

Best Practices

for

Integrating Social Sciences
into Social Ecological Systems
Science: Future Directions for
Building a More Resilient
America



Lilian Alessa | Andrew Kliskey | Mark Altaweel | Michael Barton | Steve Bankes
Eduardo Bondizio | Dan Brown | Johannes Feddema | Colin Grier
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William Rand | Shaowen Wang | Daniel Rogers

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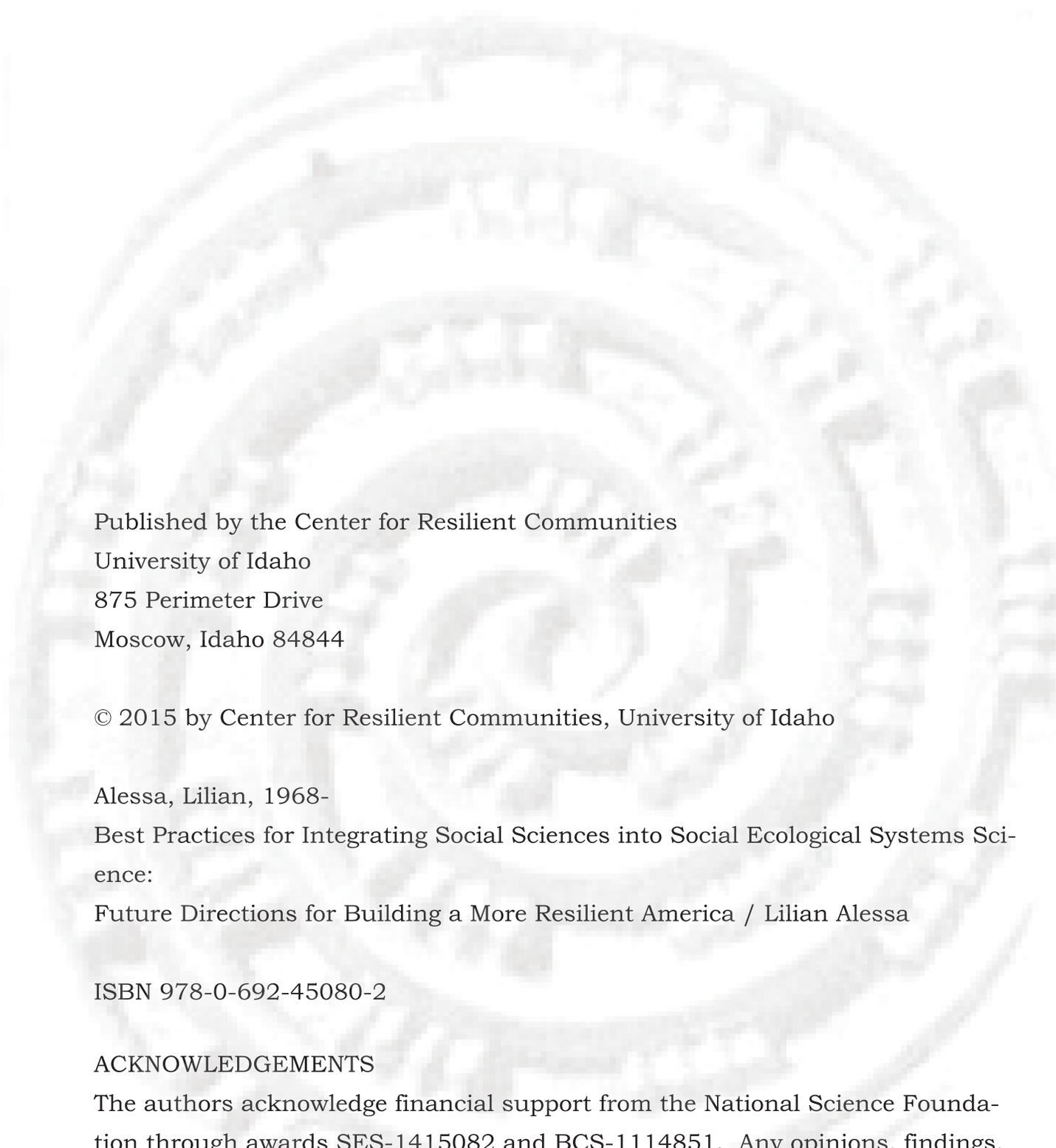
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Introduction

Social Science and a Resilient America

In an era of rapid globalization and environmental change the need for understanding the interactions between humans and their environment has never been greater. The combined influences of increased climate variability, population pressures, globalization, environmental change, and the need for a new paradigm of built and engineered environments increasingly challenge us to adapt. In response, communities have refocused their efforts generally toward “interdisciplinary science,” and more specifically, toward a science reflecting coupled social-ecological-technological systems. These integrated systems are synonymous with other terms, including coupled natural human systems (CNH), coupled human and natural systems (CHANS), coupled human-earth systems (CHE), and complex social ecological systems (CSES). Hereafter, we refer simply to social ecological systems (SES), for convenience and clarity. Ultimately, SES science is essential to understanding and responding to the complex grand challenges facing society because it more accurately reflects the real, and messy, world in which we live. It is distinguished from historically discipline-specific science by being

- 1) explicitly transdisciplinary and integrative across practices, schools, and worldviews of inquiry;
- 2) problem-oriented and contextual in nature, informed by sociocultural, geopolitical, bio physical, and engineered dimensions
- 3) a recursive process involving co-definition of the problem and its ongoing refinement;
- 4) cognizant of the role of, and engaged with, local, place-based and Indigenous knowledge;
- 5) informed by comparative, multi-temporal, and multi-scale analysis;
- 6) a process of a partnership between researchers and stakeholders;
- 7) based on the recognition that human values increasingly define and modify landscapes.

We define “resilience” in the context of a resilient America to be the ability to design SES as coupled sociopolitical, built, and ecological systems so that they remain functional under a range of environmental conditions and human desires. Resilience emerged from the field of ecology and remains largely rhetorical. As a concept it needs to move beyond “balls and basins” and it needs to be articulated in the context of applied SES. Moving toward an “applied resilience” requires that integration similarly move beyond the compilation of information to systematic, cyberGIS enabled analyses. Such methods can accommodate a vast range of issues, and need systematic workflows and documentation to build a body of knowledge which can be quickly drawn upon to inform strategic management and policy decisions. This is the science of SES in which integration is an active set of analytical processes. Ultimately, our hope is that we can develop an SES science that allows for early warning systems (EWS) to be developed. These EWS would allow decision-mak-

“Moving toward an ‘applied resilience’ requires that integration similarly move beyond the compilation of information to systematic, cyberGIS enabled analyses.”



ers in diverse settings to anticipate undesired outcomes, foresee opportunities, and cultivate the abilities and means to respond to change proactively.

The social sciences are critical to SES because they constitute the paired tools, bodies of knowledge and theories by which we understand coupled systems. More importantly, they allow us to characterize the feedbacks in human-resource-security systems so as to be able to design and manage them for positive and desired outcomes. Increasingly, agencies, institutions, and communities around the world are looking toward adapting to a changing world. The scale and connectivity of global systems imply that problems implicate global scales, whereas responses are local and regional. Agencies and governments have allocated billions of dollars toward research and development to meet these challenges. A disciplinary legacy in scientific inquiry means that understanding has been built around disaggregated variables. This has been of enormous value to a range of fields. In order to address SES, we now struggle to integrate this knowledge in ways that are meaningful, accurate, and useful in practice. However, while the concept of integration appears intuitive—after all we know our world is complex, interconnected, and emergent—the practice of SES science has been more nebulous, resulting in diverse and uneven outcomes leading to loosely connected research and development investments. Rather than focusing explicitly on catastrophic drivers of change, for example, hurricanes, floods, and earthquakes, we propose that views toward a resilient America must expand its scope to include civil unrest, for example, due to shifts in population burdens, purposeful or inadvertent degradation of infrastructure or critical natural resources, and an over-reliance on technologies

“Bringing the social sciences to bear in SES science will allow us to proactively nudge our trajectories toward those that are most desirable, equitable and beneficial for our Nation. ”

as solutions rather than as tools. Because SES are constantly changing, complex and open, social science cannot provide fixed solutions. Yet there are Grand Challenges—for example, in water and food systems, development of early warning systems, and in fact, much of what bears on human wellbeing, explicitly dependent on balancing healthy ecosystems with human needs—for which social sciences can lead

with innovations and provide effective guidance for policy. Bringing the social sciences to bear in SES science will allow us to proactively nudge our trajectories toward those that are most desirable, equitable and beneficial for our Nation.

Addressing these core issues hinges on successful integration across the boundaries of problem identification, teams, concepts, datasets and methodologies. Required for this integration is the engage-

ment of stakeholders—policy makers and the public at large—in the resulting science’s co-development and application. This will call for a re-examination of how we cultivate scholarship, specifically how and among whom we diversify cadres of SES scientists and practitioners. This report addresses the key challenges related to integrating social sciences into SES science and forwards an agenda for guiding, supporting and creating a more systematic and useable body of knowledge.

Motivations and Origins of the Report

“All we know, we know because we have known it through others”. —The Authors

The calls to attend to a science of sustainability and of integration are ancient. The formalization of the fields which constitute this vague and dispersed pursuit is similarly a process rather than a fixed event. For those of us who practice some form of computationally-supported social, social ecological or coupled human natural science the concepts around WHY one should take an approach are not the issue. Rather it remains a challenge as to HOW to integrate knowledge about humans and their social systems with knowledge about the non-human natural, physical and engineered world in a more systematic manner. This matters greatly. Without cohesion and coordination in such a complicated and complex inquiry, that is, without Best Practices, it is difficult to build the kind of knowledge that can be taken from theory to application on the ground and, in decision making on a daily basis for setting policies.

In 2009 the National Science Foundation funded the Open ABM research coordination network (RCN). As a result of this effort, the Community for Modeling Social ecological Systems (COMSES) was formed (www.openabm.org). Similarly NSF made investments in three other RCNs: The Coupled Human and Natural Systems (CHANS) network (www.chans-net.org) and the Social Observatories Coordinating Network (SOCN, www.socialobservatories.org), and the Mountain Social Ecological Observing Network (MtnSEON, <http://webpages.uidaho.edu/mtnseon/>). These groups coalesced several individuals, institutions and organizations across the country, as well as internationally. Each of its members and partners had, in parallel, been working toward similar goals: attempting to find the best pathways to enable the social sciences to be integrated meaningfully and usefully into global system science writ large. Our colleagues represent diverse fields bringing with them a range of perspectives and critiques. It was through this tension of determination, strategic thinking and skepticism that we have been able to create a momentum toward advancing the social sciences in a new, more systematic, context.

In 2011, during a meeting of the Advisory Committee for Environmental Research and Education (AC-ERE) at the National Science Foundation, a group of Assistant Directors, representing diverse programs across the Foundation, expressed their frustration with a lack of best practices for integrating the social sciences into sustainability science. Without this, they argued, the best possible integrative science and hence knowledge could not be developed. To address this gap, a proposal was submitted, merit reviewed and awarded to initiate a process of road-mapping paths toward best practices. The workshop, held at the University of Chicago’s Computation Institute, had the advantage of leveraging the inertia started by OpenABM and further coalesced a loosely coordinated group of scholars. Since then, the authors have been soliciting input, both formally and informally, across a range of practitioners. Each are active innovators in the fields of SES science and dedicated to a vision of being able to use the social sciences to help guide our future earth as a thriving SES. Most

recently, in March 2015, these three large networks convened a planning meeting in Washington D.C. around creating blueprints for a proposed National Center for Advanced Social Analytics.

The authors of this report humbly recognize the many other individuals who share their goals and vision. To them we extend the invitation to further contribute to this Living Document.

Purpose of the Report

There are three purposes to this Best Practices Report:

1. Outline potential pathways to establish best practices in integrating the social sciences into social ecological systems (SES) science.
2. To provide a framework and actions that can be vetted, refined and used nationally.
3. To rapidly, but systematically, advance social ecological systems science to the point where it can be more readily applied to pressing management needs, from local to global scales.

Scope of the Report

What this report does not do is dictate which fields of social science are more or less important. Instead, it maps out actions that can be taken in diverse settings at multiple scales.

A Living Document: Interacting with the Report

Unlike other reports, this is a living document. It will be updated annually to reflect emerging frontiers. You are encouraged to interact with it by submitting updates and emerging frontiers in best practices. You may do so by either contacting the Report Chair, Dr. Lilian Alessa (crc@uidaho.edu) or through the Report Update submission page on the Center for Resilient Communities (CRC) or the COMSES OpenABM website (www.openABM.org).

1

Establishing Common Reference Frames, Data Analytics & New Technologies

At a Glance:

Successful integration requires:

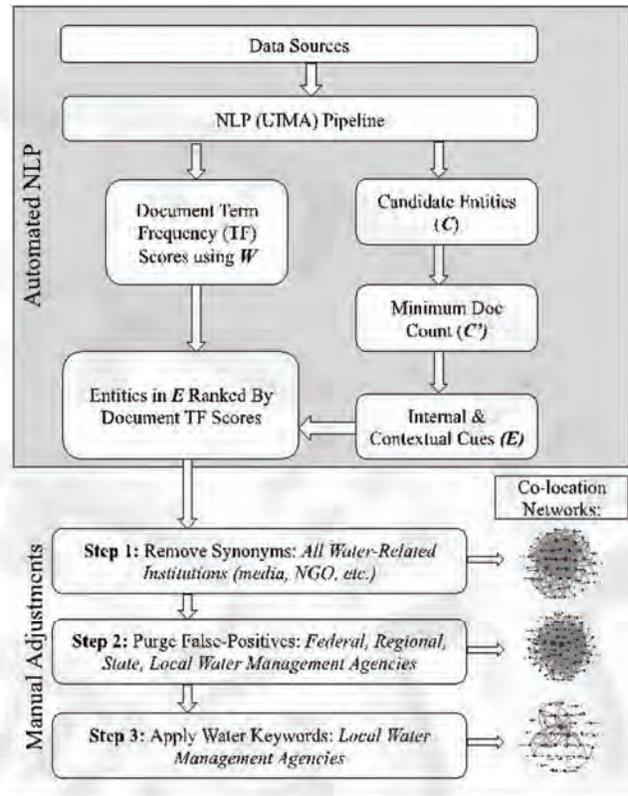
- A Community of Data: common data formats, policies, standards, ontologies, and workflows
- A Community of Methods: transparent, well-documented, and replicable methods
- A Community of Language and Concepts: a common language and set of concepts for the social sciences in the context of SES.

Advancing SES science requires practitioners to generate and share knowledge within common frames of reference. In addressing sustainability-related research issues, it is possible to share data among the different expertise and perspectives of researchers who need to analyze those data across multiple dimensions – space, time, and organizational levels. It is also possible to disseminate new methodologies for data synthesis, analysis, modeling, and visualization effectively, to enable rapid innovation in scientific research into SES dynamics. For this interchange of information and practice to lead to meaningful advances in the knowledge and understanding that are necessary to manage the complex dynamics of SES, scientists need a shared lexicon, a research language developed for SES science, not one merely borrowed from other disciplines. A common understanding of concepts and explanatory principles will also be necessary. We believe integrative SES science must operate as a coherent community of practice with a shared paradigm and common language accommodating diverse research agendas but also providing mechanisms for consilience. Here, we offer examples of key elements for achieving shared bodies of data, methods, and knowledge needed to advance SES science.

A Community of Data

Understanding global-scale sustainability requires realization of SES as complex, complicated and diverse open systems, which means that data informing SES science use an extremely diverse array

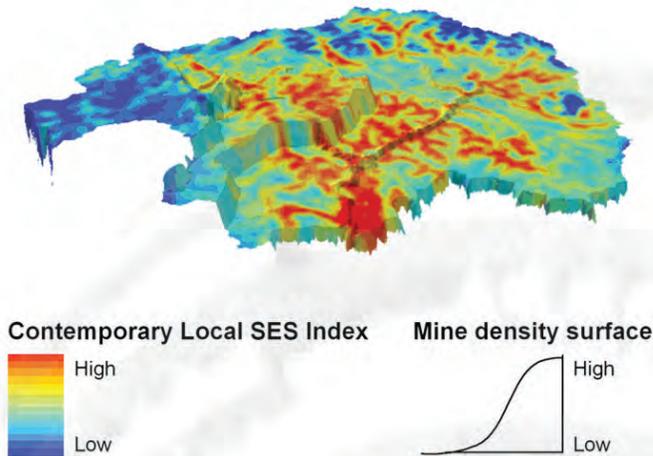
of media, formats, and ontologies. SES science therefore faces a twofold challenge with respect to data: a) ensuring that data collected in future research can manageably contribute to continuing scientific understanding of phenomena that impact resilient SES, and b) reconciling legacy data with new data, technologies, and methodologies, so that the investment in prior research serves as a foundation to ongoing science. Although each of these challenges entails unique needs, there are issues common to all. The ability to translate across different types, properties, and relationships (ontologies) is essential for large-scale data synthesis. There is a widespread misconception that data about biophysical systems are inherently quantitative, whereas data about human societies are largely qualitative. Moreover, qualitative and quantitative data are widely considered inherently incommensurate, requiring distinct analytical protocols, evaluation standards, and epistemological claims. The format of data can indeed limit potential analytical procedures, but there is more of a continuum than a dichotomy between qualitative and quantitative (as in the of conversation, through written field notes, photo inventories, structured surveys, taxonomies and counts, to numerical matrices or remote sensing imagery). One of the main challenges we face are incompatible formats for data, and thus a chief task for advancing SES science will need to be to develop a center or centers which can serve the community by developing best methods for making data across all formats usable by all members of the community—a monumental yet achievable task.



Example workflow for natural language processing

Information can be expressed and re-expressed in multiple ways across this continuum to enable different research goals and foster integration of its quantitative and qualitative aspects. Advances in computational data mining and parsing tools able to deal with information as text, imagery, or sound—for example, parsing tools based on unstructured information management architecture (UIMA), and natural language processing (NLP) more broadly—can facilitate these efforts.

These kinds of tools can also help integrate existing legacy data with new information, for instance, by parsing scanned paper documents (e.g., ethnographic field notes) and microfiche, restructuring outmoded digital formats, or creating semantic mappings across different data structures. Once thus restructured, indexical variables and equivalence classes (captured, for example through category theory or semantic mappings) can help identify and evaluate relationships between quantitative and qualitative data. A range of strategies could be helpful, ranging from those governing principal investigator-driven initiatives to the establishment of national-level institutes, data archives, and regional SES synthesis centers.



Integrative social-ecological system modeling should be spatially explicit

Data for SES science spans multiple temporal and spatial scales, requiring geospatial and temporal frameworks to facilitate comparisons and synthesis across their diverse ranges (see section 3). The development of a network of environments in which information from different sources or data represented in different ways can be synthesized and analyzed as a common body of knowledge could be also facilitated by a national advanced analytics research center.

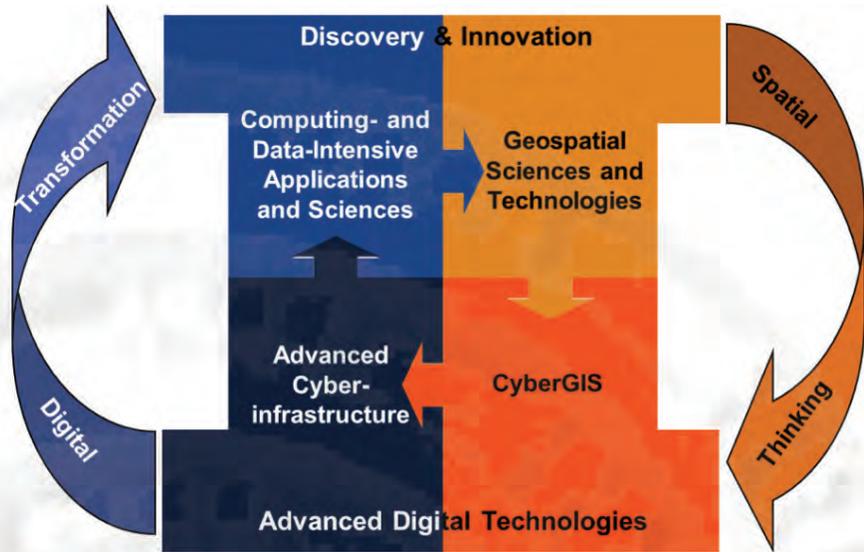
including information about the data collection methodology, base theories, the questions that instigated data collection, and the data validation protocols. Documenting data structure topologies can reveal ways in which the structure of the data may inadvertently predetermine analyses and models.

The SES science community is responsible for building and maintaining these frameworks of connection. This includes alignment with standardized data collection already carried out under the mandate of government agencies, such as related to census and social-economic indicators collected at various resolution and in many cases following agreed international standards. Although science funding should invest in coordination efforts and in the development of information processing tools to facilitate data consilience, the scientific community must establish the standards and best practices for data management, to promote integrative data synthesis. Some current data management plan requirements at NSF can serve as a model to be applied across SES science domains more generally, but might evolve with current practice and technology and facilitate better cross-community integration.

“Documenting data structure topologies can reveal ways in which the structure of the data may inadvertently predetermine analyses and models.”

Rather than seeking to create single archives with rigidly enforced data formats and structures, it may be more practical and flexible for future research to follow a polycentric system that encourages distributed data storage, where multiple organizations take responsibility for the maintenance of data across different domains. This will help SES science practitioners establish common, community-supported APIs (application programming interfaces) for data access and ensure that data across multiple servers in multiple physical locales are available. Both standards and tools should have freely available open source code, to ensure the transparency essential for knowledge evaluation and the scaffolding required by this new science.

Finally, it is critical to recognize important sources of information being rapidly created outside publicly funded scientific enterprises. Intellectual property and privacy considerations could restrict data availability. New data processing environments offer the possibility for data-holding organizations to use backend processing to restrict access to sensitive information, while making other less sensitive aspects of data available for synthesis and analysis. This has the potential to open much more diverse and valuable information sources to SES science than have been available previously.



Emerging infrastructure such as the national CyberGIS center helps enable spatially explicit SES models

A Community of Methods

The great diversity of research questions and the rapidly changing nature of SES science call for a rapidly evolving and adaptable ecosystem of methodologies. At the same time, methods must remain transparent, well documented, and replicable in order to demonstrate scientific integrity to the broader public and to validate results. Such features are critical to building trust and credibility in public and political venues. The practice of SES science requires development and use of methods enabling and promoting interdisciplinary, team science. Most of the methods for data access and analysis now employed by scientists are designed to be used by individuals; results of individual research must be manually passed to other researchers who wish to use them. The challenge of interdisciplinary integration will grow as SES science increasingly involves larger teams of scientists whose expertise and protocols span different research traditions. A project involving soil sampling, survey interviews, remote sensing, data mining, qualitative and quantitative data analyses, modeling, and visualization would need to create tightly integrated, well-documented, transparent and efficient chains of procedures and protocols that can be accessed, replicated, and built upon over time and in different settings.

Conventional scientific approaches to understanding the complexity of SES currently tend to be fragmented in space and time and constrained by the inability to take advantage of complex, diverse, and massive geospatial data, which make extrapolation over the connectedness across large and multiple spatial and temporal scales difficult or infeasible. An integrated approach combines rich and complex geospatial data, analysis and models, and is expected to ignite transformative geospatial innovation (e.g. cyberGIS – geographic information science and systems based on advanced cyberinfrastructure) and discovery for enabling effective and timely resolutions of related grand challenges. The recent data-intensive transformation of SES science has significantly exacerbated

the challenges of geospatial integration. The proliferation of primary geospatial data sources (e.g., remote sensing, sensor networks, social media, and surveys) and substantive changes in secondary geospatial data sources (e.g. US Census) have brought up new challenges such as poor or unknown data quality, missing metadata, and lack of well-defined sampling schemes. The proliferation of these data streams represents a pressing big data problem that is not likely to ebb in the foreseeable future, thus innovation of advanced cyberinfrastructure-enabled geospatial data capabilities is required to address it. This innovation opportunity is significant and unique because geospatial integration workflows often simultaneously involve computing-, data-, and visualization-intensive capabilities with responsive user interactivity expected and, thus, cannot be effectively supported by existing cyberinfrastructure. Major scientific and technological breakthroughs need to be pursued through holistic approaches to socio-geospatial and temporal integration supported by cyberGIS.

Formal, cyber-enabled workflows provide a means of defining and documenting the complicated multiplicity of methodological domains and steps involved in large-scale SES science, as well as allowing team members to revise key segments of the research process as they go. The importance of workflows is gaining wider recognition, and in some sciences, such as genomics, they are commonly employed and are often detailed in associated publications. New computational platforms present potential to track and functionally automate chains of procedure, from data acquisition through synthesis, to presentation of results, making possible new levels of transparency, rigor, and reproducibility in domains within SES science. Cyber-enabled workflows offer SES science practitioners

“One mechanism for enhancing a community of data, methods, and concepts is through the development and establishment of a national center for advanced social analytics.”

a readily available and accessible toolbox whose components can be used flexibly. The validation protocols for data should also be part of these workflows. Chaining different protocols can create opportunities for new research strategies for studying SES dynamics. Given the complexity of SES science, documentation is critical to making sure that science in this space is replicable.

To make such workflow environments successful, field methods should be documented in compatible, and preferably machine-readable metadata formats. Analytical or modeling tools should use open source code and share application program interfaces (APIs). This can also allow workflow elements to be coupled or added into processing chains in novel ways. Data mining and synthesis can feed into agent-based models or other analytical tools and model output can be displayed as high-dimensional visualizations or scenarios of SES dynamics; these results can form the basis for participatory and exploratory decision-making in face-to-face or virtual environments. The potential and benefits of using these collaborative research environments will be increasingly apparent once training in their use and development is more widely available. This again argues for the need for creating a national center for advanced methods in integrative SES science, which can focus on these challenges.

A Community of Language and Concepts

SES science a common language and common suite of underlying concepts about SES dynamics that embrace biophysical and social processes simultaneously. These shared reference frames enable interdisciplinary teams to carry out transdisciplinary research by focusing on appropriate data and

From Data and Models to Insight – example of a workflow structure

1. Identify the problem - there is a social-ecological change but we do not know the magnitude and direction of the change.
2. Develop a conceptual agreement among researchers on the approach.
3. Determine the type of data each domain specialist can develop and how much it will cost
4. Secure funding.
5. Domain specialists collect the data using their methodologies; field work is done together where possible – interaction on a regular basis, constant communication.
6. Construct a dynamic model of all the components based on the data - linking climate, hydrology, geomorphology, settlement patterns.
7. Apply statistical and analytic approaches to develop insights.
8. Check the outcomes from model exploration against the initial conceptual model.
9. Re-evaluate the conceptual model and the dynamic model to identify missing or poorly conceived processes, and surprises.

methods to address critical research questions.

At the most basic level, scientists involved in SES science need to use a common lexicon for planning research strategies, developing sampling design, identifying key variables, and sharing knowledge across complex workflows. Developing common understanding of terms and concepts takes time and effort, but contributes to promote respect and appreciation for research teams working across disciplines. Agreement on the meaning of key terms is equally important to the ability to establish community wide APIs for accessing data, translating ontologies, and chaining multiple methods into sophisticated workflows.

Sustainability science practitioners should also share a suite of concepts to be applied to questions that cut across traditional disciplinary boundaries. This includes agreement on a general epistemology, and on generative principles that help to explain the interactions and feedbacks found in SES dynamics. This will require a clear distinction between rhetoric and proof-of-concept data which can be used to build and test SES theories. While the many academic disciplines with relevance for SES science have different histories with differing disciplinary literature and theoretical frameworks, it will be important to identify commonalities to foster a cohesive SES science. We propose that a generic language for SES, sustainability, and complex adaptive systems approaches, be developed building upon ongoing efforts by the international research community and already extant languages in these areas.

One mechanism for enhancing a community of data, methods, and concepts is through the development and support for a national advanced social analytics research center, an initiative being championed by the NSF-funded Bringing the Social Sciences into the 21st Century program (BC21).

2

Co-design and Co-production of Knowledge

At a Glance:

Effective SES science will require transformational practice in how we observe our environment as well as how we think about global and environmental change. Such observatories will facilitate the co-production of knowledge that is actionable in developing appropriate interventions to capitalize on change in SES, and reflects:

- the multi-disciplinary nature of sustainability problems
- variation in spatial and temporal scales in iSETS
- an emphasis on feedbacks and adaptation
- participatory methods and scenario planning
- the development of scenario testing and early warning systems



Designing Resilient Landscapes

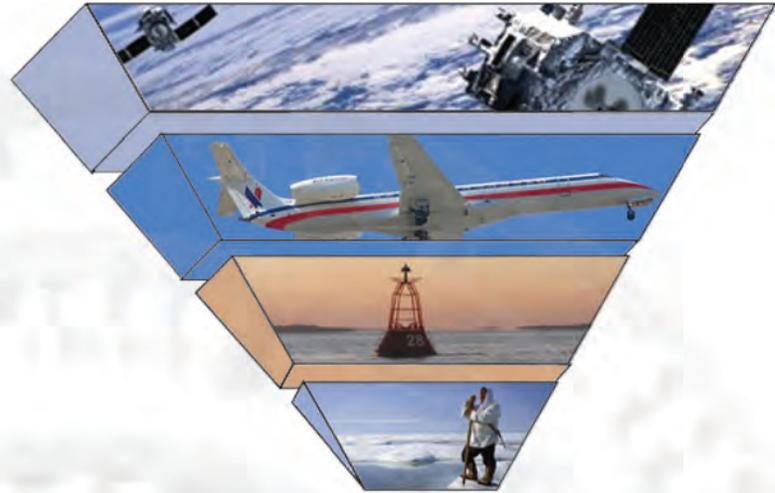
Resilient landscapes are defined as earth surfaces and human communities which are actively designed and managed so that ecological systems, human uses (i.e., cultures and economies) and the built environment act in concert to optimize energy use and maintain ecosystem services for a wide range of users, including non-human. The benefits of designing resilient landscapes include that since they are inherently people-centered, the public has strong buy-in to the development and management of their resilience.

Co-defining Issues, Co-producing Knowledge

Transformational practice in SES science requires the co-identification of issues, dependent variables, types of variable operationalization and measurement, and analysis. This will improve the production and dissemination of knowledge among scientists, communities, and policy-makers, and involves stakeholder engagement (funders, policy-makers, research subjects), an understanding of the ethics and responsibilities for working with other groups and interests, and effectively translating research to be accessible and understandable to decision- and policy-makers. Critical for helping to not only build and

“This co-production of knowledge reflects the multi-disciplinary and pluralistic nature of problems.”

validate theories but also for developing management decisions in SES on the ground is the co-production of science and knowledge through working with stakeholders to develop science agendas, co-identify issues, research questions, and research design. Participatory methods are critical and a significant step forward but still engage stakeholders late in the inquiry process. This co-production of knowledge reflects the multi-disciplinary and pluralistic nature of problems; the different spatial and temporal scales for the different components of SES;



Nested scales of observation from global to local.

the need for better coupling between kinds of observatories and with existing tools in other disciplines; and the fundamental need for integration and understanding the mechanism for this integration. Social science in the service of SES science must include within its purview extant stakeholder agendas, research questions, concepts, and research designs. Analysis should target implications of stakeholder activities and policies for both sustainability itself, perceptions of sustainability, and expenditures on sustainability research. At the same time, it is critical to study the wide range of types of decision-making logic pursued by public and private organizations actively involved in sustainability-oriented programs, and recognize differences that may exist in the traditions followed by different nations and communities. These include assuming the importance of the free market, regulatory practice, biological preserves, precautionary policy, or issues of inequality versus productive efficiency. Research is needed to refine and critique data supporting any and each stance.

“Sustainability” is a relatively new goal for many corporations and global organizations, one that still often sits uneasily with other goals. Sustainability runs the risk of being treated as an engineering and technological process, which, paradoxically and by definition, would limit sustainability, because of the added maintenance demand that either process inherently carries. Within academic research, as much as within major corporations or global organizations, explicit constraints, both self-imposed and those defined by near term possibilities, shape behaviors with significant impacts on SES. Subject to different pressures and at different rates, public perceptions of the concept of sustainability, resilience and the need, and ways, to adapt to change also evolve over time. Political perceptions can polarize sustainability issues, generating fear, mistrust, confusion, and conflict. Despite a broad range of stakeholders collecting information critical to understanding societal sustainability, little coordination or communication exists between them. In other words, even though several types of ‘observatories’ to collect data exist across disciplines, from demographics to economics to climate, conceptual frameworks for integration and synthesis of data among them for specific purposes are diffuse and, in most cases, non-existent.



CBON participants discussing structured data intake forms.

Observing Global and Environmental Change from an SES Perspective

The criticality of observing global change across multiple variables has never been greater. However, funding for building and sustaining observing networks remains problematic. One approach gaining momentum is that of regional hubs of social ecological observatories. These are entities that engage residents in data collection with the explicit purpose of placing biogeophysical change in social context for the benefit of society. Ensuring this occurs will allow social and natural scientists alike to collaboratively understand SES change, and to further engage a broader public in citizen science efforts.

One of the key components for understanding changing SES and avoiding surprises, in a way that enables the social sciences to inform solutions, is being able to accurately monitor and respond to change. Current monitoring networks provide critical data so we may ideally be able to forecast outcomes based on biophysical variables. However, these networks do not have sufficient spatial and temporal coverage to best document environmental changes, particularly at more local scales, nor can they assess those changes' societal implications. In spite of the strong tradition of longitudinal research in both social and biophysical sciences, much of these efforts are individualistic and/or not shared beyond specific research communities. Just as important, many of our current instrument networks were established under significantly more robust budget conditions, and may thus not be sustainable. Community-based observing networks (CBONs) are an innovative way to address this limitation by enabling knowledgeable community members—also referred to as High Fidelity Observers—to share their current observations of local environmental conditions and place them in a historical context, resulting in unique and much needed type of data. This is especially critical since SES baseline data are limited, dispersed, and in many cases of limited comparability. Because the societal consequences of different types of change are relatively unknown, the capacity of communities, industry, and agencies to develop desired, equitable, and sustainable development, mitigation, and adaptation plans is limited. These CBONs could potentially expand our ability to monitor a changing environ-



Wales, AK – A community-based observing network village on the Bering Sea coast.

ment in a manner that not only can be financially sustainable but also can enhance development of a STEM workforce and engage traditionally marginalized communities. An example is the community-based monitoring and information systems (CB-MIS) increasingly promoted by the UN Convention on Biological Diversity (CBD) as a way of involving Indigenous and local communities in environmental monitoring activities.

Social science in SES science can powerfully inform the design of CBONs that allow data to be

placed not only in a societal context, but also in a way that enables workflows to occur and datasets to be compatible. CBONs are social observing networks built on partnerships between scientists and stakeholders, and can be defined as a distributed array of residents in communities throughout the same region who are able regularly to observe their environments. In this capacity they are capable of detecting events that indicate that the system is operating unusually. CBONs, as a network of human sensors, better allow a region to be observed as an SES since they simultaneously acquire data, at local scales, in their societal contexts. That is, they learn

Example of a Community-based Observing Network – CONAS



The Community Observing Network for Adaptation and Security (CONAS) is an international network of observers in remote, Indigenous communities around the Bering Sea. It includes residents in both Alaska and the Russian Far East who share observations, implications and lessons learned. The purpose of CONAS is to better understand the types and rates of environmental change occurring in this critical area. CONAS focuses on weather, flora, fauna and marine conditions. It uses systematic data collection techniques that are validated and verified, and it integrates observational data with data from automated instruments to provide a more accurate picture of change occurring at local scales, and it allows observations and data of environmental change to be placed into a societal context.

- 1) what changes are occurring;
- 2) why these changes are of concern to a community;
- 3) what types of response is the community planning or initiating;
- 4) what the consequences or trade-offs are for different outcomes of change.

Social observing networks have often run into questions regarding individual privacy, making their implementation in countries where law protects the privacy of human subjects, such as the U.S., problematic. On the other hand, biophysical data, so central in SES science, are often collected outside socioeconomic and cultural contexts; this dichotomy requires that more attention be paid to integrating these two domains. CBONs represent a set of powerful approaches that allow networks of people with particular skills to make systematic observations with high precision and

“Improving early warning capabilities would force the clarifying discussion in a diverse community of what constitutes a danger, on which timescale, how such threats compare to previous experiences and responses.”

fidelity. In other words, they are humans who act as sensors much as instruments (e.g., met stations, ocean buoys) do; the data are collected in coordination with other instrumented networks, and are structured to augment the latter’s spatiotemporal coverage; CBONs are developed as a partnership between academic/government and community practitioners where the variables of concern are collectively determined in the context of adaptation; CBONs themselves are adaptive and can modify the format or types of observations if necessary; observations are placed in the context of other variables, reflecting a coupled social eco-

logical technological system. Knowledge is co-produced and shared using multiple worldviews and approaches. The community is a partner in the process of science, rather than a contractee to carry out specific observations of flora and/or fauna counts.

Observing Networks, Adaptive Capacity, and Early Warning Systems

Currently, observations inform us of changes to many ecological processes, yet to assist the development of appropriate societal responses and adaptive capacity, they need to be placed into system-wide context. This necessitates the documentation and understanding of the social context of observations through SES observing networks. By expanding the parameters of current observatories, we can support data streams relevant to the development of adaptive capacity. There exists an enormous opportunity to leverage existing infrastructure so as to help inform community-based adaptive capacity indices (ACI). This can, in part, be achieved through innovations such as CBONs. ACIs provide a systematic synthesis of key social, biological and physical indicators that allow for targeted, coordinated responses to occur under changing conditions for the purpose of sustaining desired livelihoods and wellbeing. A system of integrated observing networks inform a recurrent gauge of system changes, and with a focus on enhancement of adaptive capacity, can be used to develop early warning systems for critical SES responses. Improving early warning capabilities would force the clarifying discussion in a diverse community of what constitutes a danger, on which timescale, how

such threats compare to previous experiences and responses, how nonlinear SES processes can result in emergent threats, and enhance preparedness. These kinds of discussions could stimulate further dialogue about priorities, repurposing existing systems, and decisions about new investments in a system of observing networks.

Example of an Early Warning System – Arctic PACE

The Arctic Predicting Arctic Critical Events (Arctic PACE) comprises the set of human, organizational and technological capacities needed to generate and disseminate timely and meaningful warning information concerning significant events in local and regional areas of the Arctic. Arctic PACE is an early warning system (EWS) that enables individuals, communities and organizations threatened by anticipated and undesired change or imminent threat to take necessary preparedness measures and act appropriately in sufficient time to reduce the possibility of harm or loss. Arctic PACE includes the process and framework for supporting successful on-the-ground responses, and involves:

1. An active stakeholder group that is part of a co-designed framework and co-developed solutions (planners and responders).
2. Identification and assembly of best available data (academic and agency scientists, community-based knowledge).
3. Data integration that acknowledges interoperability across diverse data types including generation of adaptive capacity indices and SES vulnerability mapping.
4. Suitable representation and visualization of SES dynamics (e.g, geovisualization, generation of SES maps, and SES system status dashboards).
5. Generation of a range of plausible future scenarios and projection of possible outcomes using geovisualization tools.
6. Development of potential responses to scenarios to guide preparedness.

3

Means of Sustaining and Evolving Best Practices

At a Glance:

Integrated SES science requires:

- An open source environment for cumulative and evolving best practices for integrative SES science – the Best Practices Collection
 - including a ‘test bed’ of SES protocols for comparing best practices and lessons learned as they are developed;
- A sharp focus on shared conceptual frameworks, methods and means of integrating biological, physical and social data

An urgent and emerging need exists for establishing consensus and documentation of best practices for integrative SES science. A Best Practices Collection (BPC) would be a significant first step in articulating and evolving core theories as well as approaches to developing and applying integrative SES science. Currently, there is no community-agreed mechanism or venue for archiving integrative SES science best practices. This includes mechanisms by which interdisciplinary teams are formed, and steps they undertake to engage partner communities, co-develop the science and use the resultant knowledge to address a particular issue. Neither is there a current representative inventory and synthesis of best practices in the context of, for example, different policy settings, natural resource management issues, or environmental security threats, that could be used

“A Best Practices Collection (BPC) would be a significant first step in articulating and evolving core theories as well as approaches to developing and applying integrative SES science.”

to cross-reference and compare resource management issues and the processes governing them, whether formal or informal.

A BPC could provide a transparent, available framework for establishing baseline terminologies, contexts, meaning and actions including knowledge dissemination and scientific scaffolding for integrative SES science practices. Many of the tools that social scientists use to develop robust frameworks for study, both within their domains and across other disciplines, already exist, but a collective sense various combinations of these as Best Practices does not. A BPC could be organized so that author teams could remotely upload integrative SES science cases, including documentation, protocols, procedures, timelines, data files, and outcomes. To rapidly build value into a BPC, a standard template

could be developed through consensus of integrative SES science practitioners. This BPC could provide a forum for peer-review and expert vetting. This peer review would also help to rank and order the best practices in order to make sure that they are truly reflective of best practices. Author teams could refer to it, for example, for article or grant submission purposes. In addition to providing a unique resource for integrative SES science practitioners nationally it would be valuable for practitioners globally, to share expertise, concepts and implementation in ways not currently possible. It would include SES protocols and outcomes, yielding ‘lessons learned’ that could be linked to publications and offer feedback to participants. A BPC would also allow practitioners to resolve what

processes are, and are not, transferable from local, place-based, to global scales. A BPC supported by a diverse group of practitioners in SES science (from early career to more experienced researchers, among practitioners of different backgrounds and worldviews) could provide additional flexibility in inquiry and application. A key component of best practices lies in the improved utilization of social science datasets and their integration with biophysical ones, for example, spatially coupling datasets to the environments in which they exist, a method increasingly used to resolve typologies of SES.

A BPC Test Bed

As part of a BPC an internet-accessible test bed of SES protocols should be created for comparing best practices as they are developed. This test bed would not require large datasets for analytics but rather rely on a range of issues and settings (e.g., from an isolated rural community to those more connected as well as urban-wilderness interfaces) in which SES dynamics are explicitly recorded and the nature of relevant parameters tracked in such a way that implementation and outcomes may be compared. In addition, through consensus and expert vetting by SES practitioners, a set of ‘Exemplar SES Protocols’, can be identified to highlight particularly innovative examples. For example, the archaeology community has pioneered online integration of old and new data and is moving fast towards large scale integration of data and open source online platforms.

SES science has been applied in very diverse domains – the physical, natural, and social sciences --which benefits implementation of a useable and accessible test bed for SES protocol evaluation. However, common protocols across all these fields would be impossible to find. Instead, it prac-



Conceptual diagram of how a geodatacenter could support a Best Practices Collection



Community partner discussing co-produced geodatabase, Eklutna, AK.

ticality argues for focus on those related specifically to natural resource management, for example, those concerning fresh water, urban expansion, fisheries, wildlife, invasive species, or changing fire regimes. With a scope sufficiently broad, it would require a diverse suite of standardized datasets, such as those emphasizing diverse human interactions with the atmosphere, ground water, surface water, or terrestrial surface dynamics; ones concerning rural or urban settings; and those applying to long-term (archaeological or historic) and short-term longitudinal change. It is important to note

that the majority of projects and their extant datasets are not intended to serve as testing platforms for SES protocol or outcomes evaluation. They would thus require a large investment of labor to reformat and/or rescale. Moreover, few actively collected relevant micro-level or behavioral information.

Development and adoption of best practices archives and protocols for SES science is in its infancy, but is essential for supporting and enhancing robust SES science. A test bed for a best-practices archive is a concrete short-term goal for advancing the goal of documenting, comparing, and sharing best practices. Such an undertaking could be sustained through the establishment of a national social analytics center.

“Development and adoption of best practices collections and protocols for SES science is in its infancy, but is essential for supporting and enhancing robust SES science.”

Example of Protocols for a Best Practices Collection



1. Issue/question – Sustaining salmon for mixed economies on the Kenai Peninsula, AK.
2. Personnel – team of community stakeholders, agency managers, interdisciplinary scientists and students.
3. Data types needed – human demographics.

4. Data sources – US Census Bureau.
5. Data acquired to date – 1939 to 2010 at decadal increments.
6. Data format(s) – CSV spreadsheet.
7. Data gaps – Cooper Landing prior to 1950, Soldotna and Sterling prior to 1960.
8. Integration methods – coupled modeling using agent-based model.
9. Outcomes (products) – change in human population including rate and spatial distribution.
10. Application(s) – development of scenarios for changes in hydrology and landscape in 20 years.
11. Catalog record - <http://southcentral.epscor.alaska.edu/catalogs/7805>

Since change is constant and non-linear, the goal of sustainability cannot be to prevent our global SES from changing. Rather, it is to a) anticipate potential thresholds of adaptive capacity that, if passed, will reduce the quality of life on the planet, and b) effectively and proactively manage change in social and ecological systems to avoid reaching undesired thresholds.

Significant pressures being exerted on human systems have both social and ecological origins, that emerge and are realized at multiple scales. Successful adaptation will require effective decisions to shape our immediate and long-term future. Effective decisions require sound SES science, they simply cannot be made without it, and these must be based on:



Shell midden excavation at an ancient Coast Salish village site, Galiano Island, BC., Canada.

- 1) the identification of adaptive strategies for social-ecological change (including social responses, technological innovations, and ecosystem management), understanding the contexts in which they work and illuminate human decision-making strategies that make effective adaptation possible;
- 2) the recognition of the trade-offs and consequences inherent in all decisions, and that these need to be explicitly articulated and understood, yet no decision is without uncertainty - quantifying uncertainty is, at best, an analysis of data and statistical limitations, such that, tradeoffs may be more easily and precisely articulated;
- 3) anticipating when we might reach adaptive limitations, identifying strategies for mitigating those situations, and clarifying trade-offs and consequences for different strategies.
- 4) The development of SES early warning systems.

Success at achieving these goals depends on the ability of SES science to harness a broad range of scientific expertise using data derived from global and local scales, from long and short time frames, and from a range of systems.

Looking to the Past to Understand the Future

Kia whakatomuri te haere ki mua

To walk into the future our eyes must be fixed on the past

- Maori proverb

We have an inherent focus on the future. Working in the present and projecting from the recent past, we can leverage scenario development and computational modeling to identify critical relationships among social, technological and ecological systems that require better clarification. Models and scenario creation are useful ways to generate complex hypotheses for testing and guiding research, particularly in the context of uncertainties and trade-offs.

Yet future projections and hypothetical scenarios must be coupled with understanding of outcomes—what has happened in the past. An important strength of modeling is its ability to handle complex datasets and produce alternative outcomes and scenarios. But it draws on data with a very limited depth of time. Many of the important trade-offs and consequences from decision-making happen over longer time scales. Paleo, archeological and historical data, or data derived from past social and ecological systems, are the only data available for examining both cause and effect through long time, and for studying the consequences of decisions.

These types of data provide records of the outcomes of specific decisions that were part of adaptive strategies in the past. It also illuminates some of the decision-making strategies themselves, and the ecological and social circumstances in which decisions were made. Although technological innovation has been an important, seemingly distinct part of human problem solving, it is never implemented outside of social context. Paleo, archeological, and historical data offer an opportunity to study the social circumstances in which specific technological solutions were found to be feasible and when they were not. In this respect, strategies of decision-making are as important to successful adaptation as the decisions themselves. There is a need for data that provide a broad temporal window for inferring the kinds of decision-making that have been successful over the long term. For example, were solutions implemented in top-down ways over large regions, or were decisions made locally? Which ones were more successful? And why? In SES science, context is critical.

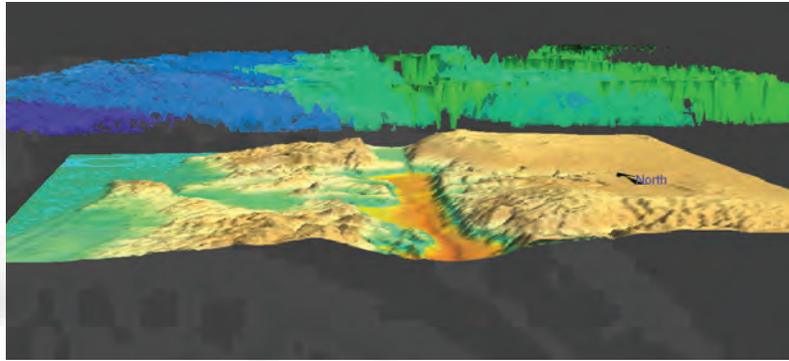
Circumstances in the past may not be directly analogous to the problems we face today, but the relationships between causes and effects are. In this respect, SES science requires both forecasting and hindcasting. SES research needs likewise to consider multiple scales, both temporal and spatial, and use deep temporal data to “ground truth” suppositions embedded in computational models and scenario development. Without this, we risk missing the complete range of possible available solutions, and confronting the future without full knowledge of what has and has not worked in the past.

“Best practices for SES science involve a complementarity of approaches that encompasses both looking to the past and looking to the future.”

Bringing the Past into the Future

Best practices for SES science involve a complementarity of approaches that encompasses both looking to the past and looking to the future. SES requires acknowledging the significant gaps in recent historical and spatial records, and recognizing that some solutions may in fact be unforeseeable from our stance in the present. Whereas better models and better data from recent times may diminish these limitations, it is also necessary to look to datasets covering long timeframes, which can suggest alternative scenarios and possibilities for building new models.

In several important respects, multi-generational place-based societies (e.g., Indigenous communities) provide an analogue for a potentially powerful methodology for SES. Community-based Observing Networks (see Section 2), through which ecologies were monitored quite closely and locally, have been part of traditional life-ways for millennia. Closely monitoring the environment has provided a foundation for: a) anticipating when and where adaptive stresses emerge; b) implementing practices that mitigate negative effects of change on human quality of life; c) developing successful adaptive strategies for negotiating unavoidable change; and d) developing social institutions to collect, manage and preserve ecological information. Ecological observations pooled through various social mechanisms created broad networks of knowledge holders integrated by expansive social networks.



Paleoclimate model for the Levant, Southwest Asia, represented as a space-time cube above terrain.

However, those recent observations and cumulative oral histories held in current traditional communities have their limitations, as data. Paleoecological and archaeological data can be used to bolster the resolution of observations of the deeper past. Paleoecologists and archaeologists are now regularly generating data spanning multiple millennia, yet providing annual to decadal reconstructions of past ecological and social conditions. These data offer an unparalleled opportunity to address relationships between ecological, technological and social change over many scales of time.

Paleo, archeological, and historical data also provide a record of the ways in which knowledge was maintained in the past. Analysis of community-based traditional societies both recent and ancient reveals that active retention of historical knowledge concerning ecological change, and developing mechanisms and institutions to maintain that knowledge, were major components of adaptive capacity. Although maintaining this knowledge pool was not without cost, it allowed a wide repertoire of potential solutions, providing flexibility in the face of an equally wide array of potential challenges. Today, we tend to promote a narrow range of solutions to a wide range of problems (e.g., exporting dry region agricultural practices to diverse ecosystems around the world), which stand in direct contrast to what we know about successful past adaptive strategies.

Strategies for Contemporary Problems Based on the Past

We propose that analysis of deep temporal data can be, at least in part, a means to overcome the limitations of future-casting research that employs primarily recent data in computational modeling and scenario development. Paleo, archaeological, and historical data allow us to see relationships between social and ecological change at multiple scales of time and space. They also allow us to understand social contexts in which decisions were made and how strategies played out. It offers the only way to assess the outcomes of decisions in terms of trade-offs and consequences as they actually happened

– as close as we might come to gaining the full benefit of hindsight.

“Social sciences research provides a means to study the inherently social components of adaptive capacity alongside the technological and ecological elements that we recognize as critical for generating solutions to modern problems.”

From a best practices perspective, it is critical to recognize these contributions as uniquely social science-based. Social sciences research provides a means to study the inherently social components of adaptive capacity alongside the technological and ecological elements that we recognize as critical for generating solutions to modern problems. SES research, too, must develop a diversity of strategies and diverse body of knowledge concerning potential solutions. The diversity of human societies, and therefore our potential knowledge pool, is significantly changing in configuration with globalization, from which we lose and gain forms of retaining experiences from the

past. An understanding of the complete range of potential solutions to change can only be achieved through the generation and analysis of paleo, archeological, and historical data.



Example of lessons learned from paleodata – Coast Salish

Paleodata provide us with examples of situations in which social change occurred in the absence of significant climate and associated ecological changes – on the Pacific Northwest Coast of North America, ecological change during much of the Holocene (circa 8000 years ago to recent) was less dramatic than in the late Pleistocene and early Holocene. The relevant data include archaeological and paleoecological records, the core of which come from long-standing village locations. These locations have been the focus of settlement in the Coast Salish region for as much as 5000 years. Analysis of village locations from the southern Gulf Islands reveals that adaptation to changing circumstances, particularly ensuring resource access for expanding permanent communities, was through technological investments in large-scale resource harvesting infrastructure, e.g., clam gardens, fish weirs and engineered wetland systems. Technological innovation, such as these, are implemented in a social context and are only successful as a solution if the social and institutional arrangements exist to capitalize on that technology.

5

Growing Human Capital & Diversity for SES Science

At a Glance:

Growing an SES science of integration depends on several conditions:

- Formation and maintenance of diverse teams across institutions capable of sustaining SES science products
- Training and re-training of scientists and practitioners at multiple stages, e.g., Interdisciplinary Graduate Education and Training (IGERT) program, and the National Research Training (NRT) programs, and the Social-ecological Systems Training and Education Program (SESTEP)
- Co-production of knowledge with stakeholders and decision-makers, including participatory approaches and scenario capabilities
- Integrating local, place-based knowledge, including Indigenous science



The Social-ecological Systems Training and Education Program (SESTEP)

SESTEP was developed using a flexible process to provide professional certification and graduate-level accreditation of SES in practice for land and natural resource practitioners, managers, and decision-makers. The 10-week SESTEP program includes a residential one week introduction, eight weeks of virtual course work on selected modules, and a residential one week capstone to conclude. During the in-person training, participants learn SES theory, communication and collaboration skills of working across disciplines, regulatory considerations, and a process to identify and analyze the SES system in which they work.

SES science is characterized by problem-oriented, multi-method, recursive, reflexive, and contextual approaches. Ultimately, our world is now more driven by social dynamics than it is by biophysical ones. Sustainable earth systems are combinations of social, biological, and physical processes, so for SES science to be successful, research on social as well as biophysical dynamics and processes must receive equal consideration in research effort and funding levels. Moreover, the importance of social decisions for the fate of earth systems sustaining our society means that knowledge must be accessible and useful to those making these decisions at all levels. This must go beyond open-source to become a part of the co-identification of the issues to be addressed and the pathways to understanding. By these approaches end-users will be more likely to the resulting knowledge as something they own,



Stakeholders and scientists co-designing a social geodatabase

and because of this, are more likely to use it. We have moved beyond convincing social and natural scientists of the need for their participation in SES science to coalescing the numerous willing scientists whose interests and practices are SES-focused. The challenge is not only that of how to fund this type of work, but also how to co-design and co-produce shared questions, research design, comparable protocols, and the skills necessary to implement them. This emphasizes the importance of interdisciplinary research teams, the fostering of group processes and personalities facilitating collaborative research, and the co-production of knowledge through engagement with stakeholders and decision-makers. Programs such as Science and Technology Alliance for Global Sustainability sponsored Future Earth are contributing to move the

international research community in these directions.

Growing Knowledge

Knowledge generated by SES science is of little use in anticipating and adapting to change if it is generated in isolation from broader society which has historically been a practice in disciplinary science. New forms of communication and close collaboration between science and policy are more important for SES science than for many other fields. We recommend that scientists, practitioners, funding agencies, stakeholders, and community members collaborate in the co-production of periodic state-of-coupled earth systems syntheses of SES science for broad dissemination to the public. Such a report could highlight new conceptual frameworks, data sources, methodological advances, relevant studies, near-term threats to sustainability, potential critical transitions in key aspects of global-scale SES, and relevant adaptation and mitigation strategies. Because of the rapidly changing conditions of SES, such a report should be updated at regular intervals. With telecouplings (socioeconomic and environmental over long distances) such as disease spread, for instance, previously unseen diseases appearing rapidly in North America, and cross-country operations of multi-nation-

“Knowledge generated by SES science is of little use in anticipating and adapting to change if it is generated in isolation from broader society.”



Hydroelectric and other infrastructure have rarely been examined in an SES context.

al corporations, global markets, and international NGOs. Sustaining resilient SES is a global issue as well as a regional, national, and local issue. As should be clear from phenomena like Asian dust in North America, declining global fisheries, and the recent global recession, events in one part of the world can rapidly cascade to have consequences in neighboring and distant parts of the globe. SES science needs to embody a similarly global scope. A report on the state of sustainability knowledge needs its focus to be global but can be composed of regional nodes.

Interdisciplinary Teams

Formation and maintenance of interdisciplinary teams is essential for developing and evolving an integrated SES science, that is, a Science of Integration. Having shared and complementary goals across domains is critical to enabling the best inquiry teams. There are significant challenges in overcoming institutional barriers to collaborative/interdisciplinary research and consequently in developing institutions that encourage integrative and interdisciplinary science. A potential mechanism within funding agencies (e.g., National Science Foundation) to better enable functional interdisciplinary teams would be to expand requirements documenting the processes involved in forming and sustaining interdisciplinary teams. New interdisciplinary-based programs could build upon the experiences from previous programs (e.g., Human Social Dynamics HSD) and existing programs (e.g., Dynamics of Coupled Natural Human systems CNH), such that methods of co-design and co-production, as a science of team science, can be advanced through SES science. This expansion enhances cost sharing and leveraging but may initially be resisted both by program managers and practitioners. Recognizing that the team context is crucial, interdisciplinary teams should undertake explicit self-assessment of the challenges for, and strengths in, integration projects, in order to understand the factors encouraging and discouraging integration in SES science. Such factors operate at multiple levels – the individual, the team, the project, and the broader institutional context in which they occur. Current practices in stand-alone disciplines for training students to be researchers are inadequate in preparing students for the kind of work needed in SES science. Students need to learn to work in teams, in which each member has diverse skills, can complement others' work, and employ an adequate division of labor. Training in social sciences and computational science may need to be adjusted to allow social scientists and computational scientists to work productively together. Social scientists' training should include more quantitative and computational skills. This could be in the form of a basic course (e.g., "Computational Social Science Methods and Applications") or a certificate program. In short, we need to change how we train PhD students to support SES science by establishing both content and pedagogy for a 'Science of Integration.

Academic training or professional development creatively re-envisioned to be more robust would include a number of general characteristics. Training in statistics, for example, could be expanded to encompass data analysis applied to real world case studies and accompanied by training in models and scenarios; this can emphasize the intimate connection between data and models, and would include training in both making and using models. In academia or in professional practice, students should be aware of the power and limitations of the tools they use. For example, they should be skeptical



Designing resilient landscapes graduate student class, Moscow, ID

about model outputs or topologies and should understand the importance of making assumptions precise. Training should be cross-disciplinary and transcend institutional boundaries—for example, by embedding upper level students in other domains for cross training and experience or allowing capstone or practicum course students to work with clients (e.g., university researchers, community organizations, or decision makers). Unfortunately, some of the most resistant barriers lie among faculty and administrators themselves.

In part, because of this, it is important to incentivize participation in integrative science, particularly for pre-tenure-level researchers. Senior scientists, faculty members, and university administrators must take on this obligation; they should be strongly promoted by prestigious academic organizations like the National Academy of Sciences (NAS). To this end, universities and research institutions could be ranked by the NAS according to the degree to which they encourage and reward team-based SES science. Community-wide standards should be established to indicate the contribution of each individual to interdisciplinary research, standards that could be enforced by journals publishing such research.

“We should be skeptical about model outputs or topologies and should understand the importance of making assumptions precise.”

The goal would be to ensure that senior faculty are motivated and junior faculty are rewarded (rather than punished) for participation in large-scale, interdisciplinary SES science. The archaic practice of allocating credit to a single individual must be carefully re-examined if we are to build a culture of team-based SES science. The task of universities is to explicitly train the next generation of scientists in the practice of team-based research, to prepare them for leading SES science

projects. The NSF’s Integrative Graduate Education and Research Traineeship (IGERT) program, and its successor the NSF Research Traineeship (NRT), explicitly encourages this kind of training, but it should also be broadly embedded in both undergraduate and graduate training for the disciplines contributing to SES science and more rigorously evaluated. This will be another benefit of the establishment of community standards through a Best Practices Collection and test bed.

Building Toolboxes for SES Scientists

Recent mandates by the U.S. government call for increased integration of social and natural sciences among practitioners, scholars, and policy makers. The field of SES, explored in theory, has seen little cohesive advancement in practical application. Mid-career practitioners, particularly those in state and federal agencies, are a forgotten demographic albeit one that is critical to advancing an SES science of integration from theory to practice. To fill this gap, the Social Ecological Systems Training and Education Program (SESTEP) was developed in 2014, using a flexible process to provide SES training to working professionals and improve SES tools available for natural resource management through building on inherent knowledge within the program participant group.

SESTEP offers a mechanism to train managers, professionals, and agency personnel at all levels, so that they are better prepared to tackle the complex human and environmental challenges present in natural and built landscapes. It is a modular, mixed methods program that focuses on understanding how to identify discrete SES for the purposes of developing better management strategies, and understanding the connections and feedback dynamics between its different components.

Education, training and professional development should focus on producing integrative scientists from diverse disciplines. We expect these individuals will be self-selected, particularly at mid-career levels. However, broadening the participation in SES science is also needed, and could benefit from training at the undergraduate and graduate levels—even as early as K-12 education. This training should incorporate complex systems thinking at the earliest levels. Broadening participation is crucial beyond the metrics of ‘diversity’. Since many of the most difficult SES issues have the greatest consequences to marginalized populations we desperately need those perspectives, worldviews, and experience to build a SES science that has broader meaning.

Both students and established researchers working in SES science need training to work in the new ways that this report advocates. For example, they may need training in creating and documenting effective workflows or in using new tools for data integration. Courses and training that formally engage decision makers may also be especially valuable because we need to move from theory to application in diverse and messy types of SES. Because these skills are new to many scientists a new community of practice may be needed. Organizations, including, management and funding agencies, NGOs, and foundations, will need to incentivize individuals who contribute to, and promote, this community of practice.

6

Moving Toward A Science of Integration: Building a Better America

To achieve a systematic, integrative, and multi-scale program described in this report will require that funding agencies expand their thinking to re-evaluate a broader range of outcomes and products. More importantly, we urge far greater communication and coordination across agencies.

Below we offer specific actions needed, in part, to address this urgent need to advance SES science.

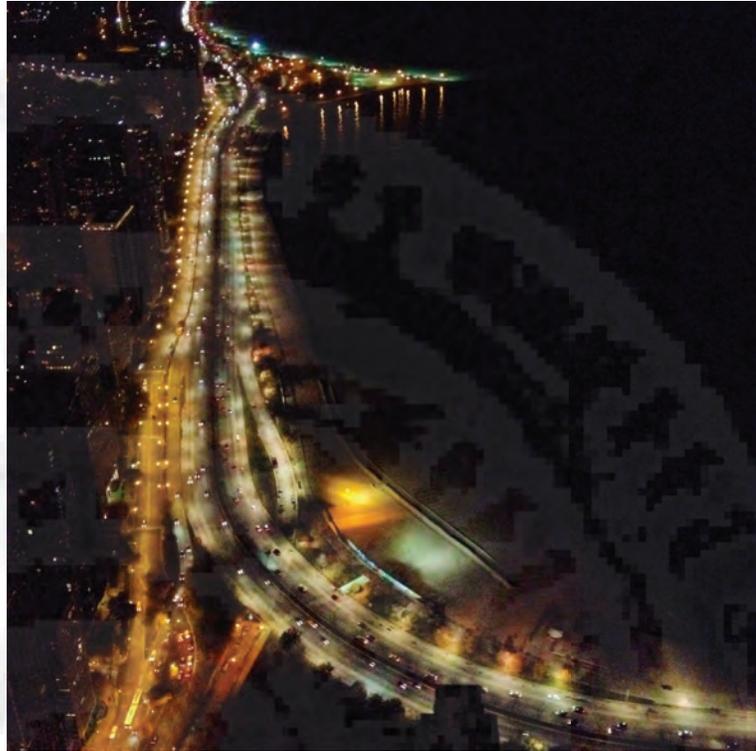
Investments in infrastructure will be required. One component of this we might loosely call ‘hardware,’ an area that has traditionally been funded. But the infrastructure required for SES science will have additional facets. To create a common framework required for large-scale, multidisciplinary, team-based science requires new software for sharing and analyzing data, and for creating and documenting workflows. It will require not only new code but, possibly, new programming languages, new data formats (especially self-describing formats), new data analysis packages, new database structures, harmonization of existing data within these structures, metadata, and ontologies, and new platforms for workflow management. Software development must echo, and complement, advances in knowledge gained in theoretical developments. Reconciliations between existing theoretical concepts, sharpening of focus and resolution of ambiguities in existing theoretical constructs, and the development of entirely new theoretical approaches should be supported as a key complement to other advancements in sustainability research.

“Investments in infrastructure will be required.”

These software and theoretical tools will, additionally, play a part in achieving the larger goal of creating communities of practice that collaborate effectively in a broad program of issues and solutions-based inquiry. A crucial goal is the development of a community of scholars who will work together across disciplines in ways demanded by the SES science. Funding agencies are encouraged to find means of contributing to the development of these communities, as well as supporting institutional changes that provide incentive for participation in these communities, not only by scholars in traditional disciplines but also by

young researchers and students beginning their careers.

SES science will require a new paradigm of engagement with stakeholders: organizations, institutions, and individuals who participate in the systems under study. This will ultimately necessitate a new way of thinking about how we form science teams. Only then will SES science be better able to build a more secure nation. This will require the co-identification of issues with stakeholders, and then co-production of knowledge to tackle these issues. The ways these communities perceive and define change and risks at multiple time scales and the ways they assess and select alternative actions in the face of a changing nation are core to this; the use of integrated models and scenarios as tools to explore such issues are similarly key to SES science.



Critical Infrastructure is a central component of a SES early warning system..

These approaches will be new. They will require training a new type of researcher and practitioner. This process must also be encouraged, rather than discouraged, by institutional systems in which they work: opportunities and promotions must be available to those who contribute to team-based science. Funding agencies should facilitate professional development for researchers who push forward SES science programs.

With these concerns at the fore, we recommend that as a community, we the following specific actions:

Section 1: Establishing Common Reference Frames, Data Analytics and New Technologies

“SES science will require a new paradigm of engagement with stakeholders: organizations, institutions, and individuals who participate in the systems under study.”

1. Encourage common data formats, policies, standards, ontologies, and workflows;
2. Encourage transparent, well-documented, and replicable methods;
3. Require that any federally funded research include documentation of project workflows during instrument design and before data collection, include descriptions of the appropriate measurements to be taken, and describe both the data and the metadata (this goes beyond a simple data management plan);

4. Support the establishment of a national center for advanced social analytics.

Section 2: Co-design and Co-production of Knowledge

1. Develop protocols and standards for the co-identification of issues, the data to be collected, and the kinds of knowledge that need to be co-produced and protected, if necessary;
2. Encourage research recognizing the real theoretical advantages of the interdisciplinary co-production of knowledge more deeply and precisely than an assemblage of multiple experts remaining in their own disciplinary silos, integration starts at the beginning of a workflow plan, not as a collection of information in one place;
3. Support development and implementation of community-based observation networks as social observing networks built on partnerships between scientists and stakeholders;
4. Support development and implementation of adaptive capacity indices and early warning systems that provide a systematic synthesis of key social, biological and physical indicators that allow for targeted coordinated preparedness and responses to occur under changing conditions.

Section 3: Means of Sustaining and Evolving Best Practices

1. Support development of an open source, curated collection of current SES best practices so as to accelerate a science of integration;
2. Encourage sharing and archiving of SES science practices as an integral requirement for research awards as part of the development of national standards;
3. Move toward a computational framework for SES science that includes strong, if not implicit, geospatial foundations.
4. Ensure that co-produced SES products are the result of clear work-flows and vetted methods of integration.

Section 4: Leveraging Lessons Learned in the Past

1. Identify strategies for adapting to the impacts of social-ecological change (including social responses, technological innovations, and ecosystem management), understand in what context they work, and illuminate human decision-making strategies that make effective adaptation possible;
2. Quantify the trade-offs and consequences to decisions;
3. Promote and implement research in early warning systems that allows for better informed decision-making, involving anticipating critical transitions in SES, identifying strategies for mitigating their impact, and clarifying the trade-offs and consequences of different strategies;
4. Support a three-pronged strategy for research, involving the use of deep temporal data, computational modeling, and scenario development.

Section 5: Growing Human Capital and Diversity for SES Science

1. SES scientists, funding agencies, universities, private institutions, and research centers should collaborate in the production of periodic state-of-coupled human earth systems syntheses of SES science for broad dissemination to the public;
2. Agencies should support SES training for practitioners who have historically been omitted from the “K through gray” continuum, e.g., the Social-ecological systems training and education program (SESTEP).

3. Systems, and specifically complex systems-thinking should be built into science curricular standards at all levels across disciplines beyond just STEM;
4. Undergraduate and graduate students should become competent in interdisciplinary team-based work as well as various computational tools for data integration, which will help develop the cognitive skills required for systems thinking as well as the continued development and use of these methods throughout their careers.



Key References and Suggested Reading

Section 1: Establishing Common Reference Frames, Data Analytics and New Technologies

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Lilian Alessa, Director, The Alaska Experimental Program to Stimulate Competitive Research (EPSCoR); President's Professor and co-Director of the Center for Resilient Communities at the University of Idaho. She conducts extensive research on human adaptation to global and environmental change, funded by the National Science Foundation, including Arctic Observing Network and Dynamics of Coupled Natural Human Systems projects as well as the Department of Homeland Security. Canadian-born and raised, Alessa received her degrees from the University of British Columbia. Her expertise is in social-ecological systems science and the development of highly integrated approaches to better understanding complex environmental processes, particularly through the incorporation of place-based knowledge.

Andrew Kliskey



Andrew Kliskey, University of Idaho is a Professor of Landscape Social-ecology, he co-led the Resilience and Adaptive Management (RAM) Group at University of Alaska Anchorage for 10 years, and is now co-Director of the Center for Resilient Communities at UIIdaho. Originally from Aotearoa / New Zealand he trained as a land surveyor, resource planner, and earned a PhD degree in geography that integrated geographic information systems, behavioral geography, and resource management. He has spent the last 10 years working with people in Inupiat communities in northwestern Alaska and Denai'na communities in southcentral Alaska examining community perception and response to environmental change.

Mark Altaweel



Mark Altaweel, University College London a Lecturer whose research interests include understanding social-environmental change in modern and ancient societies in a variety of regions throughout the world including in the Arctic, Near East, Southeast Asia, North America, and Central Asia. In the first seven years after finishing his PhD, he has led a number of grants as a PI or Co-PI with collaborators in Economics, Anthropology, Archaeology, Sociology, Environmental Studies, Geography, Computer Science, and other fields. In addition to academic publications, Mark is interested in developing and applying open source tools to research problems in complexity science. While his current appointment is at University College London, he has held previous appointments at the University of Chicago, University of Alaska, and Argonne National Laboratory. He is currently on the editorial board of two journals.

C. Michael Barton



C. Michael Barton, Arizona State University, is Director of the Center for Social Dynamics and Complexity and Professor of Anthropology in the School of Human Evolution and Social Change, and Visiting Research Professor at the Universitat de València. He also is the director of CoMSES Net (Network for Computational Modeling in Social and Ecological Sciences). A Fulbright Senior Fellow, Barton holds a PhD in anthropology/archaeology and geosciences from the University of Arizona. Barton's research interests center around long-term human ecology, and the dynamic interactions of societies and landscapes. He also co-directs research on the social impacts of future climate change, in collaboration with the National Center for Atmospheric Research.

Steven C. Bankes



Steven C. Bankes, BAE Systems, is a Chief Engineer at BAE Systems-Technology Solutions. Prior to joining BAE, he was a Senior Computer Scientist with the RAND Corporation where he did computational modeling for scientific, public policy, industrial, and commercial applications and Chief Technology Officer for Evolving Logic, Inc., where he developed robust planning software for government and commercial customers. Dr. Bankes's research interests are in the areas of computational science and methods for decision analysis with computational models. His work has involved diverse topics including global climate, economic development, regional environmental policy, international relations, automotive industry product design, and technology investment.

Eduardo S. Brondizio



Professor of Anthropology, Indiana University Bloomington, co-director of the Anthropological Center for Training and Research on Global Environmental Change (ACT) and chair of the Advisory Council of the Ostrom Workshop in Political Theory and Policy Analysis. Brondizio maintains an active longitudinal research program examining the transformation of society and landscapes of the Amazon, particularly from the perspective of rural populations and their interactions with regional development, urban centers, global markets, and climate change. Brondizio has been closely engaged with international global changed research programs since the mid-1990s and has contributed to several past and on-going global assessments. Brondizio is a member of the inaugural Science Committee of Future Earth and the Science Committee of International Geosphere-Biosphere Program (IGBP), and co-Editor-in-Chief of Current Opinions in Environmental Sustainability.

Daniel G. Brown



Daniel G. Brown is a Professor in the School of Natural Resources and Environment and Research Professor in the Institute for Social Research at the University of Michigan, where he directs the Environmental Spatial Analysis Lab. His work, published in over 150 refereed articles, chapters, and proceedings papers, has aimed at understanding human-environment interactions through a focus on land-use and land-cover changes, through modeling these changes, and through spatial analysis and remote sensing methods for characterizing landscape patterns. A fellow of the American Association for the Advancement of Science, he also chairs the Carbon Cycle Steering Group and was a coordinating lead author for the National Climate Assessment, both under the auspices of the U.S. Climate Change Science Program.

Johannes Feddema



Johannes Feddema is Professor and Chair of Geography at the University of Kansas, and affiliate scientist at the National Center for Atmospheric Research. His primary interest is in understanding the human impact on the Earth's surface, and the consequences of these actions on the environment. More specifically I wish to understand anthropogenic impacts on climate, and how climate change affects the environment and society. His current research primarily aims to simulate human impacts on the Earth's surface in large-scale climate models. I am collaborating with researchers at the National Center for Atmospheric Research (NCAR) to develop an urban model in NCAR's Community Land Model. I am also building the accompanying datasets to drive these models using satellite data, historical information on human agriculture, grazing and soil degradation, and data from future scenarios from the Inter-governmental Panel on Climate Change (IPCC).

Emilio F. Moran



Emilio F. Moran is John A. Hannah Distinguished Professor at Michigan State University since 2013. His home is in the Geography Department, the Center for Global Change and Earth Observations and at the Center for Systems Integration and Sustainability. He was previously Distinguished Professor and the James H. Rudy Professor of Anthropology at Indiana University. He is the author of ten books, fifteen edited volumes, and more than 190 journal articles and book chapters. He is formally trained in anthropology, geography, ecology, soil science and satellite remote sensing. His work for the past 20 years has been focused on linking the social and natural sciences addressing questions on land use and land cover change, and population and environment. His research has been supported by NSF, NIH, NOAA, and NASA. His three latest books, *Environmental Social Science* (Wiley/Blackwell 2010), *People and Nature* (Blackwell 2006), and *Human Adaptability*, 3rd edition (Westview 2007) address broad issues of human interaction with the environment. He is a past Guggenheim Fellow, a Fellow of the Linnean Society of London, Fellow of the American Anthropological Association and the Society for Applied Anthropology, Fellow of the American Association for the Advancement of Science, and was elected a member of the U.S. National Academy of Sciences in 2010.

Jonathan Ozik



Jonathan Ozik, University of Chicago, is a Computational Social Scientist in the Center for Complex Adaptive Agent Systems Simulation within the Decision and Information Sciences Division at Argonne National Laboratory and a Fellow in the Computation Institute at UChicago. Dr. Ozik's research focus is in the broad and emerging field of social computation. His research involves the modeling of predominantly social complex systems. The goal is to better understand the mechanisms at play in the multiple spatio-temporal levels often required to encapsulate the behaviors of complex systems and the often counterintuitive emergent micro and macro patterns that such systems can exhibit.

William Rand



William Rand examines the use of computational modeling techniques, like agent-based modeling, geographic information systems, social network analysis, and machine learning, to help understand and analyze complex systems, such as the diffusion of innovation, organizational learning, and economic markets. He serves as the Director of the Center for Complexity in Business, that focuses on the application of complex systems techniques to business applications and management science. He received his doctorate in Computer Science from the University of Michigan in 2005 where he worked on the application of evolutionary computation techniques to dynamic environments, and built a large-scale agent-based model of suburban sprawl. He has recently received research awards from DARPA, Google / WPP, the National Science Foundation and the Marketing Science Institute.

Shaowen Wang



Shaowen Wang is a Professor of Geography and Geographic Information Science (Primary), Computer Science, Library and Information Science, and Urban and Regional Planning at the University of Illinois at Urbana-Champaign (UIUC). He is the Associate Director of the National Center for Supercomputing Applications (NCSA) for CyberGIS and and Founding Director of the CyberGIS Center for Advanced Digital and Spatial Studies at UIUC. He received his BS in Computer Engineering from Tianjin University in 1995, MS in Geography from Peking University in 1998, and MS of Computer Science and PhD in Geography from the University of Iowa in 2002 and 2004 respectively. His research and teaching interests include complex environmental and geospatial problems, computational and data sciences, geographic information science and systems (GIS), cyberGIS and cyberinfrastructure, high performance parallel and distributed computing, and spatial analysis and modeling.

J. Daniel Rogers



J. Daniel Rogers, is a Curator of Archaeology in the Department of Anthropology at the National Museum of Natural History (NMNH) at the Smithsonian Institution, and Adjunct Professor at George Mason University. His work has often focused on households as a bridge to understanding the structure of complex societies and the interrelatedness of settlement, subsistence and political structures on a macroscopic scale. He has also done significant research on interpreting the processes of culture contact and colonization at the edges of empires by comparing data from a variety of areas, including the Great Plains, Central Mexico, the Caribbean, and Inner Asia. His recent work explores the human impact on the environment as evidenced by archaeology. Through National Science Foundation grants, Dr. Rogers and collaborators at George Mason University are using agent-based simulations to model the rise and fall of Inner Asian empires. Eventually, the team will explore long-term human impacts on the environment, especially the sustainability and resilience of different social systems.

NSF-Sponsored Workshop Participant List

In October 2012, the NSF-sponsored workshop “Best Practices for Integrating Social Sciences into Sustainability Science” took place at the University of Chicago, Computation Institute. 35 of the country’s leading integrative scientists came together to address key challenges related to integrating the social sciences into sustainability science.

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Altaweel, Mark.....	UCL
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