Synthesis Centers as Critical Research Infrastructure

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Synthesis centers offer a unique amalgam of culture, infrastructure, leadership, and support that facilitates creative discovery on issues crucial to science and society. The combination of logistical support, postdoctoral or senior fellowships, complex data management, informatics and computing capability or expertise, and most of all, opportunity for group discussion and reflection lowers the "activation energy" necessary to promote creativity and the cross-fertilization of ideas. Synthesis centers are explicitly created and operated as community-oriented infrastructure, with scholarly directions driven by the ever-changing interests and needs of an open and inclusive scientific community. The last decade has seen a rise in the number of synthesis centers globally but also the end of core federal funding for several, challenging the sustainability of the infrastructure for this key research strategy. Here, we present the history and rationale for supporting synthesis centers, integrate insights arising from two decades of experience, and explore the challenges and opportunities for long-term sustainability.

Keywords: synthesis, collaboration, interdisciplinary research

Demand for the opportunity to participate in a synthesis-center activity has increased in the years since the US National Science Foundation (NSF)–funded National Center for Ecological Analysis and Synthesis (NCEAS) opened its doors in 1995 and as more scientists across a diversity of scientific disciplines have become aware of what synthesis centers provide. The NSF has funded four synthesis centers, and more than a dozen new synthesis centers have been established around the world, some following the NSF model and others following different models suited to their national funding environment (*http://synthesis-consortium.org*).

Scientific synthesis integrates diverse data and knowledge to increase the scope and applicability of results and yield novel insights or explanations within and across disciplines (Pickett et al. 2007, Carpenter et al. 2009). The demand for synthesis comes from the pressing societal need to address grand challenges related to global change and other issues that cut across multiple societal sectors and disciplines and from recognition that substantial added scientific value can be achieved through the synthesis-based analysis of existing data. Demand also comes from groups of scientists who see exciting opportunities to generate new knowledge from interdisciplinary and transdisciplinary collaboration, often capitalizing on the increasingly large volume and variety of available data (Kelling et al. 2009, Bishop et al. 2014, Specht et al. 2015b). The ever-changing nature of societal challenges and the availability of data with which to address them suggest there will be an expanding need for synthesis.

However, we are now entering a phase in which government support for some existing synthesis centers has ended or will be ending soon, forcing those centers to close or develop new operational models, approaches, and funding streams. We argue here that synthesis centers play such a unique role in science that continued long-term public investment to maximize benefits to science and society is justified. In particular, we argue that synthesis centers represent community infrastructure more akin to research vessels than to term-funded centers of science and technology (e.g., NSF Science and Technology Centers). Through our experience running synthesis centers and, in some cases, developing postfederal funding models, we offer our perspective on the purpose and value of synthesis centers. We present case studies of different outcomes of transition plans and argue for a fundamental shift in the conception of synthesis science and the strategic funding of these centers by government funding agencies.

A brief overview of synthesis centers

The first synthesis center, NCEAS, arose in response to evolving scientific knowledge and research technologies, the growing need for interdisciplinary and transdisciplinary

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explanations, and increasing requests by practitioners to connect science to applications (Hackett et al. 2008). Recognizing these changes, the Ecological Society of America (ESA), the Association of Ecological Research Centers (AERC), and O. J. Reichman at the NSF called for the establishment of a place to undertake "multidisciplinary analysis of complex environmental problems"; the enabling language stated, "Synthesis is needed to advance basic science, organize ecological information for decision makers concerned with pressing national issues, and make cost-effective use of the nation's extant and accumulating database" (as was reported in Hackett et al. 2008). Although the specific themes may differ among today's newer synthesis centers, these three tenets form the foundation for all of them to this day. As the pioneering centers such as NCEAS and the National Evolutionary Synthesis Center (NESCent) matured, they, along with newer centers, developed a science infrastructure for catalyzing new ideas that can be and are used for scientific advancement and public benefit.

Synthesis centers share many commonalities (Lynch et al. 2015). The fundamental unit of most synthesis centers is the working group; some synthesis centers also support other activities, including workshops, short courses, and catalysis meetings. These are one-time meetings of up to about 30 scientists to focus on grand challenges and high-risk, high-reward initiatives. In contrast, working groups are teams of up to 20 people that come together for intensive collaboration for several days at a time, often across a series of meetings housed within the center and supported by an integrated research staff. Teams are designed to be collaborative and convergent, often combining experts with different backgrounds, expertise, and perspectives to approach a common question or topic. Existing data from multiple researchers that may span space and timescales across multiple disciplines are analyzed. All synthesis centers provide some degree of computational support, data management, and informatics expertise (box 1).

Synthesis centers often function as effective boundary organizations linking science, management, and governance (box 2). Formal and informal partnerships develop when people from different organizations come together around mutually important topics, increasing the role of science in decision-making. One example of this is the Science for Nature and People Partnership (*www.snap.is*) between NCEAS, The Nature Conservancy (*www.tnc.org*), and the Wildlife Conservation Society (*www.wcs.org*), which brings interdisciplinary and transdisciplinary science to bear on the nexus of biodiversity conservation and human development (Stokstad 2011). Policymakers and managers were active participants in examining the impacts of land use and hydrological intensification in Australia (Davis et al. 2015). The US Socio-Environmental Synthesis Center (SESYNC) opened its doors in 2012 with the specific goal of accelerating synthesis for the advancement of actionable science. By 2015, SESYNC had supported over 50 synthesis teams, and 25% of the participants in those were from government, nongovernmental organizations, or businesses with a strong interest in the relevance of science to decision-making (Palmer et al. 2016). By involving decision-making organizations and practitioners at the synthesis stage of science discovery, results are more likely to be rapidly transformed into actionable science and implemented (Stokstad 2014).

Participation in synthesis-center research fosters lasting increases in collaborative behavior among the participants who pass through them (Hampton and Parker 2011, Lynch et al. 2015, Specht et al. 2015a). A wealth of studies and essays show the relationship between in-person interdisciplinary collaboration and knowledge creation (Rhoten et al. 2009, Parker and Hackett 2012, Alberts 2013). Lifting terms from the ecological vocabulary, Parker and Hackett (2012) noted that having focused time at locations isolated from outside distraction led to "hot spots and hot moments"—bursts of unusually high creativity that enable potentially transformative science. These elements are the distinguishing ingredients of synthesis centers, and evidence shows that the benefits persist and the culture of collaboration spreads outward from group members. At the National Institute for Mathematical and Biological Synthesis (NIMBioS), transdisciplinary collaborations were actively nurtured between mathematics and many other disciplines over its first 5 years of activity (figure 3). The collegiality lasts well beyond the synthesis-center activity; subsequent publication-author lists after participation in NCEAS activities showed a significant increase in collaboration and more than a sixfold greater rate of increase in coauthorship on papers than a random subsample from ecological journals (Hampton and Parker 2011). Interdisciplinary collaboration and the number of coauthors increase research productivity and impact, although the effect may take more than a decade to become evident (Hampton and Parker 2011, Van Noorden 2015). With hundreds of new participants hosted at each center yearly, collectively, these results suggest a lasting influence on scientific culture and conduct.

Insights from 20 years of synthesis

Although the NCEAS model was the blueprint for the modern synthesis center, additional insights have come from the modern family of centers that have increased their effectiveness in producing transformative knowledge. Through experimentation, common sense, and adaptive management, all synthesis centers have improved their ability to nurture innovative science, highly productive groups, and opportunities for expanding the collaborative culture among scientists. Synthesis center now interact with each other and share best practices. Furthermore, the methods of practice and the lessons learned are portable and the impact magnified if adopted by other institutions. Below, we describe some of the lessons learned that make synthesis centers successful today. In general, there are six critical ingredients, presented in no particular order, for a successful synthesis center: (1) the active management of social dynamics and intellectual space for teams by synthesis-center staff; (2) cutting-edge

Box 1. What is a synthesis center?.

Although synthesis is accomplished by individuals or groups and in settings as diverse as university departments and boardrooms, synthesis centers are specifically designed to catalyze collaboration leading to breakthrough ideas (Gray 2008, Schmidt and Moyer 2008). Among the ways they do this is by taking an active role in structuring group size, composition, and interactions; managing operational and logistical details; and providing computing and informatics capabilities. In short, synthesis centers lower the activation energy needed to generate emergent ideas by providing an environment that encourages cross-fertilization of ideas, creative thinking, and associative thinking (Rodrigo et al. 2013, Scheffer 2014). Synthesis centers offer something rare: distraction-free time and space for a group to immerse themselves in a question (Hampton and Parker 2011, Lynch et al. 2015).

We distinguish synthesis centers from primary research institutions such as universities and also from other interdisciplinary research centers primarily because the topics addressed at synthesis centers respond to the evolving questions of the scientific community and because existing data, often from many different sources, are repurposed (Rodrigo et al. 2013, Bishop et al. 2014). Small, often-interdisciplinary or -transdisciplinary teams from geographically distributed locations come together for intense multiday meetings at synthesis centers to work with existing data, theories, and ideas. These meetings repeat over several years against a background of supported virtual collaboration. The ecological and Earth-system synthesis centers represented by the authors are listed in table 1.

Table 1. The ecological and Earth-system synthesis centers represented by the authors.

Synthesis center	Topics of synthesis	Location	Funding source	Dates of operation
ACEAS, the Australian Center for Ecological Analysis and Synthesis	Ecosystems	Working groups took place throughout Australia	Australian Government through the National Collaborative Research Infrastructure Strategy	2010–2014
CESAB, the CEntre for the Synthesis and Analysis of Biodiversity	Biodiversity	Aix-en-Provence, France	Multiple funding sources through the Foundation for Research on Biodiversity	2010–present
CIEE, the Canadian Institute for Ecology and Evolution	Ecology and Evolution	Headquartered at the University of Regina, working groups distributed across member universities	Seven member institutions cover operating costs	2008–present
EOS, the Environmental Omics Synthesis Centre	Environmental 'omics (e.g., genomics and metabolomics) and including bioinformatics	St. Andrews University, United Kingdom	NERC, United Kingdom	2011–present
NESCent, National Evolutionary Synthesis Center	Cross-disciplinary research in evolution	Durham, North Carolina, United States	National Science Foundation	2004–2015
➔TriCEM, Triangle Center for Evolutionary Medicine	Improve understanding of human, animal, and plant health through the application of evolutionary and ecological principles	Durham, North Carolina, United States	Nonprofit incubator, funding from universities	2014–present
NIMBios, the National Institute for Mathematical and Biological Synthesis	Cross-disciplinary research at the interface of mathematics and biology	Knoxville, Tennessee,, United States	National Science Foundation	2009–2018
➔ NIMBios Centers of Excellence	The National Institute for STEM Evaluation and Research (NISER)	Knoxville, Tennessee, United States	NSF and contracts	2016–present
NCEAS, the National Center for Ecological Analysis and Synthesis	Ecological knowledge	Santa Barbara, California, United States	National Science Foundation and State of California	1995–2010
➔NCEAS	Applied ecological knowledge	Santa Barbara, California, United States	Various sources, including foundations, NSF, and the State of California	2010–present
Powell Center, the John Wesley Powell Center for Analysis and Synthesis	Earth system sciences	Fort Collins, Colorado, United States	US Geological Survey	2009–present
sDIV, Synthesis Centre for Biodiversity Research	Biodiversity	Leipzig, Germany	iDIV, German Centre for Integrative Biodiversity Research	2013–present
SESYNC, the National Socio-Environmental Synthesis Center	Socio-environmental synthesis	Annapolis, Maryland, United States	National Science Foundation	2012–present

Box 2. Examples of policy impacts of synthesis-center research.

Perhaps the greatest role of synthesis centers now and moving into the future is their influence on management and policy (Specht et al. 2015a). A few examples of where synthesis results have led to actions are listed below.

One of the most cited papers of all time, Costanza and colleagues (1997) was generated by an NCEAS working group. This foundational paper, with nearly 16,000 citations, established the principle of ecosystem services, with international impact leading to the Millennium Ecosystem Assessment and the establishment of the formal discipline of ecological economics.

Another particularly influential NCEAS working group concerned with theory to support the design and establishment of marine reserves convened in the 1990s (figure 1; Allison et al. 2003). The group amassed evidence of the positive influence of no-take reserves on fish stock diversity, biomass, body size, and fecundity and their associated spillover effects. This evidence contributed to the establishment of a marine protected area network in California's Channel Islands and ultimately to the development of the California Marine Life Protection Act of 1999 (*www.dfg.ca.gov/marine/mpa/intro.asp*).

Figure 1. The Channel Islands National Marine Sanctuary was established, in part, because of evidence amassed on the value of marine protected areas as a result of a synthesis-center working group. Image courtesy of Julie Bursek, NOAA Channel Islands National Marine Sanctuary.

Box 2. Continued.

The North American monarch butterfly population has plunged from 1 billion to less than 60 million over the past 20 years, possibly from loss of critical habitat (figure 2). The Monarch Conservation Science Partnership convened four times over 24 months at the Powell Center to develop robust estimates of extinction risk, regional conservation priorities, priority threats, and specific restoration scenarios. Their report informed the development of a national strategy to promote the health of honeybees and other pollinators (Pollinator Health Task Force 2015). Plans for conservation have been expanded to include habitat in Canada and Mexico through the Trilateral Committee for Wildlife and Ecosystem Conservation and Management.

Figure 2. Monarch butterfly. Photo courtesy of Jacqueline Pohl, Iowa State University.

Pollen incidence across time and space and its relationship to respiratory illness were the topics of an ACEAS working group. Their results, described in Davies and colleagues (2015), provided the platform from which to establish a national pollen monitoring system, the AusPollen network (*http://pollenforecast.com.au/index.php*). The network provides the basis to implement and evaluate the utility of current local pollen data for the improved self- and clinician-management of patients with allergic respiratory diseases such as hay fever and asthma triggered by airborne pollens. The program precipitated ongoing partnerships between public, private, and academic partners. The AusPollen Partnership established Web-based and smartphone technology to support the development of patient- and clinical-education resources through partnership with the Australasian Society of Clinical Immunology and Allergy, as well as Asthma Australia.

Many governmental entities are beginning to adopt an ecosystem-services framework for decision-making. In the United States, federal agencies have mostly relied on ecological assessments as indicators of services, but ecological features and processes are not the same as ecosystem services unless there is a direct societal benefit that is valued. SESYNC hosted a workshop and conversations with federal agencies that resulted in recommendations for best practices in integrating ecosystem services in federal decision-making (Olander et al. 2015). They outlined how to use measurable indicators that go beyond narrative description by using well-defined measurement scales that that are compatible with valuation and decision-analysis methods.

Community deliberation facilitated by the UK Environmental Omics Synthesis Centre (EOS), supported the establishment of a funded Natural Environment Research Council Highlight topic: eDNA, a tool for twenty-first-century ecology (*www.nerc.ac.uk/latest/news/nerc/highlight-topic*).

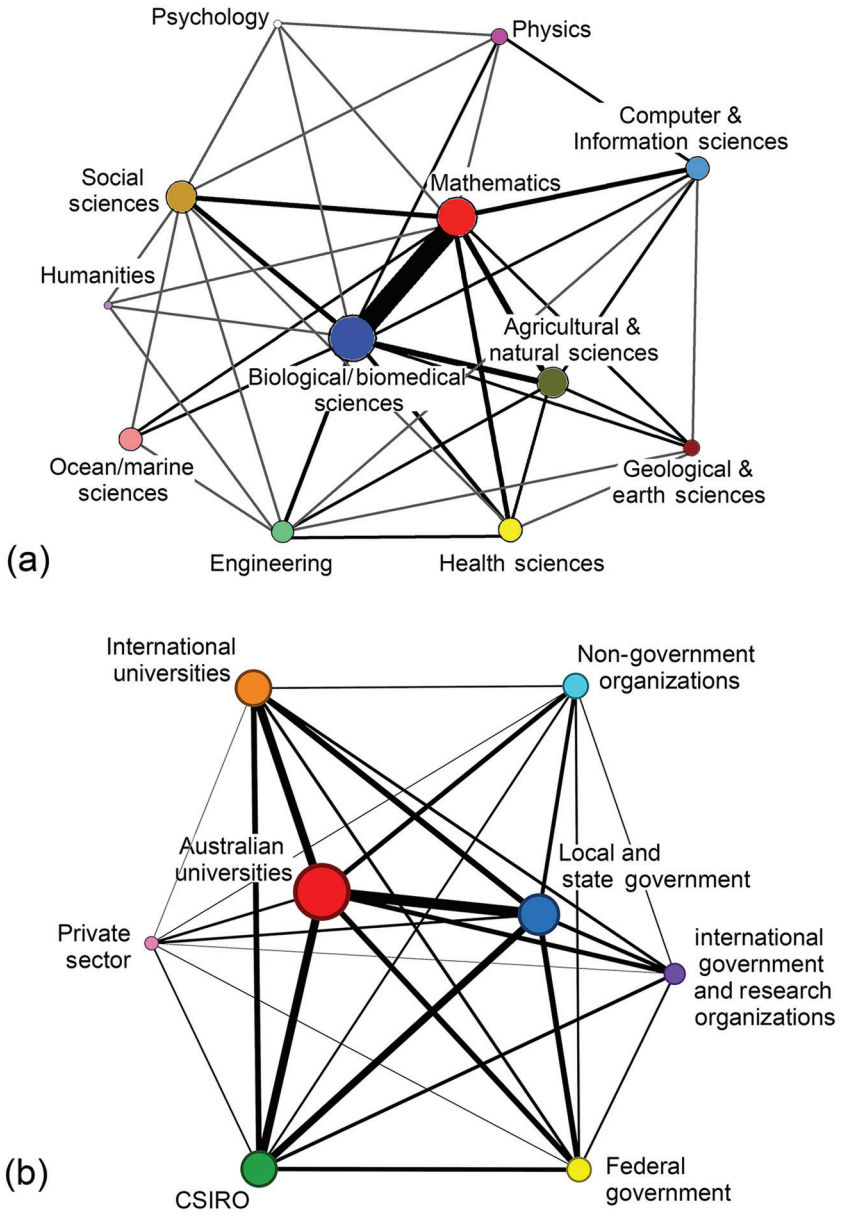

Figure 3. (a) The interdisciplinary connections fostered by the National Institute for Mathematical and Biological Synthesis (NIMBioS) for working-group participants in 2008–2012 and (b) the organizational links that the Australian Centre for Ecological Analysis and Synthesis (ACEAS) supported over the period 2010–2014. The node size represents the number of working-group participants in a given research or organizational area, where the node radius is the log number of participants. The line size represents the number of collaborations between research areas or organizations within working groups. The largest lines represent 25 (a) or 29 (b) connections, and the smallest lines represent 1 (a) or 4 (b) connections. The line width is log scaled.

computing, data management, and informatics support; (3) the organizational flexibility to accommodate the scientific and intellectual needs of working groups; (4) support for students and postdoctoral and sabbatical fellows; (5) diversity of working-group participants; and (6) the offering of time and environment for group associative thinking.

Active management. Synthesis centers are not passive entities; their staff members manage working groups to achieve success. The more diverse the collaborations, the more challenging, but many scholars are actively working to develop strategies to achieve synergy and form cohesive teams (Lyall and Fletcher 2013, NRC 2015). To help accelerate interdisciplinary and transdisciplinary team progress, SESYNC provides an array of services, including training in new methods and communication skills, assistance with codevelopment frameworks or activities, and direct facilitation of synthesis team meetings (Palmer et al. 2016).

Active management begins with a rigorous selection process. Proposals are solicited and evaluated not only for their scientific breakthrough potential and significance but also for group composition. We look for teams in which each person has an essential role. We also look for teams that include complimentary combinations of disciplines and expertise, as well as a range of career stages, genders, and ethnic perspectives. It is not uncommon for synthesis-center staff to suggest changes to group composition. Synthesis-center staff members work with working-group leaders to orchestrate productive meetings and progress toward goals before and after meetings. Indeed, the meetings are regarded as an essential component of a much longer association with the center and the working group. Working groups often use virtual meetings and common document sites months prior to arriving on site to allow the group to get to know each other and to share papers, data, and models. This allows face time while at the synthesis center to be as productive as possible. Synthesis-center staff help develop meeting agendas and goals that move projects forward. Structured talks and rigid agendas are kept to a minimum, whereas spontaneous or organized discussions and breakout groups are encouraged to pursue promising new directions or ideas. Although facilitators may help groups who do not know each other well, care must be taken to avoid poor or formulaic facilitation that can impede creative association and breakthroughs.

The ongoing evaluation of the success or failure of specific activities in promoting collaboration across disciplines, training young scholars, or producing new information is a key component of active management. There are a variety of metrics available for the assessment of activities (Bishop et al. 2014). These metrics can provide feedback for managing ongoing working groups or for organizing future activities. Evaluation also measures the extent to which synthesis centers are reaching their intended goals and provides funding agencies with much-needed information about the impacts resulting from their investment in a center.

Computing and informatics capabilities. Synthesis centers play a strong role in promoting open science, including collaboration and free access to data and results. NCEAS and NESCent were early developers of tools for the data management and publication that are today expected of all scientists. An ecoinformatics pioneer, NCEAS played a major role in advancing metadata standards and tools, data registries, online data archives, and automated workflow systems (Jones et al. 2006). Similarly, NESCent incubated the widely used Dryad data repository (*www.bioone.org/doi/abs/10.1525/bio.2010.60.5.2*), and the Australian Centre for Ecological Analysis and Synthesis (ACEAS) spearheaded the formal link between DataONE (*www.dataone.org*) and the Australian Terrestrial Ecosystem Research Network (TERN). Many of the synthesis centers offer "open-science"-style workshops to provide software and data-science training to promote collaboration, improve the synthesis process, and promote the sharing of data and tools. These tools and partnerships provide opportunities for participants to discover, reuse, and repurpose data to extract new and significant knowledge and to deliver synthesized data in a sophisticated manner.

Most working groups comprise a range of specialists, and they learn from each other and synthesis-center staff members in the process of their activity (Specht et al. 2015b). For some participants, the data and informatics education acquired may be skills rarely required in other parts of their working lives and an important outcome of participation. Few working groups have team members with real data-science or informatics backgrounds, and members may be unaware of relevant innovative methods, techniques, and technologies that can either be employed or augmented by the working groups. Synthesis-center data-management specialists help with working groups before, during, and after meetings to acquire and organize data, compile databases and models, and offer the opportunity to make the most out of the data with which they work. Synthesis-center staff members also assist in the publication of the synthesized data, thereby continuing the cycle.

Flexibility. Flexibility is fundamental to giving working groups the tools and the time needed to produce the best results. Specifically, we refer to maintaining flexibility with respect to topic, length of working-group activities, scheduling, and especially meeting structure (Bishop et al. 2014). The ability to recognize and accommodate individual and group needs can make all the difference when it comes to attracting the right student, postdoctoral, or sabbatical fellow; making sure the right people can attend working groups; and encouraging the intellectual dynamics of different types of people. When surveyed, the participants of both NIMBios and ACEAS activities identified flexibility as important to achieving their goals (Bishop et al. 2014, Lynch et al. 2015).

Student and fellow support. The template for student, postdoctoral, or senior fellows differs among centers. At NSF-funded centers and the Synthesis Centre for Biodiversity Research (sDIV), fellows work at the center, where they interact productively with each other. There are other models, such as at the US Geological Survey–supported Powell Center and in the United Kingdom, France, and Canada, where fellows are independent and geographically distributed among investigators engaged in synthesis-based research. All fellows are dedicated to the working group for 1 to 3 years and often compile data, develop and run models, write manuscripts, and maintain connectivity among the participants. For working groups, the benefit of having a dedicated postdoctoral researcher or fellow is substantial, particularly in terms of overall productivity (Hampton and Parker 2011). The benefits to fellows and working groups alike persist through time, fostering collaborative behavior, multiauthored papers, and competitiveness for jobs (Hampton and Parker 2011).

Diversity. There are direct intellectual benefits to teams that are diverse in gender, age, career stage, ethnicity, and discipline beyond the laudable goal of developing a scientific workforce that mirrors the national population. The overall performance of groups, termed *collective intelligence* by Woolley and colleagues (2010), increases with higher average social sensitivity of group members and is correlated with the proportion of women (Bear and Woolley 2011). Entire fields such as global health and sustainability science have arisen from the interdisciplinary and transdisciplinary cross-fertilization of ideas, in which methods or concepts from one discipline serve to spark new ideas in others (Whitfield 2008, Uzzi et al. 2013). Often called *convergence*, integrative thinking and analysis foster the emergence of new scientific principles and solutions to complex, vexing problems (Sharp and Langer 2011).

The value of unstructured time. Personal interactions are vital to collaborative efforts to inspire new ideas, in part because face-to-face meetings stimulate the "random collision of ideas and approaches" in ways that remote meetings do not (Alberts 2013). Stein and Stirling (2015) identified three aspects of group dynamics that not only ensure "civil" debate but also go beyond to foster the relationships that lead to emergent understanding. Unstructured group time outside the meeting room was built into every working-group

meeting. Unstructured activities foster friendship and trust rather than confrontation and help free the mind from the logical thought patterns that are the trademark of scientists (Scheffer 2014, Stein and Stirling 2015). Ground rules were set for involvement: The participants would be allowed to argue passionately for their personal views but would also then have to identify and acknowledge the weaknesses of their approach. Finally, group discussions around the table were egalitarian; no one person was in control.

This latter idea of letting the brain roam creatively among different ideas, methods, and thoughts is termed *associative thinking* by psychologists. Associative thinking is linked to creativity, and opportunities to foster it among groups of knowledgeable scientists are provided by synthesis centers. Scheffer (2014) writes, "The best science seems to come from a balanced mix of rationality and adventurous association." Synthesis centers do not have a lock on stimulating group encounters that lead to breakthroughs, but associative thinking is one of the signature opportunities provided by these facilities. In fact, it might be one of the most important values of synthesis centers: a brew, mixture, or special sauce of time for creative unstructured thought and discussion fueled by good coffee, food, beer, and pleasant surroundings (Hackett et al. 2008, Scheffer 2014).

Sustaining synthesis centers

The need for scientific synthesis is certain to increase in an ever more connected and environmentally challenged world with growing awareness of common societal challenges. Exceptional prior investment (up to $34 million USD per center) combined with a unique culture of collaboration, integration, and achievement provide synthesis centers the capability to address future challenges to the benefit of society and governments in a highly cost-effective manner. As we noted above, successful synthesis is as much a cultural transformation as it is a set of tools. The growth of this culture is difficult and expensive. Therefore, to maximize the return on government investment in science, we should consider the long-term benefits of continued federal support.

Financial security poses the greatest challenge for the long-term sustainability for any center, especially for supporting infrastructure, defined as not only the physical space and associated computational resources but also the informed and expert staff who enable a center to function. Synthesis centers also face the challenge of finding support for basic-science missions and projects, generally only the purview of government funding. Although successful transitions from centralized funding demonstrate the importance of investment in specialized personnel and infrastructure, they often also result in a narrowing of focus.

Although aspects of scientific synthesis can happen without the existence and support of centers, two highly successful and impactful attributes are particularly challenged in the absence of dedicated infrastructure: (1) the working-group approach to synthesis and (2) the nurturing of collaborative and interdisciplinary behaviors, particularly among younger scientists and fellows. Important as these are in the developed world, interdisciplinary collaboration can be catalytic for scientists from developing and transitional countries. There are a number of viable options for overcoming these challenges, although none are simple. Five case studies of transition or closure provide insight into the challenges and opportunities for sustainability.

Case study 1. NSF funding for NCEAS ended in 2010. Several key changes to the mission and funding strategy have allowed NCEAS to continue and thrive. A diverse funding portfolio has been built around a stronger emphasis on applied questions, including partnerships with Science for Nature and People Partnerships (SNAPP) and the State of Alaska Salmon and People (SASAP) funded by private philanthropy and foundations, as well as project-based science supported by an array of funders (including NSF).

Case study 2. NSF funding for NESCent ended in 2015, but the infrastructure was repurposed to become the Triangle Center for Evolutionary Medicine (TriCEM), a smaller center with a different mission (evolutionary medicine; *http://tricem.dreamhosters.com*) that focuses on engaging local scientists associated with the consortium of universities that now provide its funding.

Case study 3. NIMBioS is 2 years from the end of its NSF funding and has begun to explore sustainability options. Their strategy is to establish "centers of excellence" under the existing NIMBioS infrastructure. The first of these centers, the National Institute for STEM Evaluation and Research (NISER), has recently been launched, capitalizing on the evaluation experience of NIMBioS to offer external evaluation services to the STEM research and education community. Other centers of excellence are in development, with the hope that they will generate the necessary revenue to support a continuing mission of high-quality interdisciplinary education and synthesis-focused research.

Case study 4. The Canadian Institute of Ecology and Evolution (CIEE) arose in 2008 as a consortium of universities and academic research societies dedicated to synthesis using a geographically distributed funding and operational model. Member organizations pay annual fees to support working groups and training activities across Canada, a process that favors flexibility and regional participation but sacrifices long-term computational and postdoctoral-student support. Challenges to this system include a lower annual budget, slower development of the "culture of synthesis," and vulnerability to membership turnover or donor fatigue.

Case study 5. The Australian Centre for Ecological Analysis and Synthesis (ACEAS) was established as a component of

an ecological observatory network supported by government science infrastructure funding. It closed its doors permanently in 2014 after 4 years successfully fostering synthesis activities. ACEAS was a victim of declining funding because priority for scarce resources was given to primary research.

One solution is to adopt a long-term funding model for synthesis centers based on the provision of communal infrastructure. Examples of long-term, sustained funding include the USGS-supported Powell Center, the NSF Long Term Ecological Research (LTER) program, and the "national capability" initiatives of the United Kingdom (e.g., the Environmental Omics Synthesis Centre, EOS; *http://environmentalomics.org/omics-synthesis-centre*). The provision of consistent federal funding supports the infrastructure essential to data-intensive, culturally diverse analyses at the nexus of the synthesis approach. Such support is further justified because synthesis centers serve a large community within and among disciplines (e.g., 500–800 unique participants each year). In addition, synthesis centers are basic scientific infrastructure, like telescopes for astronomy or ocean vessels for oceanography, which enable advancements beyond the fiscal capabilities of individual research organizations. This infrastructure will evolve and adapt to scientific and social requirements but must exist first for innovation to happen. In particular, with the near-exponential growth of scientists and products (data, analytical systems, and publications), the need to extract value from existing data for the benefit of society will continue to grow. Synthesis centers represent the essential cultural transformation needed to allow scientists to exploit this opportunity.

Conclusions

When we think of research infrastructure, most people imagine complex equipment such as particle accelerators, radio telescopes, sophisticated imaging and sensing equipment, research vessels, supercomputers, and other "hard" objects—and rightly so, for these are all important tools that aid scientific discovery within disciplines. However, science is increasingly being asked to help address important and enduring global change and societal and human-health challenges that cut across multiple sectors of society and disciplines and that may require us to make sense of existing large-scale and heterogeneous data. Places and processes that accelerate the rate at which information from different sources and perspectives is transformed via synthesis into knowledge that can be applied toward solving problems are desperately needed (Wilson 1998, Carpenter et al. 2009). Synthesis centers serve this role. They will be needed more than ever going forward. As infrastructure, synthesis centers may not be as tangible as telescopes, but technology alone cannot match the brain power of a diverse group of experts who are committed to focusing their combined insights, experience, tools, and networks on a shared problem in a collegial environment.

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