbox talks had changed their ideas about the most important question for ecosystem scientists to explore in the coming decade.

The 253 survey participants were well distributed across the scientific society meetings, but the largest number of surveys came from the sessions at the LTER All Scientists Meeting (24.1%) and the ESA annual meeting (18.6%). We held sessions at two ASLO Aquatic Sciences meetings, one in Japan (13.4%) and one in New Orleans (15.4%), so

Box 2. What's in a Definition?

The two largest groups of participants by career stage were full professors (23.9%) and graduate students (23.9%); no other specific group was greater than 10%. This grouping provided an interesting perspective on the outlook and priorities of two classes of key players in ecosystem ecology at different ends of the career spectrum. These two groups had markedly similar most and least preferred definitions of the term ''ecosystem.'' Both groups expressed a clear preference for Definition E (''any unit that includes all of the organisms (that is: the ''community'') in a given area interacting with the physical environment so that a flow of energy leads to clearly defined trophic structure, biotic diversity, and material cycles (that is: exchange of materials between living and nonliving parts) within the system is an ecosystem'' and a clear lack of preference for Definition D (''an ecosystem is a biological environment consisting of all the living organisms or biotic component, in a particular area, and the nonliving, or abiotic component, with which the organisms interact, such as air, soil, water, and sunlight''). This contrast illustrates the strengths and weaknesses of our analysis. While the similarity between the youngest and oldest groups suggests that there is some intellectual coherence within the discipline, we have little basis for determining just what about these definitions appealed (or not) to different groups.

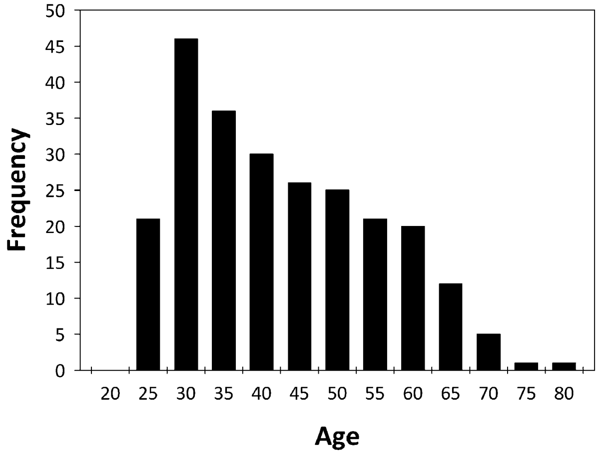

Fig. 1. Age distribution of participants in the Frontiers of Ecosystem Ecology Survey administered at scientific society Town Hall events.

approximately one third of the survey respondents came from the ''wet end'' of the discipline, and given the organizational structure of those meetings, most likely working on inland waters rather than in marine ecosystems. At the ''dry end,'' we ran a session at the SSSA (12.3%). The sessions at AGU (11.5%) and ISME (4.3%) were our smallest. Most (67.2%) survey participants held a Ph.D. and were an average of 40.7 years old (Fig. 1). Fifty-eight percent of the participants were male, 42% female. The two largest groups of participants by career stage were full professors and graduate students; no other specific group was greater than 10% (Supplement 2). Contrasts and similarities in the two largest group responses were inconclusive, but interesting (Box 2).

Cross-Check Expert Interviews

Finally, 13 expert interviews with key informants, whose focal areas spanned a wet-to-dry spectrum (Supplement 2), were conducted during the spring of 2014 using ethnographic methods from anthropology (Van Dolah and Paolisso (2014), unpublished). Experts were randomly chosen by the ethnographers from a list of approximately 20 scientists compiled by the PIs, based on broad criteria: demonstrated visionary thinking, writing, leading, and/or speaking; had not participated in the project's previous soapbox sessions or workshops; and represented diverse ecosystem foci, career stages, and demographics. The method for this analysis primarily consisted of semi-structured interviews, based on a set of open-ended questions (Supplement 3) that enables the researcher to collect in-depth descriptive text in order to identify explicit and implicit knowledge, understandings, beliefs, and values surrounding a topic area, in this case, frontiers of ecosystem ecology.

Surveys were analyzed in SPSS (v23). Transcriptions of the soapbox talks were deductively and inductively analyzed using Atlas.ti (v 6). Frontiers derived from these data were identified, quantified, discussed, and expanded upon at a workshop of approximately 30 invited participants. The data collected from expert interviews were recorded, transcribed, and analyzed in Atlas.ti, again using a deductive- and inductive-coding process (Van Dolah and Paolisso (2014), unpublished report).

FRONTIERS: INTERPRETATIONS OF THE SOAPBOX TALKS AND SURVEYS

Four overarching research frontier foci emerged from the soapbox presentations: *rethinking and unraveling new drivers of ecosystem change, elucidating ecosystem process and function, human dimensions of ecosystem ecology, and problem-solving/applied research* (Table 2). Interestingly, there was a difference in overarching frontiers identified among scientific societies. Although the town hall conducted at the AGU Fall meeting identified frontiers at bio–physical–chemical interfaces using the tools of large-scale experiments and modeling, it was the intersection of the socio–bio–physical–chemical that was most often highlighted at the ESA, LTER ASM, and ASLO meetings. The SSSA and ISME foci were on process-level frontiers involving microbes. Formal text analysis of the soapbox presentations produced two (in addition to ''research/conceptual frontiers, as noted above) major, overarching themes including ''capacity building'' and ''barriers to implementation,'' with four or five subthemes within each major theme (Table 2).

As noted above, a workshop was held at SESYNC to synthesize and expand upon the results of the surveys and soapbox presentations. Participants in the SESYNC workshop were given all of the text fragments that were used to derive these themes and subthemes in advance of the workshop and were asked to consider: (1) What were the key patterns or findings that emerged from the text? (2) What, if anything, is missing? (3) What findings surprised you? Responses to these questions formed the basis for discussions at the SESYNC workshop where small groups developed the frontier themes and discussed the frontier subthemes in greater detail. The expert interviews corroborated the topics identified, confirmed their relevance, and shed further light on the nature of frontiers in our discipline (see below). Here we review each frontier focal topic that emerged from the data, and provide more general, cross-cutting discussion of ''barriers to implementation,'' and ''capacity building.''

Table 2. Themes and Subthemes Identified Through Text Analysis of ''Soapbox'' Presentations

Frontiers: What are the frontier research themes that individuals identified as future investments needs?	Capacity Building: What are the components needed to generate frontiers?	Barriers: What are the barriers preventing us from moving forward with frontier research?
Rethinking the drivers of ecosystem change (25)	Holistic approaches (17)	Theoretical thinking is limited (26)
New insights into ecosystem process and function (33)	Cross-disciplinary collaboration (27)	Not enough funding/support (7)
Evaluating human dimensions of ecosystem ecology (16)	Public support for research (7)	Fragmentation across discipline (17)
New angles on problem-solving/applied research (12)	Data (13)	Data access and data synthesis (9)
	Training (4)	Solutions to barriers (12)
	Technology investment (12)	Opportunities to overcome barriers (14)

The number next to each subtheme listed above represents the number of associated quotes extracted from transcriptions of the presentations.

Rethinking and Unraveling the Drivers of Ecosystem Change

A major group of frontier topics that emerged focuses on the drivers of ecosystem change. Classical thinking about drivers emphasized slow and steady change, linear processes, and systems composed of sets of processes changing at similar time scales. Ecosystem ecology is undergoing a significant reevaluation of all of these. An example is phenomena that cause ecosystems to shift abruptly to a different structure or organization. Understanding ecosystem state changes (for example, abrupt change in structure or function) that involve crossing ecological thresholds, and the components of ecosystem stability (resistance, resilience) that regulate these changes are long-established, core topics in ecosystem ecology (Odum 1969; Holling 1973; Gunderson 2000). Yet, there are new data and perspectives on these topics, and they remain frontiers, in part because it has been difficult to translate theory into practices that allow for prediction, prevention, and/or management of dramatic, and unexpected changes in ecosystem structure and function (Groffman and others 2006). Interest in this topic has heightened in recent years due to increased observations of state changes, and concerns that climate change is increasing the vulnerability of many ecosystems to these changes (CCSP 2009; Grimm and others 2013; IPCC 2014).

In addition to dramatic state change as a frontier topic, there is also interest in incremental change in ecosystem structure and function as a response to specific environmental drivers. The interaction and distinction between these types of change is a particular frontier within this broader topic, that is, which drivers tend to generate nonlinear (extreme events, disease) versus linear (average temperature change) responses? When and where do linear drivers have threshold effects?

The great challenge in this frontier area is that the drivers of ecosystem change are complex. While we have a deep understanding of the broad ''state'' factors that influence the general structure and function of ecosystems (Amundson and Jenny 1997), even this understanding is often at a level that allows us to explain patterns rather than to quantitatively predict them, and there are numerous more stochastic drivers that operate at diverse spatial and temporal scales as proximal and distal controllers that can create enormous complexity (Groffman and others 2004; Melack and others 2011). Attempts to classify these drivers have foundered on questions related to the importance of the magnitude versus the rate of change of a driver. Intersecting drivers (for example, climate and nitrogen deposition) present an array of challenges (Thomas and others 2010; Porter and others 2013). Yet, the need for developing quantitative understanding of the relationships between drivers and responses of ecosystem change continually increases with our reliance on multiple ecosystem services for human well-being (Carpenter and others 2009).

Participants in the workshop noted that major progress has been made in this frontier area in recent years. The assessment of detailed case studies of state change have led to the development of ideas about the key factors that underlie these changes, for example, the importance of ''big, slow'' nutrient pools in soils and sediments (Groffman and others 2006; Bestelmeyer and others 2013) or cross-scale interactions where a process at one scale (for example, shrub establishment) interact with other processes at larger scales (for example, wind erosion) to result in nonlinear dynamics that create threshold responses (for example, conversion of grassland to shrubland) (Peters and others 2007; Wang and Loreau 2014). New ideas about changes in variability as an ''early warning'' of state change may lead to improved ability to predict and prevent these changes (Brock and Carpenter 2010; Carpenter and others 2011; Scheffer and others 2009, 2012). Long-term manipulation studies have led to quantitative understanding of how linear changes in drivers (for example, fertilization, warming) can lead to ecosystem collapse (for example, salt marshes) (Deegan and others 2012) or structural change (for example, tundra to shrub) (Sistla and others 2013).

New ideas about the nature of environmental drivers have also led to progress in this frontier area. Investigations of climate change as a driver of ecosystem change have moved past simple analyses of abiotic variation, such as focusing on average temperature and precipitation as controllers, to emphasizing critical components of those averages. For example, demonstration of how extreme climate factors can drive insect and disease outbreaks that can disrupt ecosystem structure and function (Paradis and others 2008; Raffa and others 2008; Dukes and others 2009). There has been notable progress in conceptualizing and then operationalizing interactions between climate and socioecological drivers of change, such as the interaction of changes in agricultural management practices and climate change in driving the ''re-eutrophication'' of Lake Erie (Michalak and others 2013). Understanding the effects of land-use change on ecosystem structure and function and, perhaps more importantly, understanding the socioeconomic drivers of the land-use change itself is critically important. In addition, illuminating the feedbacks between these changes in socioecological structure and function, expressed as ecosystem services, on drivers is a research frontier (Turner and others 2007).

New perspectives on the drivers of ecosystem change have been incorporated into management and planning efforts to improve ecosystem resilience and/or to maintain ecosystem services in the face of environmental change (Tallis and others 2008). There has been particular progress in understanding how ecosystems, such as coastal marshes and wetlands, buffer adjacent water bodies to flooding and nutrient loading (Peters and others 2011), and in understanding how management, climate, and vegetation interact to control the nature and extent of fire (Larson and others 2013). However, using this understanding in actual landscapes remains a frontier (see ''human dimensions of ecosystem ecology'' frontier below).

New Understandings of Ecosystem Process and Function

Although ecosystem ecology is a fundamentally holistic and integrative science, understanding the fine-scale processes that drive ecosystem functions remains fundamental to the field. Process-level topics remain at the frontiers of ecosystem science due in part to the emergence of new concepts, tools, and research approaches. Within this overall focus, a key frontier has been, and continues to be understanding the nature and strength of feedbacks among system compartments, as these feedbacks not only regulate the functioning of individual ecosystems but also interactions with the larger earth system. Another dynamic area is processes regulated by microbes that carry out much of the production, consumption, decomposition, and nutrient cycling within ecosystems (Zimmerman and others 2014). New molecular, enzymatic, and isotopic techniques have revolutionized our ability to ''open the black box'' of the microbial communities. As a consequence of these advances, ecosystem ecology has fundamentally ''rewired'' some of the classical depictions of nutrient cycles. Nitrogen, for instance, is now known to be transformed in ways previously unknown (Francis and others 2007; Yang and others 2014) by organisms previously undescribed. There is also continued strong interest in the interactions between producers and consumers with a focus on aboveground/belowground interactions, mycorrhizal associations, and root/microbial interactions in terrestrial ecosystems (Wardle 2002) and in recycling—as well as priming effects between producers and consumers in both aquatic and terrestrial systems (Janssens and others 2010; Cottingham and others 2015). These process-level frontiers are being driven by expansive thinking about the capabilities of microbes and plants, for example, the ability of plants to take up organic forms of nutrients (e.g., Eviner and Chapin 2003; Schimel and Bennett 2004; Näsholm and others 2009), the discovery of ocean vent food webs driven solely by chemical sources of energy, or the field of aerobiology (Kellogg and Griffin 2006).

At larger scales, technology is expanding our senses and ability to link process and function. For example, ecological observatories, especially those that use high temporal and spatial resolution sensors, are increasing worldwide (for example, National Ecological Observatory Network, NEON; Global Lake Ecological Observatory Network, GLEON; Ocean Observations Initiative (OOI); Critical Zone Observatories (CZO); Bonan and others 2012; Weathers and others 2013a; Wieder and others 2014). We are now able to 'see' aspects of ecosystems that were previously invisible, whether because we can measure continuously on the span of minutes to days, or across meters to kilometers, or because we can remotely sense indices of ecological function using new tools (canopy chemistry from airborne sensors, for example, Asner and Vitousek 2005). Further, with the growth of networks of scientists (for example, LIDET 1995; LTER; GLEON; NUTNET (Borer and others 2014); International Geosphere Biophere Programme (IGBP.net)), the community as a whole is able to address classical questions at global scales and even to ask different, new questions because of the diverse approaches, tools, and minds that are brought to the table (Bechtold and others 2013). As a consequence, we now have complex datasets through which we can both identify patterns, and ultimately, discover new relationships between pattern (structure) and function.

Further, new tools and approaches allow us to confront new and or existing models and theory with new high-resolution datasets. Increasingly, this is happening with community-owned open source models (Hamilton and others 2014; GitHub; www.gleon.org). When NEON is fully operational, our capacity to study ecosystem processes from regional to continental scales using high-frequency (temporal and spatial) data will increase significantly (Schimel and others 2007). An ambitious, but critically important, and feasible goal is to incorporate more biology and ecology into Earth system models (see community land model) (Thomas and others 2013).

An additional frontier identified by the community is to link evolutionary processes to ecosystem ecology in the context of global environmental change (Lau and others 2014). Over decadal time scales, organisms will adapt to the changing selective pressures, and thus change their specific functional characteristics, altering ecosystem function, and species interactions. These interactions play out dramatically in the assembly and function of novel ecosystems driven by climate change and invasive species (Lau 2006; Chisholm and Levin 2012), and are a novel platform for investigating connections between structure (including genetic) and ecological function.

Ecosystem biogeochemistry is also changing as unidimensional approaches (for example, earlier work focused mainly on single element, or one element and carbon) give way to multidimensional ones (Melack and others 2011; Schlesinger and others 2011). For example, the emergence and growth of ecological stoichiometry (Sterner and Elser 2002) is putting focus on understanding how linked element cycles impart structure to ecosystems. Understanding linked biogeochemical cycles within socioenvironmental systems is a nascent field, but it has great potential for furthering understanding of complex ecosystem responses to multiple dimensions of environmental change.

Finally, environmental disasters (for example, hurricanes, floods, ice storms, extreme droughts), which are predicted to increase with global change (IPCC), present remarkable challenges as well as opportunities for studying links and disconnects between ecosystem structure and function (Smith 2011). Our best understanding is of ecosystem response to gradual change or to ''regular'' disturbance and successional recovery, such as forest harvest. There is great uncertainty about response to ''unseasonal'' disruptions, combinations of unusual disruptions, or disruptions that occur more frequently or at different times than anticipated. For example, chaparral burns regularly and normally recovers back to chaparral within a decade. However, if fire frequency increases, say from 20 to

50 years apart to 5 years, chaparral ecosystems may become grasslands. Understanding when and how novel disturbance regimes trigger state change is a frontier for mechanistic ecosystem ecology. Another clear frontier, therefore, is to develop new monitoring, experimental manipulation, and modeling approaches to document and understand these increasingly common, uncommon events (Wuebbles and others 2014).

Evaluating Human Dimensions of Ecosystem Ecology from New Angles

Humans affect the environment at all scales—no species since the first cyanobacterium has had such a dramatic effect on ecosystem structure or function. Ecosystem ecologists have long acknowledged this (Odum 1969; McDonnell and Pickett 1993), initially studying humans as drivers of ecosystem change, but in recent decades incorporating humans into ecosystem studies. Conceptually, we have moved from humans *affecting* the environment to humans as *part of* the environment. Thus, a new frontier is integrating human impacts and interactions within our knowledge of ecosystems to better understand current, and predict future ecosystem states. A recent compilation of critical questions in the field did not include humans (Sutherland and others 2013), emphasizing that this is still a frontier challenge.

Understanding socioenvironmental systems in a truly interdisciplinary, if not transdisciplinary manner, remains a frontier from the perspectives of both the social and ecological sciences (Pickett and others 2005; Collins and others 2010). Humans redistribute, concentrate, and disperse chemicals, mass, organisms, and information around the planet (Weathers and others 2013a). Sometimes these actions are deliberate, such as with phosphorus that is mined and reapplied (Childers and others 2011), and with nitrogen that is fixed through both industrial chemical production and as a byproduct of combustion; these processes have increased exponentially since World War II (Galloway and others 2008). Many of the frontiers for ecosystem ecology sit squarely in the realm of understanding novel socioenvironmental controls and feedbacks that result from considering humans as components of ecosystems (Alberti and others 2003; Redman and others 2004; Liu and others 2007). The role of cultural contexts, such as socioeconomic status, cultural value, belief systems, and governance structures in regulating changes in ecosystem structure and function, is ripe for study (Grove and others 2006a, b; Chowdhury and others 2011). Sociocultural change is accelerating ecosystem processes, and resulting in ecological 'surprises' such as high biodiversity and net primary production in human settlements (Knapp and others 2012; Groffman and others 2014). As with understanding ecosystem processes, functions, and drivers of change, there are increasingly, new analytical and synthesis tools and cross-system dynamic comparisons that enable us to ask questions about how human factors regulate responses to environmental change, and to determine how understanding socioenvironmental systems leads to actionable science (Collins and others 2010; Harden and others 2014). There is a clear need to understand how human knowledge and value systems are linked to human actions in the environment (Ostrom 2009).

As noted above in regard to linked biogeochemical cycles, we must develop currencies for comparing ecosystem impacts of land-use change, resource extraction, and more ecologically based functions (for example, water-quality maintenance, climate regulation) in order to accurately assess tradeoffs in ecosystem services or function. Doing so will help address questions on projected entrainment of element cycles by markets (Vitousek and others 1997; Galloway and others 2008; Graedel 2011) and how this will influence water and air qualities. The emergence of ''ecosystem services'' as a platform for making these assessments has been, and will likely continue to be a clear frontier area over the next decades (MEA 2005; Tallis and others 2008).

There are also clear frontiers in scaling issues (see also below). Examples include: at what spatial scale and in what combinations are humans affecting ecosystems, and how does human impact vary with scale (economies of scale, variations in affluence/diet/cultural expectations, and technologies)? Further, it is important to understand historical influences on current issues: How do decisions made in the past constrain options for managing ecosystems today and in the future? For example, are contaminant and land-use legacies constraining options for present and future ecosystem structure and function (Cadenasso and others 2006; Troy and others 2007; Bigsby and others 2014; Lewis and others 2014)? Do these legacies limit opportunities to restore/enhance ecosystem functions in degraded landscapes (Palmer and others 2005)? How can restored ecosystems be designed for resilience to environmental change and deliver the maximum level of ecosystem services (Felson and others 2013)?

Although analyzing the past as a constraint is important, there are also clear frontiers in considering the future, in particular the need to anticipate and avoid global environmental change-induced bottlenecks in food and water supplies. Demographic and climate change projections for the future must be merged, and predictions must be downscaled to regions (Grimm and others 2008a, b). The emergence of ‘‘scenario science’’ may provide a platform for developing multidisciplinary research programs to investigate future trajectories of coupled human–natural systems (Clark and others 2001; Coreau and others 2009; Thompson and others 2011; Staudinger and others 2013).

Problem-Solving/Applied Research: Enhancing Relevance to Human Welfare

A clear frontier that emerged from the soapbox presentations was the desire to solve pressing problems of current environmental relevance. Although we recognize that ecosystem ecology has long functioned as a basic science with applied relevance, we were still somewhat surprised at the number of speakers who suggested that we should focus on unraveling the mysteries of nature to the end of applied (that is, research to solve problems) socioenvironmental research. This was particularly true of the ESA and LTER ASM meetings. Our community assessment clearly suggested that there is enthusiasm among ecosystem ecologists for solving real problems, or generating actionable synthesis and science (Chapin and others 2010).

The list of problems to which ecosystem ecology can contribute is large and significant. Future Earth, a 10-year international program co-sponsored by the Science and Technology Alliance that aims to achieve greater global sustainability using integrated transdisciplinary approaches, has identified eight focal challenges for humanity (futureearth.org). Most if not all of these challenges will require input from ecosystem ecologists. Indeed, the components of ecosystems and functions of the whole serve humanity and are fundamentally important to food production, and the health of animals, water, air, and soil (see above). For example, many, if not most, biodiversity and ecosystem processes are fundamental to food security (Foley and others 2005; Duarte and others 2009; Rockstrom and others 2009; Tilman and others 2009; Foley and others 2011), and water security (Dodds and others 2009; Smith and Schindler 2009). A clear frontier that has emerged in recent years is recognition of the importance of ecosystem processes in human health, including determining disease risk (Myers and others 2013). Again, new approaches to evaluate ecosystem services have improved our ability to examine tradeoffs between provisioning services such as food production, regulating services related to air and water qualities, and cultural services related to aesthetic and spiritual aspects of ecosystems (Chan and others 2012). One major challenge of frontiers is how ecosystem scientists could engage more broadly in decision-making processes. Indeed, ecosystem approaches help to provide integrated solutions to major challenges in synergistic ways, for example on topics such as coastal erosion, or increasing biodiversity and C capture (Duarte and others 2013). Furthermore, integrated ecosystem evaluations that consider biogeochemical and physical complexities will be essential to either support or counter technological and geo-engineered fixes to major environmental issues (Wallace and others 2010; Conley 2012).

Enhance Prediction Capabilities

Especially at the AGU Fall meeting, there was a clear call for developing ecosystem models that can be modular, linked (that is, social data that feed into ecosystem models and vice versa) and open source, and that can confront large, publically available datasets, and be further developed in collaboration between empiricists and modelers in real time. At other society meetings, there was interest in developing models that will enable better prediction of ecosystem function or response to change in drivers (Coreau and others 2009). This finding dovetails with another major theme of soapbox presentations which was the need for interdisciplinary, if not transdisciplinary (Eigenbrode and others 2007) research, education, and outreach where ecosystem ecology and ecologists can play fundamental roles.

CAPACITY BUILDING: OPPORTUNITIES, CHALLENGES, FRONTIERS

Ecosystem Ecology’s Holistic, Systems Approach

In science there remains an age-old tension and challenge at the intersection between reductionism and holism (Levins and Lewontin 1980). This is a genuine tension and struggle that has played out over centuries (Likens 1992). A hallmark of ecosystem ecology is that it employs a systems approach and is holistic (Odum 1969; Likens 1992; Weathers and others 2013a); this has arguably been both a boon and a bane to progress. In a positive sense, the holistic nature of ecosystem ecology facilitates the interdisciplinary interactions that are essential for progress in modern environmental and sustainability science (Uriarte and others 2007). On the other hand, holistic thinking can also highlight the limitations of theory, or theoretical frameworks that underpin ecosystem ecology (see Cadenasso and others 2006; Burke and Lauenroth 2011), as mentioned by many soapbox speakers and survey participants (see below). Although ecosystem ecology has frameworks that help us to organize our questions, theories that can drive the development of mechanistic hypotheses about whole system function are less well developed. For example, there is an increasing debate about thresholds, resilience, resistance, and early warning indicators in the literature and in practice, and little agreement on whether these ideas can be defined, managed, predicted or avoided (Groffman and others 2006; Duarte and others 2009; Bracken and others 2013; Cottingham and others 2015). A similar area of holistic need identified by respondents was for more scaling laws to answer a wide range of questions (Wu and others 2006).

Although the need for holism and cross-disciplinary collaboration is well recognized in environmental science as a whole, disciplinary chauvinism remains a problem (Eigenbrode and others 2007; Cheruvelil and others 2014; Goring and others 2014) and can hamstring truly holistic and interdisciplinary advances. There is also concern that current scientific culture offers few rewards and many costs for collaboration across disciplines, especially for early career scientists (Uriarte and others 2007; Goring and others 2014). These challenges stand in contrast to the fact that nature ‘‘doesn't do disciplines'' and neither do people when considering complex system problems. Thus, there are many opportunities for building capacity on the holistic framework of ecosystem ecology. The emergence of urban-, agro-, and global-ecosystem ecology is an excellent example of subdisciplinary foci where such capacity has been built (Grimm and others 2008a; Robertson and others 2012). Modeling tools and new quantitative analyses also hold promise for bridging systems and traditional disciplinary silos (Ibanez and others 2010; van Oijen and others 2011).

Data, Technology, and Networks

‘‘Big data'' are predicted to underpin discoveries into the future (Hampton and others 2013) and clearly present new opportunities for synthesis and analysis of complex systems (Jones and others 2006). However, ‘‘big data'' also pose significant challenges and uncertainties. For example, no one entity is in charge of keeping track of the ‘‘omics'' and ‘‘sensors,'' and as a result, significant data are not easily accessible, not useful when they can be accessed, or their synthesis leads to spurious findings (Noor and others 2006; Borgman and others 2007). Nonetheless, the era of big, complex datasets will provide opportunities for understanding as well as developing new tools, including the validation and further development of system models (Michener and others 2007; Hamilton and others 2014). Indeed, addressing many of the critical frontier topics listed above (for example, thresholds, state changes, novel drivers of ecosystem change) is likely to rely on new capacities to compile and analyze large datasets (Bascompte and Stouffer 2009).

Data sharing and cyberinfrastructure to support exchange, exploration, and maintenance of data are far from being perfect, available, and useable—specific network efforts (for example, LTER, NEON, GLEON) notwithstanding (Keller and others 2008; Michener and others 2011; Reichman and others 2011). Further, challenges are marked in the social sciences and in coupled natural–human systems research where many data must remain confidential. There is also a huge need to match the spatial and temporal scales of data between and among disciplines. For example, some social science disciplines rely on census data collected at decadal time steps and on ‘‘city block'' spatial scales, while ecosystem scientists are collecting data at increasingly fine temporal and spatial resolutions (Grove and others 2006a; Vemuri and others 2011). Efforts to build socioecological informatics are increasing (for example at SESYNC), however, and these efforts should open enormous opportunities.

Many new technologies make ecosystem measurements easier, enabling scientists as well as citizens to contribute data (for example, National Phenology Network and GLEON Lake Observer apps www.lakeobserver.org) that can be used to monitor change for early detection/ rapid response assessments (Bonney and others 2009; Theobald and others 2015). However, many challenges still exist (Dickinson and others 2010). For example, there are few technologies that can measure biotic activity or function (for example, mineralization by microbes, N or C fixation), and classifying and elucidating the role of specific microbes in ecosystem function in water, soil, or air is a frontier topic not yet amenable to big data approaches. There are some opportunities for using microbes as sensors of change caused by drivers, for example, biotic monitoring of water-quality and aquatic ecosystem conditions (Paerl and others 2009). A real frontier is to use new sensors, technologies (for example, sequencing), and data methods to help open the microbial ''black box'' and especially to understand the role of microbes in ecosystem function (Wallenstein and Hall 2012).

Networks

As noted above, networks of people, information, and data in service of science are on the rise. The science that has and will emerge from these networks is exciting (Schimel and others 2007; Klug and others 2012; Robertson and others 2012) but whether organized and administered from the top-down or bottom-up, there are concerns about the sustenance and sustainability of these networks, including funding support, and people's enthusiasm for network science, especially as networks grow in size and complexity. NEON, and other EONS (for example, GLEON) will offer some tremendous opportunities for collection, analysis, and sharing of high-quality data that are highly relevant to analyzing the drivers of environmental change (Klug and others 2012). However, they will also need to be mindful of the need to build and maintain network infrastructure and culture (Weathers and others 2013b).

Training

The community noted the need for and emergence of innovative programs designed for interdisciplinary training of graduate students (Careers: STEM education 2015) (for example, Integrative Graduate Education Research Training (IGERT) Fellowships, now replaced by National Research Traineeships) and network and systems training for young investigators (for example, Macrosystems Biology principal investigator meetings; GLEON Graduate Student Association and Fellows' Program; Weathers and others 2013b; Read and others unpublished manuscript; Hetherington and others unpublished manuscript). The emergence of these programs should be a significant aid in addressing the frontiers of ecosystem ecology, but they must be sustained, tailored, and revamped to match the opportunities and needs of current and future generations. We suggest that training programs that are created around an (eco) systems approach can be used across disciplines (see Hogan and Weathers 2003; Uriarte and others 2007; Weathers and others 2013a; Cheruvelil and others 2014; Goring and others 2014). Further, these training programs will be most successful if they include retraining, and trainer trainings. New interest in sustainability, and the large-scale, interdisciplinary, and enormously complex problems that must be solved to progress toward sustainability, should be strong motivation for these programs.

BARRIERS TO RESEARCH AT THE FRONTIER

Both the survey respondents and the workshop participants identified significant barriers that must be overcome to address scientific frontiers in ecosystem ecology. Although we identify some of these barriers to progress (such as theoretical thinking, and new training models) above, here we detail other barriers identified by the community. We stress that many of these have significant cultural roots, meaning some of the barriers are interwoven with how the scientific community defines success, how we (do or do not) value collaboration, and whether and how we give credit to participants in collaborative or network projects (for example, Uriarte and others 2007; Cheruvelil and others 2014; Goring and others 2014). Thus, we assert that many of these barriers can be overcome.

Fragmentation Across Ecosystem Ecology

There has been an increasing trend by funding and mission agencies (NSF and others) to catalyze cross- and interdisciplinary research (Box 3), but the sense of the community is that not all agencies or groups within agencies are equally willing to identify common questions and reach across disciplinary boundaries to support research outside of disciplinary silos or across systems (for example, marine to terrestrial, or aquatic vs terrestrial, hydrology, and biogeochemistry). Academically, the ecosystem community is distributed across multiple scientific societies. This brings both richness and division to the discipline. Indeed, soapbox foci and conversations at different society meetings yielded different insights about frontiers.

Data Access and Data Synthesis

As noted above, there are significant challenges in the new era of ''big data'' (Schimel 2011; Hampton and others 2013; Soranno and Schimel 2014).

Box 3. Programmatic and Funding Catalysis of Frontier Foci

In addition to the essential core funding programs in ecosystem ecology (e.g., NSF, USDA, NASA, EPA), programmatic stimuli and funding opportunities have resulted in advances in understanding drivers of ecosystem change. For example, specific interdisciplinary requests for proposals (e.g., NSF programs on Coupled Natural Human Systems, Science, Engineering and Education for Sustainability (SEES), Macrosystems Biology) have motivated scholars to develop new ways to analyze the interactions among biophysical and social drivers of ecosystem change at ecosystem, landscape, regional, and continental scales (Chen and Liu 2014; Heffernan and others 2014; Soranno and others 2014). The continued focus, by NSF and others, on creating synthesis centers, such as NCEAS, NimBios, the Powell Center, and SESYNC is also a huge catalyst in understanding complex interactions among drivers and responses (Hampton and Parker 2011).

Of particular concern is that no one entity is in charge of keeping track of the different data streams and compliance with data-sharing mandates is uneven (Noor and others 2006; Borgman and others 2007). There is also concern that many of the new innovations are not easily available, affordable or accessible (for example, Hinckley and others 2014). Challenges with privacy issues in sharing social science data may be a barrier to addressing multidisciplinary, socioecological frontiers (see above).

Not Enough Funding

Although we structured our survey and community engagement to deliberately avoid the inevitable concern that funding for frontiers research is inadequate, both the community and the workshop attendees identified a few areas that, without significant funding support, will limit progress in our field. Of particular concern in ecosystem ecology are the difficulties of funding large-scale experiments and large interdisciplinary collaborations that are a hallmark of the discipline. There is also concern about support for crucial cyberinfrastructure and, more broadly, data management/IT support for ecosystem ecology. The recent NSF interdisciplinary programs within SEES and Macrosystems Biology are hopeful signs (Box 3), but the sustainability and persistence of these programs is not clear. An additional challenge is that the size and structure of teams needed to advance complex system understanding requires different management, collaboration, and success models (Cheruvelil and others 2014). Training and support to develop these models will require new resources and new modes of training (Read and others unpublished manuscript; Hetherington and others unpublished manuscript). Finally, interagency funding (for example, NASA–NSF–DOE–USDA) was identified as a potential opportunity, but currently, lack of interdisciplinary funding is a barrier to new efforts in ecosystem ecology.

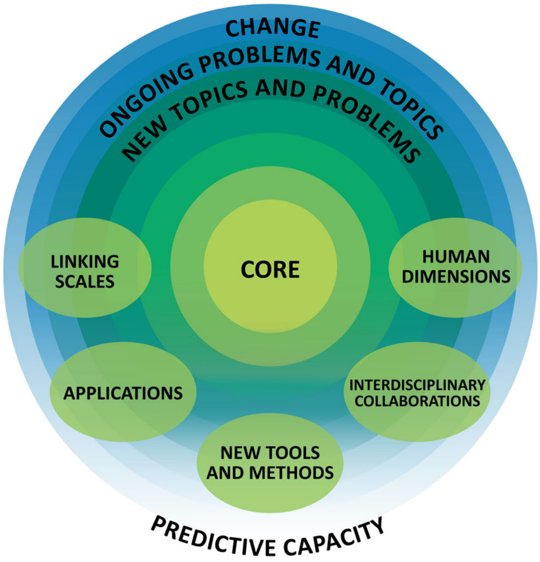

Fig. 2. The core of ecosystem ecology provides the foundational knowledge that bounds ecosystem science as a discipline, and defines the edges of knowledge as it is currently understood. Frontiers expand the edges of the core in a ripple effect fashion, pushing outward in response to environmental change, emerging environmental problems and topics, and ongoing challenges in order to find new ways of making sense of complexity and developing a more holistic understanding of ecosystems. Without the foundation of the core, frontier research cannot sustain its transformational power.

FRONTIERS IN ECOSYSTEM ECOLOGY, THE CORE, AND THE INTERDISCIPLINARY INTERFACE

The heart of the frontier—the core of ecosystem ecology—is driven by questions about system level processes, function, and structure in place-based ecological context (Fig. 2). Expert interviews underscored the many basic scientific frontiers that were identified in our analysis. What also emerged from expert interviews was a list of 10 defining characteristic criteria for frontier research, including: core relevance, linking scales, change, human dimensions, interdisciplinary collaboration, new tools and methods, application, new topics and problems, ongoing challenges and topics, and predictive capacity. We highlight briefly two of these criteria—linking scales and core relevance—because they, unlike the other criteria, did not explicitly emerge as important frontier considerations in the soapbox and survey analyses. Linking scales: Several key informants argued that ecosystem ecology must enhance understanding of feedbacks between various temporal and spatial scales, and that investments made in new tools and interdisciplinary collaboration should be explicitly focused on linking scales. In fact, one key informant suggested that frontiers become transformational because they encourage researchers to think across scales, and through that process they expand the foundations of ecosystem ecology. Core relevance: Most of the frontiers identified by the community reside at the core of ecosystem ecology and are driven by questions about system level process, function, and structure in a place-based ecological context (Fig. 2). The relationship between frontiers and the core of ecosystem ecology is such that the two cannot be measured as mutually exclusive. The core provides the foundational knowledge that bounds ecosystem ecology as a discipline, and the frontiers defines the edges of knowledge as currently understood. Each dynamically feeds the other: the core helps define frontiers while frontiers simultaneously push the core beyond preexisting boundaries of knowledge. This dynamism between the core and frontiers renders them nonstatic, as each continuously transforms the other, and through this process advances the science as a whole. Researchers who actively engage in both core and frontier research through a process described by one key informant as, ‘‘jumping past the edge and then kind of working your way back.’’ It is at the interface of disciplines that some of the most innovative understanding emerges (Wiek and others 2015).

Our detailed ethnographic analysis of key informant interviews further suggested that without the core—the discipline’s foundational knowledge, frontier research cannot sustain its transformational power. However, at the same time, this analysis suggested that frontiers expand the edges of the core in a ripple effect fashion, pushing outward in response to environmental change, emerging environmental problems and topics, and ongoing challenges in order to find new ways of making sense of complexity and develop a more holistic understanding of ecosystems. These expansions require interaction with other disciplines (Table 2; Fig. 1).

There is convergence in what ecosystem ecologists see as the global socioenvironmental frontiers and the frontiers of many other disciplines. This is a good sign, suggesting that across-disciplines, we are heading in the same direction, and using a systems approach. But this convergence raises questions about the appropriate roles for different disciplines in multidisciplinary frontiers and how these disciplines can maintain their core focus while moving forward and sharing knowledge, technology, and tools.

SUMMARY AND CONCLUSIONS

Through surveys, soapbox talks, community engagement at town halls, and expert interviews it became clear that there are cutting edge ideas, and tremendous energy and excitement about new research in ecosystem ecology. To our knowledge, no comparable past scientific community assessment in such a co-designed fashion has been carried out. Yet, interestingly, many of the overarching frontiers are enduring (for example, Baron and Galvin 1990; Pace and Groffman 1999; Bechtold and others 2013)—meaning that they have shown up before in past frontiers assessments. This persistence suggests that the core of ecosystem ecology as a discipline is robust, but is consistently expanding. With the application of new tools, new data, and new approaches, it is possible to unravel the details of critically important topics in ecosystem ecology, for example, the nature and impact of state changes, thresholds and tipping points, and the details of nutrient cycles. There is also new work, both empirical and modeling, on the drivers of change, such as climate, land use, and invasive species, and on the details of the black boxes that carry out ecosystem processes. What is both surprising and encouraging is that there is impressive ongoing work on fundamental processes and unanswered questions that underpin life, such as the controls and feedbacks on production, consumption, decomposition, nutrient cycling, and energy dynamics. This work is being carried out in human-dominated as well as ‘natural’ systems.

New tools and technologies are increasingly available (for example, sensors, genomics, new techniques for data analysis, and remote sensing products) and are being integrated into ecosystem experiments, models, long-term data, comparative studies, and used to test theory, fundamental to new knowledge on ecosystem structure, and function. Our ability to measure and model fundamental processes has improved enormously but still has a long way to go. We anticipate that as sensors and instruments are developed that can measure (or measure indices of) biotic activity, and more robust nonlinear models are developed to link pattern and process, the next wave of transformational knowledge will result.

The barriers to advancing the frontiers of ecosystem ecology are largely surmountable: support, training, cyberinfrastructure to share and explore 'big data.' However, catalyzing the cultural shift that must happen in order to redefine both the reward system for transdisciplinary research, as well as what constitutes success in this research is a bigger challenge.

Ecosystem ecologists are increasingly engaging in critically important and new interfaces between disciplines and between science and society, such as urban and global ecology, and sustainability studies. Given the systems and multidisciplinary approaches are the hallmarks of ecosystem ecology, this suggests that our science has a critical and a leading role to play in these new spaces and places; the future of ecosystem ecology appears bright, and fully energized.

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