The Future of Synthesis in Ecology and Environmental Sciences

by

Stephen R. Carpenter*, Virginia Armbrust, Peter Arzberger, Terry Chapin, James Elser, Edward Hackett, Tony Ives, Peter Kareiva, Mathew Leibold, Per Lundberg, Marc Mangel, Nirav Merchant, William Murdoch, Margaret Palmer, Debra Peters, Steward Pickett, Kathleen Smith, Diana Wall, Ann Zimmerman

*correspondence: srcarpen@wisc.edu

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Summary

Synthesis is the process of putting together disparate data, concepts or theories to create new knowledge, tools or other innovations. Synthesis is essential for progress in ecology and the environmental sciences, which are inherently interdisciplinary. Ecology is centrally and traditionally one of the biological sciences, yet it embraces elements of the geosciences and social sciences. Moreover, applied ecology connects closely to engineering. Computational sciences are essential in all forms of ecology and environmental science, and the co-evolution of ecology and cyber-infrastructure greatly accelerates synthesis.

Ecological synthesis is increasingly important due to changes in knowledge itself, the culture of the discipline, and society's demands for education and information. The huge and growing body of knowledge confounds traditional mechanisms of innovation and is manageable only through synthesis. Because synthesis engages diverse scientists with diverse expertise, it is capable of vetting vast amounts of information for use by other scientists, educators or society.

Education depends on integration of information and therefore demands synthesis. Conversely, education is essential for synthesis, because we need more experts trained in the skills of synthesis. These skills are not within the purview of any one discipline, yet they can and must be taught.

Synthesis creates knowledge and innovation by integrating ideas, findings, data, and other information (such as environmental or social needs and constraints) in ways that are original and perhaps unexpected. With recent and potential new investments in the scientific, computational, and social infrastructure necessary for synthesis, the U.S. is poised to lead the world in this powerful, innovative activity. Ecology has a head start in developing this technology because of experience with bringing together diverse multi-national data sets, disciplines and cultural perspectives to address a wide range of issues in basic and applied science. Now is the time to build on this foundation and invest in ecological synthesis.

A national program of synthesis for ecology and environmental sciences is needed. Such a program would promote optimal use of existing data, expertise and information. By investing in synthesis, we take stock of what we know and identify crucial questions for further research. Synthesis itself also creates new emergent knowledge and innovations.

A Center, or network of Centers, should be the heart of the national program for synthesis in ecology and environmental sciences. Centers bring unique capabilities and unmatched opportunities for synthesis due to the intensity of interaction among scientists, great diversity of participation across disciplines and into the realms of policy and decision making, emergence of new networks among scientists, financial and logistic efficiencies, prominence and credibility, and the close interaction of environmental sciences with cyber-infrastructure, education, decision making, and other key stakeholders. The high tenor of creativity, innovation and productivity at Centers simply cannot be matched by any other mechanisms for synthesis.

Introduction

Biology is a data-rich quantitative science that is technologically and conceptually sophisticated. Synthesis of data, concepts and technology provides a new and deeper method of reasoning (Bangham and Asquith 2001, Pickett et al. 2007). Theoretical, technological and analytical advances allow researchers to integrate across organizational, spatial and temporal scales to examine complex biological phenomena. Synthesis and related activities – those that involve single or multiple investigators utilizing existing data, metadata and analytical tools to address questions and broaden conceptual foundations – play an increasingly important role in advancing our understanding of the natural world (Hackett et al. 2008).

Synthesis and related activities often:

- occur through sustained, intense interactions among individuals with ready access to raw data, metadata and sophisticated analytical tools;
- link disparate, existing data sets and mine them from new perspectives that allow novel analyses;
- develop and use new analytical, computational, visualization and modeling tools that may lead to greater insights;
- bring theoreticians, empiricists, modelers and practitioners together to formulate new approaches to existing questions; and
- integrate science with education and real-world problems in novel ways.

In ecology, a number of synthesis activities and approaches have developed and matured over the past two decades. These include the establishment of synthesis Centers, collaboration among groups of researchers who share similar scientific objectives or interests, and individual efforts to analyze or synthesize information gathered over an extended research career. At the same time, new tools – particularly computational and statistical ones – have been developed for the ecological toolbox. Each of these approaches provides a distinct mechanism for synthesis and plays different roles in, or accomplishes a different type of, synthesis and analysis. These activities also differ in their success, their products, and the role they have played in advancing ecology in its broadest definition.

After nearly two decades of growing appreciation for synthesis and its importance in advancing biological disciplines, it is time to evaluate the accomplishments of synthetic activities along with the various mechanisms by which these activities have been carried out, and to discuss the future of synthesis activities. As a step toward this broad goal, we examined synthesis activities in ecology and closely-related environmental sciences during a workshop 9-10 December 2008. After presentations that reviewed current synthesis activities funded by NSF and the charge to the workshop, our discussions began by considering four broad questions:

1) How do different kinds of synthesis activities and approaches differ? What are the strengths and weaknesses? Are there important gaps that are not met by existing activities and approaches?

2) What are alternate approaches for facilitating ecological analysis and synthesis? What are the roles of, for example, Centers, self-organized collaborative groups that are not affiliated with

Centers, and individual efforts? Are there approaches to synthesis from other fields that should be imported to ecology?

3) What are the possibilities for enhancing ecological synthesis through emerging technologies, eco-informatics, and cyber-infrastructure? How do these technologies change the synthesis questions that ecologists can or should ask? What are the implications of these technologies for approaches to synthesis?

4) What is the role for other disciplines (e.g. computational sciences, geosciences, social sciences) in ecological synthesis? How do these disciplines alter the questions and approaches for ecological synthesis?

We conclude that synthesis is essential for progress in ecology and the environmental sciences – even more essential than it was in the past. The increasing need for synthesis is driven in part by changing tools and culture of the disciplines themselves and by the urgency of important applied problems. Centers provide unique capabilities for focusing and accelerating synthesis. In this paper, we develop these points in more detail. Within each major section of the paper, the main points are highlighted in **bold font** and essential supporting points are in regular font.

Synthesis is Essential

Synthesis is unusually important for ecology and environmental sciences because these are hybrid disciplines that occupy extensive conceptual landscapes. Education, training and innovation in these fields are intrinsically synthetic. Explosive expansion of the already vast body of knowledge has made synthesis ever more important for creation of new knowledge. Beyond its necessity for innovation in basic science, synthesis is increasingly needed for finding novel and effective solutions for pressing environmental problems. Finally, synthesis itself is synergistic and proactive, leading to emergence of new ideas or even entire fields of inquiry that were unexpected before the synthesis took place.

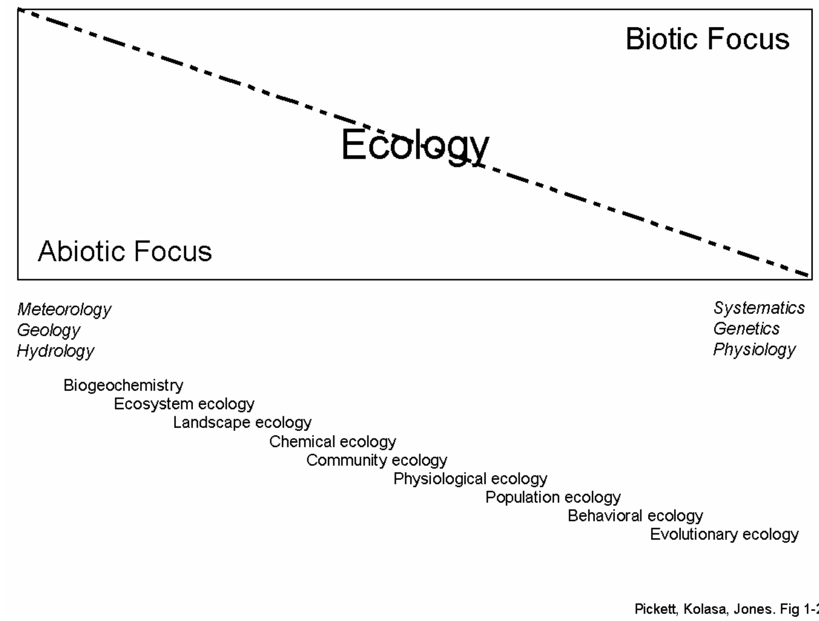
Synthesis occurs when disparate data, concepts or theories are integrated ways that yield new knowledge, insights, or explanations. It creates emergent knowledge in which the whole is greater than the sum of the parts. It may take many forms, such as summarization, generalization and unification (Pickett et al. 2007). The attention of scientists with multiple perspectives suggests that synthesis can be a tool for vetting a vast body of scientific information for use by other disciplines or by society. Synthesis can address various scales, processes and kinds of environments.

Conceptual landscape

The science of ecology occupies a large conceptual landscape. It encompasses biological topics, physical topics and social topics. One depiction of ecology places the discipline across a spectrum of foci from abiotic to biotic (Figure 1). Synthesis across the variety of scales, concepts, data, and models that are attuned to the different ranges of this disciplinary gradient remains a pressing need for the basic science of ecology.

The conceptual landscape is further complicated by the growing recognition that social structures and processes interact with ecological phenomena. Hence, a second disciplinary dimension of increasing importance is one describing social conditions, interactions, institutions, and motivations. Feedbacks between ecology and social phenomena are widespread. This is evident in the rise of new fundamental research on earth system science and social-ecological systems as well as new applied research in sustainability science (Clark et al. 2004).

Figure 1. A conceptual landscape of ecology along axes that bridge the biological and earth sciences (Pickett et al. 2007).



Burden of knowledge

Ironically, innovation has become increasingly difficult as the foundational knowledge in the sciences has increased. The growth of knowledge is indicated by the growth of the number of journals, for example, that ecologists and environmental problem solvers must consult. This explosion of information that must be summarized, generalized or confirmed is the "burden of knowledge" (Jones 2008). Innovation, which often involves synthesis, can be quantified by examining trends in patents. In recent years, successful innovations leading to patents are accomplished by older people who have had more time to process knowledge, in narrower areas where there is less relevant knowledge to consider, or by teams who have used synthesis to integrate knowledge. Thus teamwork leading to synthesis can be a major tool for lightening the burden of knowledge by summarizing empirical data, generalizing across cases or situations, or abstracting many observations into laws or models. Such work is fundamental for innovation.

The culture of synthesis also facilitates scientific efficiency in the face of a growing empirical base. Synthesis is needed to know what we know, and thereby avoid wasting money on research that would be unnecessary had we paused to do the synthesis.

Synthesis accelerates discovery

Synthesis is a way to accelerate the classical ontogeny of scientific discovery to address urgent questions. The ecological sciences tend to accumulate knowledge through processes of hypothesis making, initial empirical evaluation, critique and resolution via experimentation or refined analyses that often take years or decades. This approach severely limits the rate at which knowledge becomes available for other purposes. As a result, subdisciplines become isolated, terminologies differ, analogies and generalities are missed, and solutions become idiosyncratic instead of general.

Synthesis leapfrogs this linear and sequential progress of discovery by converting the serial steps into parallel interacting ones. Synthesis also forces subdisciplines and branches of ecology to borrow tools, approaches and insights from each other, hence functioning both as a self-correctional tool and the catalyst for discovering emergent properties. Synthesis thus speeds up the process of discovery.

New ways of using synthesis can also be prospective

Synthesis can help identify future research needs and methods, including, for example, key experiments that might be needed. Synthesis helps standardize, formulate, develop, and update the new data gathering and analytical tools that are beginning to emerge in existing and new observational networks (Peters 2008). This provides opportunities to address new research frontiers in a more organized way than has been done before. Synthesis is also prospective when it anticipates future environmental or natural resource management issues, or when it establishes a standardized framework by which comprehensive future studies might be performed.

Ecological discovery is key to solving environmental problems

Ecosystem services – the contributions of nature to human well-being -- flow from ecological structures and processes. Thus ecology is an essential component of sustainability science, the practical study of social-ecological systems to build and maintain human welfare (Clark 2007, Kates et al. 2001). Examples of ecological phenomena of great significance to environmental issues are adaption to climate change, capacities of ecosystems to process excess nutrients, and the effects of patterns of land use change on delivery of food, forest products, fresh water, carbon storage or other ecosystem services. Ecological processes of importance range from soil microbial processing, to the control of pollutants and invasive organisms and diseases across land use mosaics. Although disciplinary studies are important in advancing understanding of these kinds of ecological dynamics, synthesis is essential to assess complex causes that have social, physical and biological origins. Synthesis is also essential for evaluating the efficacy of policy instruments intended to improve ecosystem services and human well-being.

Novel insights emerge from 'meta-synthesis'

Meta-synthesis seeks to expand the scope of synthesis. Some of the key elements of meta-synthesis (Gu and Tang 2007) include combining qualitative and quantitative information, integrating across scales, conducting interdisciplinary research, integrating knowledge with decisions and action, and combining synthesis with analysis. While past work in ecological synthesis has used each of these elements and sometime used them in simple combinations, there is a great need to develop synthesis within the broader synthetic approach that fully draws upon all of these elements.

There are needs for synthesis among synthetic efforts. For example, synthesis among emerging perspectives such as stoichiometry, stochastic processes, and metacommunities could be integrated with classical understanding involving niches, ecosystems, landscapes, and biogeography. Such ambitious efforts build on synthetic foundations of ecology and are likely to transform the discipline.

Synthesis and the Changing Tools and Culture of Ecology

In the last 20 years, the landscape for ecological synthesis has changed in profound ways, particularly in terms of tools, challenges and intellectual environment. Beyond the barriers posed by the burden of knowledge, new tools, collaborative mechanisms, challenges and intellectual agendas have arisen to alter the context of ecological synthesis.

The tools have changed

According to Moore (1965), computing power doubles every two years, by 2008 giving us 256 times the computing power of 1993. Today everyone can have enormous computing power on a laptop and for $100 can buy a terabyte hard-drive. The web enables international communication and data sharing at a level that could not have been imagined even five years ago.

Looking forward, we envision larger and larger streams of data that need to be standardized, manipulated and made generally accessible, much as the human genome browser (http://genome.ucsc.edu/cgi-bin/hgGateway) does for genetic data. The accessibility of relatively complex tools for modeling and statistical analysis has greatly increased. We can no longer view the collection of data and synthesis as separate enterprises.

Over the last 20 years, the accessibility of knowledge has also changed in profound ways. JSTOR has made classical ecological studies broadly accessible. New journals, some of them open access and others (e.g. PLoS ONE) with novel publication strategies are creating a wealth of ecological information. Synthesis of classical and new studies is the requisite for the generalizations needed to move forward.

Ecology is much less of a solitary discipline than it was 20 years ago. Today, more than in the past, one's closest colleagues need not be physically nearby. High speed internet and video-conferencing provide new and more flexible ways for conducting synthesis.

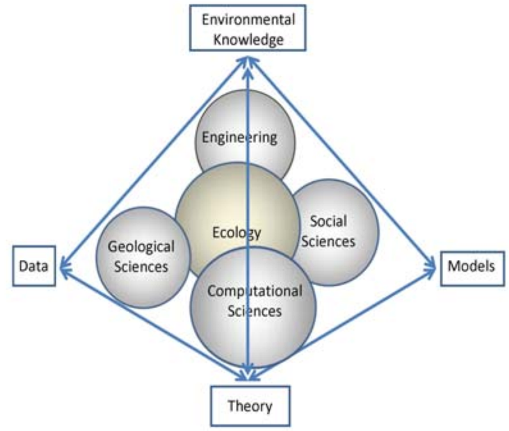
Challenges for ecologists have changed

Synthesis is now widely recognized by ecologists as an essential research activity and tool for discovering knowledge. Much of the past synthesis involved aggregation of data to document previously undocumented patterns and to provide new generalizations about patterns that emerge at larger scales. These lay the groundwork for conceptual syntheses within and across fields that previously would not have occurred.

Ecologists have broadened their vision of appropriate questions and therefore the range of disciplinary expertise that is engaged in solving ecological problems (Figure 2). Studies of ecosystem dynamics increasingly draw on an understanding of geophysical processes. The shift from viewing people as an external impact to being integral components of ecosystems requires inclusion of social as well as ecological processes in feedback loops, and environmental problem solving often combines engineering and ecology. Computational sciences pervade ecological analyses and syntheses. As a consequence, collaboration among researchers of different disciplines becomes increasingly common, leading to synthesis that addresses new questions with fresh perspectives.

Similarly, as other fields expand their horizons and become more interdisciplinary, they increasingly draw -- or should draw -- on ecology to inform their science. Ecologists now regularly contribute to issues of urban planning, agricultural and fisheries management, climate dynamics, analysis of the patterns of human behavior, and myriad other topics. These collaborations require synthesis at the interfaces among disciplines and raise new questions for ecologists that might not have appeared interesting or important in a purely ecological context.

Figure 2. The relationship of ecology to other disciplines crucial to solving environmental problems. Solving environmental problems rests on a base of data, theory and models, and requires a linkage of ecology with engineering, geological sciences, computational sciences and social sciences.



Changes in the types and magnitude of environmental issues faced by ecologists also raise new questions requiring synthesis. For example, the expanded use of genetically modified organisms raises new questions about biological interactions; rapid rates of environmental change challenge the value of ecological restoration that conforms to historical patterns; and the global scale of movement of organisms, materials, and people, raises new questions about the scale and types of biological feedbacks and interactions that are important to society. The urgency and magnitude of the problems demand ecological synthesis.

The intellectual environment has changed

Over the last 20 years, a major change in the intellectual environment of ecologists is the broad acceptance that concerted efforts for synthesis are essential for the rapid development of scientific thought and progress (Hackett et al.2008). This change clearly represents a much broader cultural shift driven in part by the challenges that ecologists have been forced to face. For example, the confirmation of global climate change has energized the synthetic search for the fingerprint of current anthropogenic climate modification on world ecosystems.

This cultural change does not diminish the challenges for synthesis in ecology, but instead introduces new and more complex challenges. The challenge is no longer to convince the ecological community that synthesis is fundamentally important, but instead to identify the most successful modes and models of synthesis, and to spread the acceptance of the importance of synthesis to allied fields that are critical for solving environmental problems.

Research is increasingly international in scope. This increases the challenge of synthesis to straddle international and cultural boundaries, encompassing not only diverse scientists but also diverse institutional expectations and constraints that these scientists face.

Synthesis is essentially an information technology in which ecology has a head start because of the historically synthetic nature of the discipline. The U.S. is poised to lead the world in this information technology because of prescient investments in the past. These successes are now emulated overseas by such institutions as the Center for Advanced Study (http://www.cas.uio.no/), Institute Para Limes (http://www.paralimes.org/), Stockholm Resilience Centre (http://www.stockholmresilience.org/), and other synthesis activities in planning stages. There will be opportunities for increasing the power of synthesis by global linkages among these Centers. Now is the time for the U.S. to build on its leadership in synthesis.

Interactions of Education and Synthesis Must be Strengthened

We must make rapid progress in education for synthesis. Synthesis skills are as important as field or laboratory skills for the practicing scientist. Environmental problem-solving depends increasingly on synthesis and the results of syntheses formalized as assessments. The necessary skills can be taught, and our capacity to provide this education must increase ever faster. Moreover, development of curricular materials, courses and other educational tools is itself a process of synthesis, requiring the combination of diverse kinds of knowledge and prioritization and organization of information.

Synthetic skills must be taught and opportunities to use those skills must be created, and both are best done early in a scientist's career. We need education for synthesis at the undergraduate and graduate levels. Education should involve not only the analytical tools for synthesis, but also the motivation for synthesis. The current generation of students and post-docs has unprecedented motivation to do important applied work, access to information and the tools to process the information, but requires formal training in the process of synthesis.

Assessments that synthesize scientific knowledge relevant to environmental decisions have become crucial for environmental policy. The Intergovernmental Panel on Climate Change (http://www.ipcc.ch/), the Millennium Ecosystem Assessment (http://www.MAweb.org) and the Heinz Center Report on the State of the Nation's Ecosystems (http://www.heinzctr.org/ecosystems/) are a few examples. Miller (2009) states that a principal role of Assessments is to

> identify, synthesize, evaluate, and assess scientific facts, data, studies, and theories, as well as other knowledge and ideas, for their relevance and significance with respect to the policy question at hand. This is crucial, as science, at least as currently organized, tends to produce a vast array of publications containing data, analyses, theories, and conjectures. Individually, often, these publications are extremely narrow, contain relatively greater or lesser amounts of uncertainty, and provide little or no information regarding their relevance to a range of policy questions. Nor do they include all that scientists know regarding their subjects. There is a considerable need, therefore, for assessments to sift and winnow through the available publications and combine the resulting information with the tacit knowledge of participating scientists to produce a synthetic statement of what is known about the policy question of relevance.

Assessment processes are limited by a shortage of experts trained in synthesis, more than by lack of deep knowledge from the contributing disciplines. Training in synthesis conveys abilities to condense the essential points from one's own discipline, work constructively with diverse experts, maintain an appropriately critical perspective, respect diverse ways of knowing and kinds of knowledge, recognize and distill pattern from complexity, and explain synthetic findings in unbiased and clear ways. Progress in environmental policy and ecosystem management therefore requires training in synthesis.

Just as synthetic skills must be learned, synthesis is crucial for education and training. Ecology as a discipline needs to find novel ways to educate future scientists and the broader public. Education is inherently synthetic. In curricular materials and in the classroom, disparate kinds of information are integrated and organized. Synthesis should transform the contents of ecological curricula.

Cyber-infrastructure plays an expanding role in synthesis for education, just as it does in research. Progress in ecological education depends on collaborative integration of ecology, education and computational sciences, so that the research agendas of these contributing disciplines are intermingled.

Finally, there are important opportunities for teaching-as-synthesis. There are many examples of activities that bring together diverse experts and students for intensive courses that generate novel syntheses while teaching good practices for synthesis as well as core information from the participating disciplines. Teaching-as-synthesis activities must be accelerated to greatly enhance the synergies among ecology, education, cyber-infrastructure and other disciplines.

Cyber-Infrastructure and Environmental Synthesis Must Co-Evolve

Cyber-infrastructure (CI) provides new opportunities for the scientific and social processes of synthesis and must co-evolve in a collaborative fashion with the synthesis process. CI can also help to sustain, train and build the community of synthesizers, thereby enhancing the social capital needed for future innovation.

Cyber-infrastructure (Atkins et al 2003) refers to technologies that bring together distributed resources such as data, instruments, computational tools and services, and people (NSF 07-28):

> At the heart of the cyber-infrastructure vision is the development of a cultural community that supports peer-to-peer collaboration and new modes of education based upon broad and open access to leadership computing; data and information resources; online instruments and observatories; and visualization and collaboration services. Cyber-infrastructure enables distributed knowledge communities that collaborate and communicate across disciplines, distances and cultures. These research and education communities extend beyond traditional brick-and-mortar facilities, becoming virtual organizations that transcend geographic and institutional boundaries.

In particular, there are several important roles for CI in ecological and environmental synthesis.

- To facilitate the documentation, organization, preservation of data, and sharing of data so they can be located and reused in synthetic activities;
- To support the movement of data across sites and collaborations through high-speed networks;
- To facilitate collaboration and the process of synthesis among the many individuals who are important to synthesis, including researchers from one or more disciplines, data and information managers, and international investigators;

- To broaden the participation in synthesis
- To support and deliver education, outreach, and training activities around synthesis, for current and future researchers, and developers

Here, we discuss opportunities, trends, and challenges as they relate to the topics described above. It is important to note, however, that the activity of synthesis is "doing science," and that it is subject to the same norms, requirements, and limitations of all research in general. Given this, it should not be surprising that the use of existing data, concepts, or theories to create knowledge is a complex, difficult, and iterative process. CI can provide significant support to synthesis, but the task can never be fully automated.

Needs and opportunities

Today, because of investments in CI (including observing systems), we are able to receive and control multiple streams of data, access remote databases, conduct analysis on remote computers, and collaborate via high-definition video teleconferencing. Collectively, these technologies enable synthesis, analysis, collaboration and education at a pace and scale not possible before. For example, we have access to more data, more accessible computational resources (with new business models for computing without owning), and the more regular interactions using high-definition video teleconferencing with colleagues distributed across the world.

However, these opportunities are accompanied by challenges. Some of these will be addressed by trends in technology and industry, but many others require involvement of a broader range of researchers, such as computer scientists, applied mathematicians and statisticians, and social scientists. Examples of these challenges include issues of data handling and query of the tidal wave of data being produced by observing systems, data and software standards, new algorithms for analysis, building services that can be used by all, and new collaborative tools that are affordable and easy to use. In addition, there is the challenge of preparing students for the process of synthesis and the process of creating standards and policies to share data.

Trends

Computing power, data storage and high-performance networking grow exponentially (Moore 1965, Stix 2001). The fast exponent is in networking, which removes distance barriers and thereby sets the stage for new opportunities in synthesis.

Emerging technological tools have already proven to be essential for ecological and environmental synthesis, and the co-evolution of CI and synthesis must continue for the mutual benefit of both. In many dimensions the pace of synthesis is limited by CI. To move forward, ecological synthesizers and computational scientists must collaborate so that problems of ecological synthesis are assimilated into the research challenges of computational science. To facilitate synthesis activities the required CI needs to exploit existing trends and be agile in adapting and shaping emerging technologies to enhance productivity of the community.

The future synthesis activities will expect and demand more interactive, integrative and collaborative workspaces. This highly pervasive CI needs to be accessible from hand held devices to desktops, and include high definition video communications that integrates desktop applications, video and audio in a seamless manner with the underlying data and analysis methods. The ubiquitous and transparent aspect of CI will facilitate cross disciplinary collaboration by making resources more accessible while reducing the technological barriers for widespread adoption

Collectively, these technologies will accelerate synthesis through more rapid access to data or collaborators, and broaden networks of those involved with synthesis. Even in situations where not everyone can travel to meetings, with emerging networking and collaborative tools, researchers can participate at a distance without feeling disconnected intellectually and physically. These tools can also change the educational structure, providing distributed classes, and active involvement of graduate students in teams of distributed researchers. Collectively, these trends help address the issues raised by the burden of knowledge. Synthesis efforts and processes, to be maximally effective, should track, influence and exploit these and future trends in CI.

A National Program of Environmental Synthesis Is Needed

Ecologists and closely connected disciplines in the biological, computational, atmospheric, hydrological, geological, oceanic and social sciences need a national program of synthesis that accelerates discovery and research in basic and applied environmental science through interdisciplinary analysis and synthesis activities. Currently, NSF funds a number of mechanisms for supporting ecological synthesis activities including those associated with Centers, the Long-Term Ecological Research network, new emerging networks, individual synthesis efforts and other programs. In the future we anticipate new synthesis opportunities arising from rapid progress in observing platforms. Currently we lack a program specifically focused on environment science synthesis, that is, science where ecology intersects multiple disciplines. The need to coordinate synthesis across the approaches funded by NSF and the multiple disciplines calls for a new umbrella structure – a sort of national program for environmental synthesis. Such a program could coordinate the various mechanisms supported by NSF for ecological synthesis, as well as interactions with the computational sciences, engineering, geosciences and social sciences. A Center, or Centers, should play a prominent role in this program.

Centers bring unique capabilities and unmatched opportunities for synthesis

When scientists interact at a place away from their home institutions, and focus collectively on a topic, there is an intensity of interaction and rate of progress that does not occur in other settings. The neutral ground provided by a Center leads to more openness and encourages a greater diversity of participation. This greater diversity leads to searching questions that can trigger remarkable insights or innovations. Moreover, the networks fostered by a Center encourage novel connections among scientists that lead to unexpected synergies. A well-governed Center is unsurpassed in its efficiency for handling travel, logistics, finances, information management and CI. Thus the scientists can focus exclusively on the synthesis challenges, while the engaged staff facilitates coordination of science, education and outreach, further enhancing productivity. The high tenor of creativity, innovation and productivity at a Center evokes high expectations and performance from participants. These advantages of Centers simply cannot be matched by any other mechanisms for synthesis.

Several important considerations are involved in the design of a Center or network of Centers (Hackett et al. 2008). Among these are the following.

Motivation: Any Center or system of Centers must begin with a process for eliciting, evaluating and endorsing a suite of intellectual problems and themes that will draw scientists and scholars from a spectrum of disciplines. Doing so requires framing the activity in a fashion that secures programmatic and policy commitment – including, perhaps, financial support – from disciplinary and organizational leadership, as well as attracting the ideas and energies of scientists and scholars working at the frontiers of their fields. Practical problems, such as assessing management alternatives for ecosystem services of a watershed, add urgency and salience (visibility of consequences) to the research process, and open the door to catalytic interactions among scientists, decision makers, policy experts, and other practitioners.

Agility: An effective Centers program will adapt rapidly and flexibly to changing needs and opportunities. Some of these changes may arise from advances in research evidence or research technologies, while others may arise from changes in contextual circumstances such as an unexpected catastrophe. An adaptable system of Centers would allow new activities to organize and existing ones to redirect their energies with minimal delay, expense, disruption, and formality.

Efficiency: Research resources are limited and demands are growing in urgency and scope, so a Centers program must make parsimonious use of research funds and scientists' time. And in the environmental sciences there is particular concern to minimize environmental impacts of scientific activities.

Trust: Collaborations are built upon intellectual and interpersonal trust, an open and critical exchange of ideas, data and techniques from which new explanations are constructed. Organizations and institutions are also endowed with trust, serving as repositories for data, research technologies and personnel.

Gravitas: Organizations and institutions develop reputations that lend weight to their activities. With these reputations Centers are, in turn, able to attract people, resources and attention, and their work carries extra significance for decision makers and the general public. This quality is especially important for building a Center that will engage a global community of scientists and scholars to address problems of global concern.

Tools: Program Centers may become repositories for data collections, analytic tools and expertise, and research technologies that are expensive to purchase and maintain (such as visualization technologies). Centralizing the development, support and access to major research technologies enhances cumulative learning and expertise, and lends momentum to the activity. It may also be the most efficient way to provide certain research resources.

Scale: The choice of elements within the program entails a choice of scales for performing the work, which may range from a large, varied, enduring, highly capitalized facility through transient, purpose-built topical Centers to small, flexible, short-lived teams and networks. A coordinated program of networked synthesis Centers would have the ability to support a range of activities shaped to the varied and changing needs of the challenge.

Structural options for Synthesis Centers

Whatever the structure of the next-generation Center or system of Centers for ecological and environmental synthesis, the following features must be included: (1) Support of core synthesis activities, including meta-analysis, conceptual and theoretical integration, information management, all coupled to education and training, (2) Focus on ecologically relevant issues, even as they interface with other relevant disciplines; (3) Major components of in-place activity, with support by new communications technology; (4) Major investments in next-generation technologies in computing and communications.

Flexibility in topics and funding sources is essential. A Center should have the capacity to undertake intellectually important synthesis projects on a wide range of topics, under funding from a range of sources including NSF, other federal agencies, funders from other nations, state agencies, non-government organizations and private foundations.

Adaptability enables a Center to evolve and address novel challenges. A Center should be a learning organization that experiments with novel approaches to synthesis, retains and develops the more successful approaches, and drops any approaches that prove unsuccessful. For example, some successful approaches to synthesis include working groups, intensive efforts by individuals, distributed web-based courses, short intensive courses at field stations, and others. Synthesis can occur at a centralized location, distributed locations, field sites that contribute data, or through the internet. Center governance should become skillful at matching approaches, or sets of approaches, to synthesis challenges.

The level of support for Centers of ecological and environmental synthesis should expand rapidly by a factor of five or more. The group discussed the pros and cons of one large Center versus several regional Centers. Regional Centers could offer advantages of specialization and economies of shorter travel distances for some participants. On the other hand, there are great advantages in centrally-located CI, logistical support and administration. Even with a centralized organization, participants wanted to see mechanisms for conducting synthesis activities away from the central location. For example, a synthesis effort focused on different field sites could meet sequentially at the field sites, or a short course could meet at a field station that was well-equipped for the particular activities of the course.

We are uncertain about how to balance the central role of ecology versus the need for interdisciplinarity. Ecological synthesis is on the brink of transforming our understanding of ecological systems, the practice of ecological research, and the teaching of ecology. The teaching of ecology in 2020 will be vastly different as a result of synthesis projects that will be undertaken in the next decade. Therefore, a focus on the intellectual agenda of ecology must be a high priority. On the other hand, many important synthesis questions demand integration of ecology with other aspects of biology as well as computational sciences, geosciences and social sciences. Pressing problems of applied ecology, ecosystem-based management, and sustainability are fundamentally interdisciplinary. Often they are not intrinsically or predominantly ecological, even though ecology plays a role. Yet consideration of interdisciplinary questions often leads to new fundamental insights and may even change the core of ecology itself. These alternative viewpoints about ways to integrate ecology and its sister disciplines led to different ideas about possible structures for a future ecological synthesis Center or system of Centers. Diversity of viewpoints is simply a reflection of the excitement and turbulence of the rapidly-expanding intellectual landscape of ecological synthesis.

Ecology is a hybrid science with core questions of crucial importance and boundaries that are expanding. These characteristics have made ecology a hotbed of scientific synthesis and established synthesis as a driver of innovation. Now is the time to build on that foundation, further refining the best practices of synthesis within ecology. It is also time to spread the culture of synthesis more extensively to undergraduate and postgraduate education, across the basic-applied spectrum towards management and governance, and beyond disciplinary boundaries into sciences allied with ecology. NSF is in the key position to foster this spread of the culture and practice of synthesis, and to stimulate new synthesis that benefits science and society.

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Contributors

E. Virginia Armbrust
Center for Environmental Genomics
University of Washington
Seattle, WA 98105 USA
Email armbrust@u.washington.edu

Peter W. Arzberger
National Biomedical Computation Resource
University of California, San Diego
La Jolla, CA 92093 USA
Email parzberg@ucsd.edu

Stephen R. Carpenter
Center for Limnology
University of Wisconsin
Madison, WI 53706 USA
Email srcarpen@wisc.edu

F. Stuart Chapin, III
Department of Biology and Wildlife
Institute of Arctic Biology
University of Alaska
Fairbanks, AK 99775 USA
Email terry.chapin@uaf.edu

James J. Elser
School of Life Sciences
Arizona State University
Tempe, AZ 85287 USA
Email j.elser@asu.edu

Edward J. Hackett
School of Human Evolution and Social Change
Arizona State University
Tempe, AZ 85287 USA
Email ehackett@asu.edu

Anthony R. Ives
Department of Zoology
University of Wisconsin
Madison, WI 53706 USA
Email arives@wisc.edu

Peter M. Kareiva
The Nature Conservancy
Seattle, WA 98105 USA
Email pkareiva@tnc.org

Mathew A. Leibold
School of Biological Sciences
Section of Integrative Biology
University of Texas
Austin, TX 78712 USA
Email mleibold@mail.utexas.edu

Per Lundberg
Department of Theoretical Ecology
Lund University
Lund, Sweden
Email per.lundberg@teorekol.lu.se

Marc Mangel
Department Applied Mathematics and Statistics and
Center for Stock Assessment Research
University of California
Santa Cruz, CA 95064 USA
Email msmangel@ucsc.edu

Nirav Merchant
Biotechnology Computing
University of Arizona
Tucson, AZ 85721 USA
Email nirav@arl.arizona.edu

William W. Murdoch
Department of Biological Sciences
University of California
Santa Barbara, CA 93106 USA
Email murdoch@lifesci.ucsb.edu

Margaret A. Palmer
Chesapeake Biological Laboratory
University of Maryland Center for Environmental Sciences
Solomons, MD 20688 USA
Email palmer@cbl.umces.edu

Debra P. C. Peters
USDA-ARS, Jornada Experimental Range
Las Cruces, NM 88003 USA
Email debpeter@nmsu.edu

Steward T. A. Pickett
Cary Institute of Ecosystem Studies
Millbrook, NY 12545 USA
Email PickettS@caryinstitute.org

Kathleen K. Smith
Department of Biology
Duke University
Durham, NC 27708 USA
Email kksmith@duke.edu

Diana H. Wall
Natural Resource Ecology Lab
Colorado State University
Fort Collins, CO 80523 USA
Email Diana@nrel.colostate.edu

Ann Zimmerman
School of Information
University of Michigan
Ann Arbor, MI 48109 USA
Email asz@umich.edu