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Practices for facilitating interdisciplinary synthetic research: the National Socio-Environmental Synthesis Center (SESYNC)

Margaret A Palmer[1,2], Jonathan G Kramer[1], James Boyd[1,3] and David Hawthorne[1,2]

This paper describes the programs and processes of a new center designed to enhance interdisciplinary team effectiveness and the building of new communities of social and natural scientists undertaking socio-environmental synthesis research. The theory and organizational structure of the center is motivated by research on interdisciplinary team science from diverse social science fields. A set of core practices was developed to catalyze the formation of new teams, facilitate team development of shared conceptual frameworks and provide customized support for teams that have challenging methodological, computational, or group dynamic issues. The vast majority of the 58 teams thus far have self-reported good progress and positive team experiences and have published extensively. Most teams took advantage of one or more forms of customized support: 21% of the teams used facilitation services, 38% support for meeting design or for resolving problems that hindered team progress, and 46% of teams used advanced computational support. Throughout, we describe the most common problems teams encountered and provide perspectives on factors and practices that may best promote positive interdisciplinary outcomes on synthesis research by teams of social and natural scientists.

Addresses
[1] National Socio-Environmental Synthesis Center, 1 Park Place, Suite 300, Annapolis, MD 21401, United States
[2] University of Maryland, College Park, MD 20742, United States
[3] Resources for the Future, Washington, DC 20036, United States

Corresponding author: Palmer, Margaret A (mpalmer@umd.edu)

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Introduction

A future with vibrant natural systems that support human health and well-being requires behaviors, decisions, and policies informed by close collaborations between natural and social scientists. The need for collaboration at the interface of social and natural systems has motivated a new generation of scholars to undertake interdisciplinary research (e.g. [1–3]). This socio-environmental research (Box 1) is particularly difficult not only because of the enormity and complexity of the issues it addresses, but also because of the many challenges that come with interdisciplinary team efforts, some of which include non-academic stakeholders [4].

To address such challenges and build community capacity to tackle environmental research problems in teams with high levels of disciplinary diversity, the National Socio-Environmental Synthesis Center (SESYNC) was launched in 2011 with funding from the U.S. National Science Foundation (NSF). The center supports newly formed research teams from anywhere in the world to work collaboratively at its facility. The teams synthesize existing theories and data to advance understanding of socio-environmental systems and our ability to solve environmental problems. Participants in center activities come from a range of disciplines and sectors (including academic, NGO, governmental, and business institutions) and most teams include both social and natural scientists.

SESYNC's programs and operational strategies were motivated by its leadership team's past experience with synthetic cross-disciplinary research and by research from many fields, including cognitive and social psychology, the science of team science, interdisciplinary studies, organizational science, and adaptive management [5,6•,7•,8,9]. While the center has diverse programs that span postdoctoral training, higher education pedagogy, computational capacity and workshops in support of socio-environmental (S-E) research [10], here we focus primarily on the center's methods for accelerating progress by teams of researchers engaged in S-E synthesis. We first provide a brief background of the Center's overall mission, the core objectives associated with that mission, and the efforts to accomplish those objectives. We discuss the major challenges posed by integration and synthesis efforts, and review the evidence of progress in supporting teams as they confront those challenges. We close with lessons from the Center's first years of operation and the way in which our strategies have adapted to those lessons.

Box 1 SESYNC glossary

Socio-environmental (S-E) system — tightly linked social and biophysical subsystems that mutually influence one another. The study of S-E systems and research collaborations to understand their dynamics involves many different scholarly traditions. Sometimes the term is used interchangeably with 'socio-ecological' but ecologists are not the only natural scientists on teams.

Socio-environmental research at SESYNC — the study of co-dependent human and natural systems including their structure, dynamics, and sustainability. At SESYNC this involves fundamental synthesis research that is relevant in multiple contexts spatially, temporally or culturally.

Interdisciplinarity — the process of integrating knowledge from different disciplines and sectors to address a research problem. For the purposes here, we do not distinguish it from transdisciplinarity which some view as a higher-order process (more integrative, potentially transformative) while others use it to refer to the practice of including knowledge-users or stakeholders as participants in the production of knowledge. Each of these characterizations of transdisciplinarity can be found among the research teams SESYNC supports.

Actionable science — SESYNC uses this term to describe research of a fundamental nature that has the potential to inform decision making on the part of policy makers, non-governmental organizations, businesses and citizens. This research is informed by non-academics to help frame research questions that emphasize solutions to socio-environmental problems, provide guidance on policies and institutions affecting environmental decision-making, and communicate with broader audiences. The resulting concepts, approaches and solutions may be broadly relevant to understanding S-E systems and problems extending beyond the specifics of place-based research.

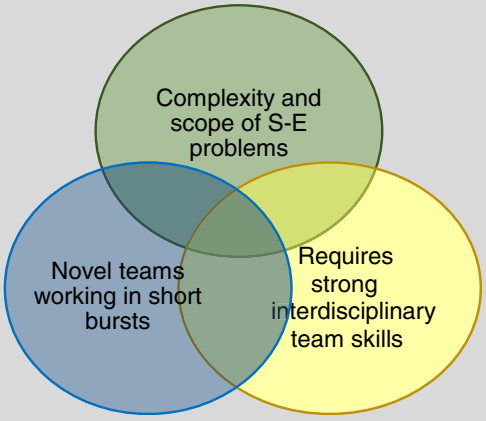
Center mission, unique aspects and challenges

SESYNC's mission is to support synthetic, actionable team science on the structure, functioning, and sustainability of socio-environmental systems. To accomplish this, five core objectives were identified: enhance the effectiveness of interdisciplinary collaborations among natural and social science research teams focused on environmental problems; build capacity and new communities of socio-environmental researchers; provide education programs to enhance interdisciplinarity and understanding of S-E synthesis; enhance computational capacity to promote socio-environmental synthesis; and, enhance relevance of socio-environmental research to decisions and behaviors via actionable scholarship. This paper focuses on the first two of these objectives.

The SESYNC leadership combined an experimental organizational approach with a developmental evaluation approach [8,11,12•] for designing, implementing and adapting a set of linked practices to achieve these objectives and overcome many challenges to effective team work (Box 2). The set of practices together with the reciprocal interactions and mutual learning between team members and SESYNC leaders we call the '*SESYNC process*' (Figure 1). This process, the way the center's

Box 2 Intersecting challenges for socio-environmental synthesis team research

Challenges to enhancing the effectiveness of research teams and to building new communities with the capacity to undertake synthetic socio-environmental team research. The majority of SESYNC teams face three types of distinctive barriers to effective collaboration.



1. Novel teams working in short bursts

- Many team members have not previously collaborated
- Members only interact a few times a year and do so in intense multi-day sessions
- Teams must rely on existing data and knowledge, not original collection of 'field' data
- Teams often face difficult computational challenges

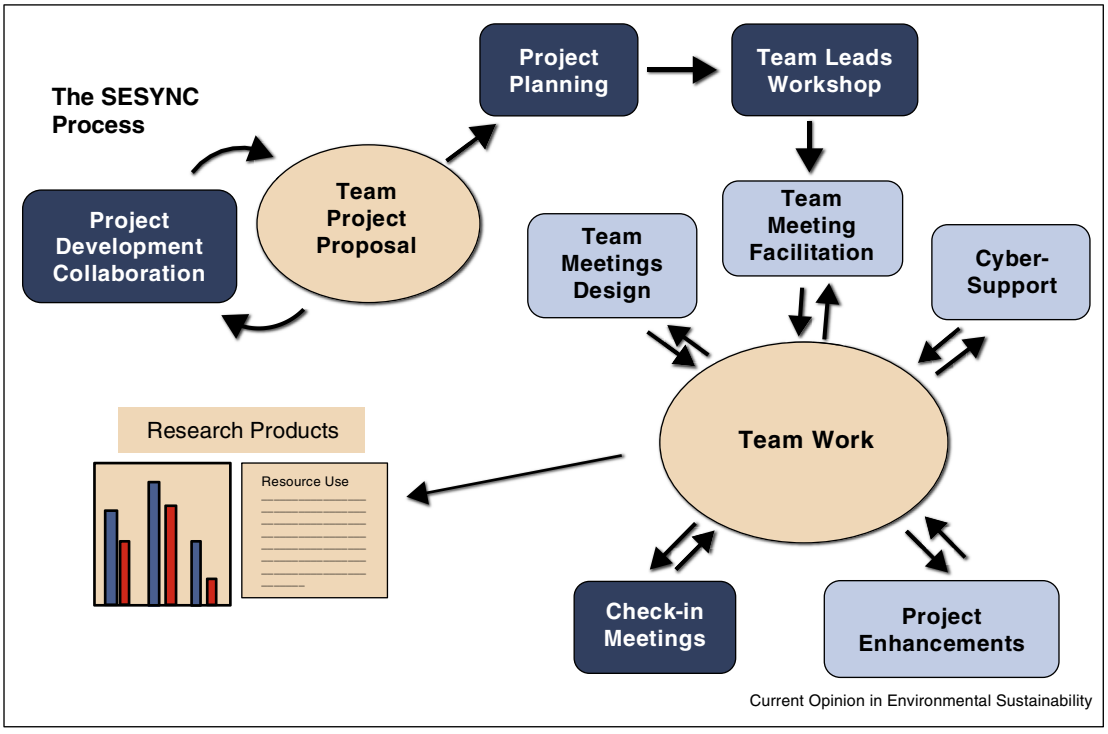
2. Complexity and scope of socio-environmental problems

- Multiple ways to view problems and multiple solutions
- Disciplines needed for analysis may be difficult to identify and recruit
- Projects must be broadly relevant to sustainability solutions
- Aspects of problem are often mismatched in terms of spatial and temporal scales
- Integration of qualitative and quantitative data often required
- High degree of uncertainty is associated with data or needed data is unavailable
- Value-laden research topics can lead to philosophical conflict within teams
- Lack of understanding or respect for methods from different disciplines may be viewed as an incompatibility (e.g., grounded theory versus falsifiable a priori hypothesis)

3. Requires strong interdisciplinary and cross-sector team skills

- Language/epistemological differences must be overcome to reach joint understanding
- Group size (too large/small) may impede progress in integrating across disciplines
- Too little/too much familiarity among participants (lack of team cohesion; cliques)
- Perceived or real power differences and/or disciplinary dominance within group
- Lack of flexibility or leaders pre-determine process and path forward
- Uncertainty over goals or lack of shared goal
- Inadequate communication and lack of clarity on each participant's role(s)
- Extended time/effort required to initiate research projects

Figure 1



The SESYNC process is a set of reflexive practices for fostering team progress in which staff iteratively engage with team members over the life of their research project. Each dark blue rectangle indicates a group of SEYSNC practices that all teams have access to; light blue rectangles are groups of practices that a subset of teams have utilized (see subsection *The SESYNC process* for a full explanation of each practice).

leadership and staff engage with research teams and with one another, has evolved throughout the lifetime of the center.

Most of SESYNC's research teams face challenges arising from three distinct sources (Box 2). First, because SESYNC hopes to help build new collaborations, the center does not fund teams in which most of the members have previously collaborated. We refer to these as 'novel teams' and research has shown that such teams face more challenges than teams in which most individuals have previously collaborated [6•]. This is particularly true for SESYNC teams because they work together only intermittently in 'short bursts' (3–5 days several times over each of 2–3 years) and thus have relatively little time for interpersonal and intellection interaction. Second, SESYNC teams include members from multiple sectors (academia, government, NGO, business) and many academic disciplines. Third, SESYNC teams are called on to synthesize existing knowledge to address socio-environmental problems that are complex and broad in scope (so-called 'wicked problems'). An additional challenge for some teams stems from SESYNC's focus on 'actionable scholarship' that is also fundamental in nature (Box 1). This differs from many sustainability or 'solution' centers that focus on more place-based issues such as water management in a specific region, the design of a new conservation program, or the measurement of a regional policy's effect on stakeholders [13–15].

SESYNC does have some attributes in common with other centers. Many institutions have research teams focused on environmental problems that require both social and natural scientists and, in some cases, nonacademic participants [7•,16]. Additionally, there are a handful of NSF-style synthesis centers (summarized in [17]), which like SESYNC support teams that only meet intermittently to integrate existing data. However, we know of no other center designed to address the three sources of challenges (Box 2) simultaneously.

The center as experiment

These challenges and the complex ways in which they can interact to influence collaboration led to a center design focused on tailoring support services to the unique needs of each research team, needs which can change over the lifetime of a team's project. The need for services also varies across teams depending on their topic, team composition and the amount of experience they have with interdisciplinary interactions. Drawing from scholarship on interdisciplinarity, organizational science, and team science and cognition (e.g., [6•,7•,8,18,19••]), as

well as our own experiences and intuition, we identified a set of core *practices* that include different types of engagement between SESYNC staff and team members as well as different services and programs (Figure 1).

These practices were conceived as 'hypotheses' on how we could foster effective teamwork. We adopted a developmental evaluation to continuously gather information as we implement practices and to adapt to research teams' needs ([12•], page 5). The leadership and staff collect quantitative information on team demographics, which practices are used by different groups, and team progress. Qualitative data is obtained from direct observation of teams, discussions with team members, and from written comments in response to queries to teams on their progress and experiences. An external evaluator with extensive experience in the evaluation of academic research centers collects quantitative and qualitative (interviews) information from a subset of teams and from SESYNC staff. Such an independent evaluator was not required by the NSF but was hired by SESYNC to provide independent feedback to the leadership during our early formative years.

The information gathered is discussed among center leadership and staff and often results in rapid changes to center processes. This has required an organizational commitment to collective reflexivity [20] within the context of meeting our objectives. The art of questioning is central to center operations — *what happened when we implemented this practice/set of practices? Why did it happen? What can we do to improve the next outcome?* While this *reflexive-adaptive process* was initially implemented only by the leadership, over time we built additional mechanisms to embed this learning-from-experience process into all center programs and activities that support synthesis teams (including our computational and educational programs). Leadership encourages staff to articulate and, as appropriate, archive observations. Interest in, and aptitude for, this kind of interaction varies across the staff, but most are quite open to discussion and experimentation.

It is important to emphasize however, that because our goal is to maximize each team's success, we are not conducting a true experiment that differentiates between treatment groups that receive SESYNC services and control groups that do not. To the extent that the SESYNC process is considered an experiment, SESYNC leadership is a part. In fact, to say that SESYNC practices evolved, is to say that we changed; how we engaged and what we 'know' both tacitly and explicitly changed over time.

The SESYNC process

The practices SESYNC developed to enhance team success fall into eight categories (Figure 1). Almost all of the practices involve recursive interactions between the staff and team members. Because the leadership and staff have a service ethos, we make every effort to provide as much support (i.e., access to practices) for every team as possible. Some of the practices below are provided for almost all teams. Others are provided only for those that request the services (e.g., meeting facilitation) or those we believe will particularly benefit from a specific intervention. In some cases a practice had not yet been developed at the time the team formed. In a few other cases, teams worked quite independently of us by their own choice.

Collaborative project development

Given the mission to build capacity in S-E research, SESYNC leadership and staff discuss and provide feedback to teams on proposed projects, and iterate with the team leads to revise proposals based on input from expert reviewers. A highly interactive panel review process facilitated by SESYNC leadership is designed not only to identify strong proposals, but to explore how projects might be improved by sharpening questions or considering new methods, clarifying conceptual frameworks, expanding or changing team composition (expertise, disciplinary diversity and degree of prior collaboration), or consideration of additional data.

Project planning

Prior to the first meeting of a team, the leads (PIs) participate in individualized webinars with a core set of SESYNC staff that focuses exclusively on their project. This discussion gives all a better understanding of the scholarly problem and further introduces the PIs to the resources at the center. A set of standard queries is posed, examining issues regarding data (access, amounts, quantitative or qualitative nature), logistics and anticipated epistemological hurdles associated with the interdisciplinary team. Special emphasis is placed on the central role(s) team leaders play in promoting effective team process.

Team leads workshop

Team leads of projects funded by SESYNC come together with PIs from other projects funded about the same time for two days of interactive work; often the PIs are part of a common SESYNC research theme (e.g., 'biodiversity and ecosystem services'). Team leads share their research framework and early project management approaches as well as data and proposed methods. They also discuss team composition and participate in sessions focused on the challenges of managing an interdisciplinary research effort. The workshop provides an opportunity for teams to discover joint interests, potentially form new collaborations, and engage in an explicit discussion of team dynamics.

Team meeting design

For a number of teams, advice on effective meeting structure is very useful. Meetings with SESYNC staff

(in person or remotely) are offered to focus on pre-meeting activities and specific goal oriented agendas that balance group work with time for individual reflection.

Team meeting facilitation

Meeting facilitation is also offered to all teams. In most cases, this requires a significant interaction between the facilitator and the team leads. The facilitator (a SESYNC staff member with extensive experience working with socio-environmental teams) becomes knowledgeable of the problem and the language of the scholarship before the first meeting and tailors the facilitation process to the specific team needs and preferences. Facilitation, particularly in projects' early phases, often focuses on the development of a shared conceptual framework and is designed to enhance the involvement of all team members and the sharing of diverse perspectives on the problem (see below, *Challenge 2. Complexity and scope of S-E problems*).

Computational support

A comprehensive list of computational, database and communication support tools are made available to all teams working at SESYNC. A dedicated 8-member team of computational and IT experts is available to help in advance of or during team meetings. These experts work to understand the unique needs of each research effort and often assist as participants combine and analyze diverse (quantitative and qualitative) types of data. SESYNC staff spend considerable time assisting groups in pre-processing data sets and identifying analytical methods. Ongoing engagement between these staff and team members is a key component of SESYNC's support structure.

Check-in meetings and project enhancements

Staff and leadership utilize both informal and formal opportunities to gather information from teams as they progress with their project. Team reporting, casual conversations and shared lunches with teams in residence as well as structured meetings and webinars with teams reveal both progress and ongoing or emergent challenges. In many cases, leadership and staff use this information to provide additional support (e.g., fund a new team member from a different discipline, provide computational support, training for a team member or additional facilitation). These interactions also provide opportunities to link teams with potentially shared interests and to invite new projects.

Relationship between the SESYNC process and challenges

Some of the challenges we list in Box 2 have been the subject of extensive scholarship, a review of which is well beyond the scope of this paper. However, as we briefly describe them we provide useful citations for readers new to the material. While we describe the challenges separately here, in reality, they interact in complex ways for SESYNC teams. Our practices can therefore assist teams in multiple ways. The goal for center leaders and staff is to apply their skills in an integrative and iterative fashion as challenges emerge over the lifetime of a team's project. Depending on the project and team composition, teams may experience all three of these challenges, some subset, or if team members have extensive experience in interdisciplinary S-E team work, none of them.

Challenge 1. Novel teams working in short bursts

Synthesis centers have been recognized as serving an important role as incubators of research innovation [17,21,22]. They provide facilities that allow teams that meet infrequently to 'sequester' themselves in an environment designed to provide state of the art collaboration space and they all work to provide an intellectually exciting atmosphere. At SESYNC we have the additional mission of motivating the formation of new communities of collaborators, which is challenging given the general lack of familiarity researchers have with one another across such diverse disciplines. The acceleration of progress by novel teams that meet only infrequently has received no scholarly attention to our knowledge. Researchers have shown that developing some social cohesion facilitates productive collaboration [23,24,25••].

To help overcome these challenges, we focused initially on the critical role that team leaders play in the formative stages of projects. Pre-meeting activities that provide a clear introduction to the project are often important and emphasis is placed on the first face-to-face meeting, as it is essential to establishing a team culture that can sustain momentum throughout the project. We often suggest that teams utilize specific introductory activities that go beyond typical 'icebreakers' to reveal how individuals think of themselves in relation to the project and their conception of S-E systems in general. Consultation also helps in the development of meeting agendas that provide adequate time for team interactions to address epistemological and semantic barriers, methodological diversity, and development of shared team goals. Because the members of teams are from many parts of the world and meet infrequently, discussions in advance of each meeting on how team tasks can be accomplished in the meeting's time frame, developing a strategy for communication, and one for coordinating the project across time can lead to more successful team outcomes [26]. SESYNC's role in this is to motivate the leads to prepare and identify ways in which SESYNC services can help their project. Because the time for teams to work together on their project is short, this pre-meeting stage with SESYNC staff is particularly helpful in identifying computational support we can provide so the team can start work quickly. We have found that relatively few teams begin with the skills needed to manage and synthesize highly heterogeneous types of data common to S-E research.

Challenge 2. Complexity and scope of S-E problems

Socio-environmental (S-E) research involves ambiguity, uncertainty, and incomplete knowledge. S-E science is a young research field and like other emerging research fields, it is still defining its intellectual boundaries, community of participants, and methodological practices. For many SESYNC groups, those with expertise in one area (e.g., hydrology) typically do not know experts from other areas (e.g., the sociology of design) yet both are needed to address a problem of mutual interest (e.g., sustainable urban storm water infrastructure). These challenges are further complicated by the ambiguity of socio-environmental problems — where does the boundary of the issue lie? How do we define a soluble S-E problem and decide how to study it? For example, one team member may view a pollution problem as a social equity issue while another views it as a technological issue. The two viewpoints suggest there are not only multiple ways to define a problem but multiple solution pathways using very different types of data, which is a characteristic of most S-E problems. Teams focused on S-E problems must navigate such different perspectives and ideally agree on how they will conceptualize the problem and the implications that has for the conduct and relevance of their work.

Once they embark on their research, teams can be faced with high levels of uncertainty associated with complex systems dynamics (nonlinear interactions among components, adapting agents, etc.), incomplete knowledge of environmental and social processes, and data limitations [27,28]. These uncertainties can be overwhelming, especially when participants are already dealing with the challenge of multiple potential approaches to a given problem [29]. Conflicts can arise if team members disagree on methodological approaches such as the validity of combining qualitative information (e.g., ethnographic information on the impacts of pollutants on people) with quantitative data (e.g., point-measurements of pollution loads across space) to address their problem. In these cases, a sort of 'group paralysis' can emerge.

SESYNC efforts to help overcome these challenges start with the development and review of proposals and continue as staff and leadership interact and build relationships with PIs and teams. Because they may not know what disciplinary expertise could be essential to their synthesis effort, prospective match-making by SESYNC during team formation is often important and most PIs and teams are very receptive to this input. We also actively seek ways to foster linkage across teams in formal and informal ways like organized events at SESYNC designed specifically to bring different teams together in relaxed settings to help expand collaborative networks across disciplines and sectors.

Facilitation is also useful to help teams bridge differences in vocabulary, methodology, and epistemology [30]. Facilitated sessions at SESYNC often focus on development of shared conceptual models. Concept-mapping or toolbox type exercises help team members externalize their understanding of problem components through verbal and nonverbal (often hand drawn images) means [31]. External representations (e.g., diagrams, maps, mathematical models, etc.) can play an important role in the development of useful boundary objects and can provide initial frameworks for teams to collectively accept or challenge as research progresses [32•,33]. Studies of macro-cognition in teams [34] emphasize that information sharing and the development of shared mental models is essential in high performing teams.

For teams that make use of SESYNC's facilitation services, we also help them focus on the role of each individual in the project and differences in individual perceptions of project goals as well as differences in the incentives that motivate members to participate for example, did they participate to solve a policy problem, to publish a paper, or to build research networks? Focusing on this early in the team process can help the team form a joint identity as well as reinforce respect for what each member brings to the project [19••,26].

Coping with high levels of data uncertainty as well as the need for creative approaches for integrating knowledge can also complicate dynamics among team members who may want to simplify problems by ignoring factors or approaches that seem foreign to them. While some teams are very good at moving past methodological roadblocks others with less experience in interdisciplinary research find this to be difficult. When we are aware of this, we introduce them to methods for integrating diverse types of knowledge (e.g., triangulation or mixed methods, systems approaches, quantitative case study analysis, meta-studies [35,36]) or to researchers with the expertise in this area. Scenario-based approaches and agent-based modeling can also be helpful and some of the leading experts in the use of these approaches are on SESYNC teams. However, these approaches are new to others; many natural scientists visiting the center have had little or no experience in integrating qualitative and quantitative approaches [37]. SESYNC's computational staff is available to help either in the form of project-specific technical assistance or leading organized learning groups.

Challenge 3. Requires strong interdisciplinary and cross-sector team skills

Practices for effective interdisciplinary team science are largely under-developed, especially for S-E research [7•]. As Lyall and Fletcher [38] have emphasized, the development of strategies to achieve synergy and form cohesive interdisciplinary research teams remains a key research challenge. There are major efforts underway by scholarly communities to advance knowledge on how best to facilitate such interdisciplinary research collaborations, prepare

students for engaging in them, and transform institutions to promote their formation [19••]. Yet, this research field is largely still at a stage of building theory and trying to identify 'best practices' [7•,19••]. Most of this work has focused on medical research, engineering, and military teams (e.g., [39,40]). Among the interdisciplinary teamwork challenges we have observed for SESYNC teams (Box 2), three have been particularly common.

First, two or three individuals generally develop SESYNC proposals, so there can be a tendency for them to pre-determine the project's direction, sometimes in a top-down way. If this happens, there is less flexibility and potentially less creativity, since most decisions are made by only a few team members [28]. In these cases, perceived or real power imbalances in the group can lead to an overall negative experience by some members that discourages them from participating fully in the project and potentially in the future on other team-based efforts [19••]. Second, without intervention many teams do not allocate sufficient (or any) time during their first meeting to develop a shared (i.e., co-developed) concept of the research problem and how best to address it [39]. Skipping this step not only limits the opportunity for innovation, but can also potentially exclude the perspectives or input of individuals on the team. This can disenfranchise members and in the worst case reduce the research process to a disciplinary or multi-disciplinary mode [5]. Third and most commonly observed for SESYNC teams, is inadequate communication among team members on the status of progress, who is doing what, and what is to happen next. Effective communication is critical to team progress [28], without it, a tremendous amount of time can be wasted as the group has to revisit the same territory ('reinvent the project') each time they meet.

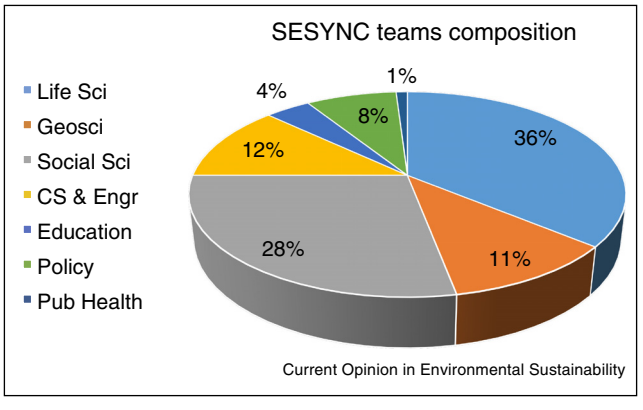
Many of the practices mentioned earlier are relevant here and we apply them in both formal and informal ways to help build capacity for interdisciplinary teamwork. For instance, team leads are asked to pay attention to and be responsible for, not only research methodology and outcomes, but also for the teamwork process. While some of this involves 'simple' project management and effective communication we also emphasize more specific team science issues. For instance, we ask team leaders to consider periodically switching their role from leading to observing process as an 'outsider.' This helps in developing a process framework and a greater awareness of their own skills, and the relative strengths of team members and how they interact and contribute. As conflicts arise, leads often consult with SESYNC staff. In some cases re-structuring agendas is effective (e.g., adding a mix of team sessions with individual work and informal time to socialize). When more pervasive challenges emerge, facilitation can help air latent issues and provide a way forward. In many cases, these sessions are effective because they allow leads to participate 'simply' as team members. As possible, we use briefings with leads to make explicit what teamwork strategies were used and to jointly assess effectiveness, alternatives and additional support needed. This process is designed to foster a reflexive approach among PIs and entire teams.

Evidence of progress

Team composition and problem focus

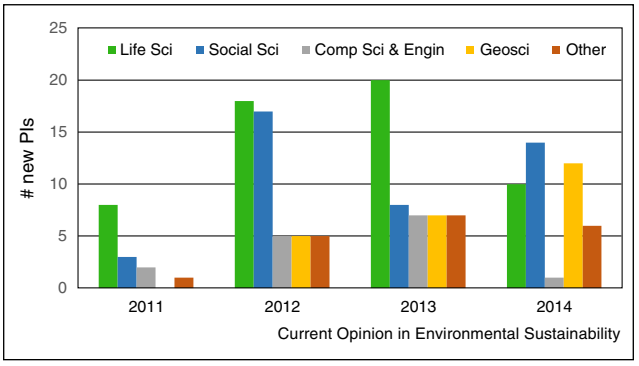
With approximately 1700 participants involved in over 100 synthesis efforts between 2011 and 2015, SESYNC has been effective in attracting new communities of collaborators to the center. Their disciplines represent a broad cross section of expertise relevant to S-E problem solving (Figures 2 and 3). About 25% of participants at SESYNC come from non-academic settings (government, NGO, business, etc.). Support for young scholars, especially postdoctoral fellows and graduate students, has been a priority at SESYNC. Thirty-two postdoctoral fellows and over 90 graduate students have participated in various programs including leading their own team synthesis projects; these young scholars span the fields of anthropology, economics, ecology, engineering, hydrology/earth science, political science, sociology, and geography. Whether senior or junior in research status, projects involved learning to work with new collaborators. Across all the projects supported through 2014, on average, about 50% of team members have not previously collaborated. The network of collaborations that existed before team formation varies greatly among teams. Most projects have one or more members who had not collaborated previously with anyone on the team but at least one team had sub-teams of former collaborators (e.g., Figure 4).

Figure 2



Disciplines of participants in SESYNC research teams through 2015. Within these broad categories, the dominant disciplines include: Life Sciences — Ecology, Conservation Biology, Disease Ecology & Epidemiology, Ecological Modeling; Geosciences — Earth Sciences, Hydrology, Ocean Sciences; Social Science — Sociology, Economics, Geography, Psychology, Anthropology; Computer Science & Engineering — General Computer Science, Civil and Environmental Engineering, Electrical and Computer Engineering; Policy — Public Policy, Planning, Environmental Policy.

Figure 3



Disciplines of team leaders of SESYNC projects by year. The spike in social scientist participation in 2012 reflects a special effort that year to engage scholars from disciplines under-represented on SESYNC research teams (psychology, environmental ethics, development sociology, environmental policy, political science). In the subsequent years, the number of projects with social science PIs grew relative to that before the 2012 effort (compare blue bars in 2011 to bars in 2013 and 2014).

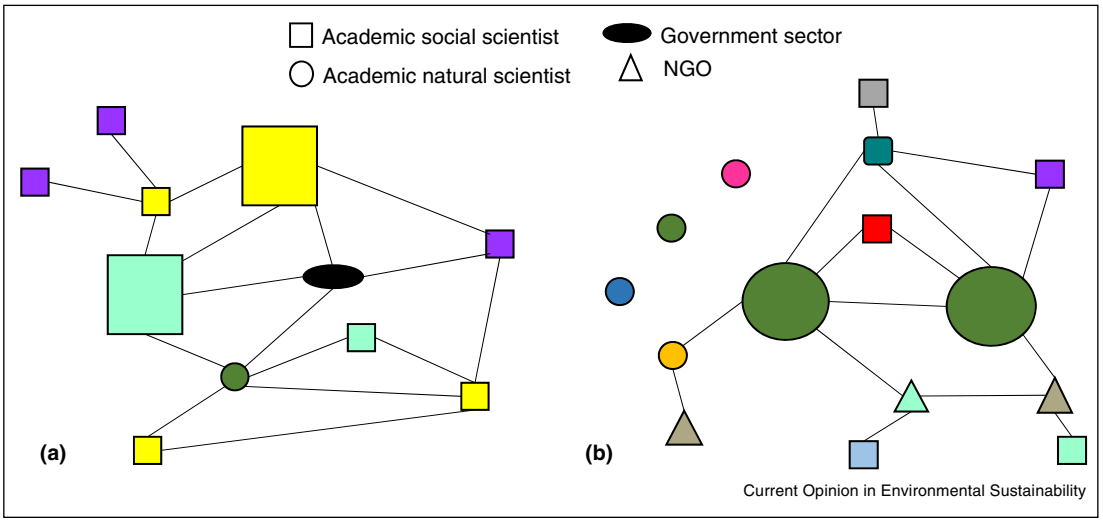
Over time, the disciplinary diversity of team leads has increased (Figure 3). We believe this is related to the 2012 implementation of an outreach effort to increase applications from social scientists along with word of the center simply spreading as the number of participants grew. SESYNC is still not at parity in terms of social versus natural science PIs. This may mean more proactive outreach efforts are needed. It may also reflect the fact that SESYNC review panels to date have favored data-based and computational projects, projects that are less common among the social science-led applications to SESYNC.

Many early proposals focused on creating new frameworks or meta-analyses to link theory or methods from a particular social science discipline (e.g., governance studies) with ecological or physical sciences (e.g., conservation biology, climate change). Projects now typically bring together a variety of remotely sensed, field-generated or geo-referenced data. Results of surveys, textual analysis, case studies and network analyses are also used by teams, as are synthesis of models and most recently large-scale data originating in social media. On the basis of an analysis of 58 projects that are furthest along in their work, teams synthesize on average 3 different forms of data (range = 1–7) in their examinations of S-E problems. About 35% of the projects involve the integration of both quantitative and qualitative data.

Overcoming challenges

Data on the types of support various teams requested and our own observations or conversations with teams revealed that most of the 58 teams discussed here have had to address multiple challenges from among those listed in Box 2. All teams experienced the challenges of only meeting intermittently and across several years,

Figure 4



Examples of the network of collaborations that existed before the formation of two SESYNC research teams. Each node represents an individual team member; the largest nodes are the team leaders. (a) This 11-member team includes individuals from these disciplines/sectors: ecology, geography, law, management, political science, and psychology. The team's synthesis project was designed to recruit multiple sub-teams of social and natural scientists with each sub-team having previously studied a different geographic region. Less than half of the individuals had previously collaborated yet this team had more prior collaborators (mostly within sub-teams) than most other SESYNC teams. (b) This 15-member team included individuals from these disciplines/sectors: anthropology, climate science, conservation biology, ecology, economics, environmental health, epidemiology, geography, human demography, hydrology, natural resource governance, NGOs, public and policy.

collaborating with new investigators, and tackling a problem relevant to sustainability that can be framed in different ways and that often has aspects mismatched spatially or temporally. The rest of the challenges were experienced to differing degrees by different teams.

Almost all of the teams took advantage of SESYNC support to help overcome challenges. This support included computational assistance (46% of the 58 teams), specialized support for meeting design or for resolving problems that hindered team progress (38%), and direct facilitation of one or more team meetings (21%). The amount and type of computational assistance teams received varied. Some teams had members participate in SESYNC's computational workshops for assistance with database development or analysis while others received individualized support in the use of software, coding or cloud computing; a few teams received help with high performance computing.

The vast majority of these teams — facilitated or not — have self-reported good progress on their projects and positive experiences working with their team. However, one team reported conflicts or incompatibilities due to issues of power or inflexibility on the part of some team members and a second experienced high turnover rate of members and has struggled due to poor communication between team leads and members. Problems persisted for both of these teams despite extensive input from SESYNC. Of the projects that have reached the final year of their funding, one-third have requested funding for an additional meeting suggesting that projects did take longer to initiate and move forward than expected. Some teams indicated that this was related to early difficulties in reaching consensus on how to move forward. One team leader wrote to us that it had never taken him/her this long to do a synthesis project with ecological colleagues; this person was leading a highly interdisciplinary team and happened to be one of only a few team leads that declined team support from SESYNC.

Based solely on the scientific outputs of projects that have been completed, SESYNC teams have been quite productive. As of December 2015, 65 manuscripts (journal articles, book chapters etc.) have been published and 30 are under review. Publication venues extend across a wide range of disciplines, and many are interdisciplinary in nature. Journal impact factors for published works range from 2.2 to 34 [41]. Examining just those journal articles published from 2012 to early 2015 ($N = 41$) shows that 14 (34%) were co-authored by academic researchers along with non-academics, 27 (66%) were authored solely by academics. SESYNC teams have made over 150 presentations to date and while the majority of these are at scientific conferences, the results of work done at the center have been shared with agencies across the U.S. federal government as well as a broad cross section of non-governmental agencies and foundations, many with an international focus. Syntheses conducted at the center have led to submission of more than 60 proposals to various funding agencies.

Formative evaluation results

SESYNC's formative evaluation was designed to gather information about the effectiveness of center processes. The external evaluator observed multiple activities and conducted semi-structured interviews with 37 participants (22 team leads and 15 team members) from 19 teams. Transcribed notes and audio files from interviews were coded based on the evaluative questions and analyzed by the external evaluator using NVivo software. The evaluation focused chiefly on early participants during the period when center processes were being actively developed and adapted. While a complete description of evaluation results are beyond the scope of this paper, key findings have reinforced SESYNC practices or led to their evolution.

Results from this external evaluation indicated that 'SESYNC has become a viable platform for S-E research that has succeeded in bringing together new collaborative teams.' The proposal review process and SESYNC's efforts to adjust the disciplinary composition of teams were both thought to be successful in catalyzing new collaborations. However, interviewees also noted that nascent connections within teams may be fragile and are difficult to maintain once work at SESYNC has concluded. Interviewees felt that SESYNC had an opportunity to go beyond convening and catalyzing to play a broader role in sustaining new collaborative S-E networks. Respondents noted that advanced cyberinfrastructure and computational support was considered to be important when utilized, as was facilitation. However some of these early participants also stated that the center needed to be more effective in communicating about the availability of SESYNC's support services and how they could be deployed by the user community to achieve intended outcomes.

The interviews and our direct interaction with participants revealed some differences in what motivated different participants to engage in synthesis projects — an expected result given the variety of institutions from which participants are drawn (academia, NGOs, government, private sector). However, the motivational differences were not vast perhaps because SESYNC encourages 'actionable' projects that produce research publications as well as projects to produce materials of potential use to natural resource managers, policy-makers or practitioners that is, all those that apply to SESYNC are somewhat motivated to do research that may have broad relevance. Some interviewees did articulate difficulties in conceptualizing, producing and disseminating actionable outcomes and felt that the center could do more in this

regard. In particular, our results to date indicate a great need to provide support for communications and outreach, particularly to academic teams.

Lessons learned

Our experiences over the past four years have taught us several important lessons that should help us as we plan future efforts. Many participants appreciate the value of SESYNC as a unique 'place' for S-E synthesis research. But, because travel support is often available from other sources, additional incentives must be in place to spark interdisciplinary team formation — not only are the other forms of support SESYCN offers critical but team members repeatedly express the need for salary or dedicated staff support.

We have learned that it is not at all unusual for a team's research methods, final products, and even the nature of the question addressed to be quite different from what they envisioned at the onset. This may be due in part to 'negotiating the interdisciplinary team process' for work on S-E problems but often when teams shifted focus it was because the data they needed to address their problem was not available or was in an unsuitable form. This has been much more common for teams seeking relevant social data on for example, human health, well-being, or behavior than for teams relying primarily on environmental data. While some participants expressed initial discomfort with uncertainty over their group's direction, many later reported enjoying the learning that came from integrating ideas across disciplines with different languages and epistemologies.

The wide use of SESYNC services suggests the need to maintain those services, if not expand them, by for example, providing large multi-day training workshops. Computational capacity to build, harmonize and work with heterogeneous datasets is a major impediment to synthesis work across the social and natural sciences. A focus on computational skills has been particularly catalytic but other efforts around S-E systems, interdisciplinary and team science and education all contribute to building skills and capacity of participants.

Facilitation can enhance problem solving when deployed across several phases of a project including pre-planning to help teams develop congruent goals, agendas and processes as well as strengthen motivation, trust and attention to team dynamics [44,45]. Highly skilled facilitators with scientific backgrounds in the environmental sciences have proven to be effective at working with SESYNC teams but are few in number. While SESYNC has a wide variety of resources that can be deployed to assist teams, many of them are reluctant to ask for support or do not understand options available to them. Our ability to appropriately and constructively intervene across a project's lifetime has evolved over time and must continue to do so if we are to advance interdisciplinary S-E science. Despite our large professional staff size relative to most synthesis centers, we are challenged to meet all the teams' needs because of the time-consuming nature of such support.

Strong team leadership is necessary, but works best in combination with a commitment to flexibility and shared learning. To be effective, team leaders need to take an integrative approach that focuses on orchestrating expertise, individuals and relationships in a manner that supports problem definition and progressive refinement and extension of ideas. Successful team leadership relies less on power than on the ability to manage the ideation process (generation, structuring and promotion) and provide incentives [42]. Because SESYNC projects involve new intellectual and social relationships, the reality or even perception that leaders are not listening or adapting to others' language, philosophies, methods, and goals can be detrimental. Attention to the creative process' antecedents (e.g., developing shared goals, defining interdependent tasks, team attitudes and socialization) is essential [43].

Conclusions

All collaborations across disciplines have challenges, but as Fischer *et al.* [46] and others have argued, collaborations between natural and social scientists pose special challenges. Academic institutional capacity to facilitate such collaborations is largely absent, although suggestions for overcoming specific issues on campuses do exist in the literature. SESYNC leadership benefitted from such suggestions and from the knowledge gained by others' attempts to bridge or study the natural and social sciences' collaborations around environmental problems (e.g., [30,47]). However, unlike for SESYNC teams, many of these collaborations involve research associated with decision-making around a specific issue or set of issues relevant to a place-based group of stakeholders (e.g., management of a fishery; [2]). Additionally, a growing number of academic sustainability centers have emerged to bring together natural and social scientists with stakeholder groups to focus on decision-making related to a regional socio-environmental issue [48–51]). While these centers differ in many ways from SESYNC they clearly demonstrated the importance of face-to-face meetings and a focus on communication as critical to collaboration between natural and social scientists [28]. As pointed out in the introduction, there is an established group of scholars doing fundamental research on socio-environmental systems but SESYNC's mission is to expand the size of this group and to foster S-E synthesis collaborations across increasingly diverse disciplines.

Placing the work of synthesis teams into an 'actionable but fundamental science' (Box 1) framework requires case-by-case consideration of how best to deploy transdisciplinary

approaches [52••,53,54]. Effective engagement and exchange with those who are not primarily researchers, particularly those positioned to influence or make decisions, is essential. This can range from a consultative role designed to facilitate co-development of research questions [55•] to discussions of effective pathways to share findings, tools, and approaches, to participation of non-academic collaborators on teams.

The challenges and experimental and adaptive nature of our approach have required SESYNC leadership and staff to be very engaged with research teams and to learn and adapt over time. We believe that strong support services such as those that make up our cluster of practices (Figure 1) are required to foster the type of interdisciplinary work SESYNC supports. As Lyall and Fletcher [38, page 2] have emphasized:

"...interdisciplinary research does not occur automatically, even when public funding encourages it. It is not a simple case of aggregating several disciplines into one research project ... effective interdisciplinary research has to be catalyzed, planned and continuously revisited."

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