Examining Threats to Iconic National Parks through Modeling Global Change, Biocomplexity, and Human Dynamics

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Among the factors posing new and complex challenges to coupled natural–human components of iconic parks systems are globalization, climate and environmental change, economic development, population migration, international tourism, land use/land cover dynamics, and political instability of governments and institutions. These challenges are evident in almost all settings and are certainly emerging within and at the edges of iconic national parks (Porter-Bolland et al. 2011; Sieck et al. 2011). Created in part to maintain biodiversity, iconic national parks focus world attention on conservation by representing special places of highly valued and emblematic species, as well as sites of fragile, sensitive, and unique ecosystems (Velarde et al. 2005; Walsh and Mena 2013). Iconic protected species and landscapes, however, are under considerable threat from population migration, economic development, and environmental dynamics, which act synergistically and are exacerbated by climate change (Stolton and Dudley 2010).

Iconic national parks are often perceived by the public to be more sensitive to these issues because of their high profile and thus become targets of human interest and concern. Ultimately, the sustainability of these places depends on the adaptive behavior of society, the vulnerability and resilience of the terrestrial and/or marine ecosystems, and the ability of the social system to cope with conflicting demands and feedbacks. Management capacity to deliver sustainable conservation and recreational outcomes is challenged by uncertainty about the internal and external dynamics between elements of the park system as well as global-level exogenous dynamics. In this paper, we propose a *biocomplexity* framework for exploring the system dynamics of iconic national parks in the context of global change, both environmental and socioeconomic. The biocomplexity framework expands on the conceptual framework of Miller et al. (this issue), and is our foundation for modeling coupled human–natural systems of iconic national park systems. Dynamic systems models are suggested as an integrative and synthetic test-bed. Such models can simulate, predict, and mediate conditions given specified stocks, flows, exchange rates, and feedback loops between key parameters.

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An overarching program of collaborative research

The general intent of this project is to position research collaborators for developing overarching research hypotheses and scientific proposals, resulting in an international network of researchers and research questions for the study of iconic national parks. To better understand the drivers and patterns of change in parks and across diverse environments, we propose the fusion of disparate data and theoretical assumptions to synthesize knowledge and generate prognostic outcomes interpreted within a biocomplexity context (complex adaptive systems, non-linear system dynamics, emergent behaviors, feedback mechanisms, and critical thresholds). The fundamental questions to be addressed are:

- Can ecological sustainability be achieved for iconic national parks threatened by the direct and indirect consequences of global change and associated social and ecological dynamics?
- How might the impacts of these changes affect iconic landscapes and species?
- How might these effects mediate tourist behavior in their choice of destinations and satisfaction levels when visiting some of the most sensitive places on earth?

Tourism, an important economic driver at local, regional, and national levels, is highlighted as an international force that influences global change, a feedback to shifting patterns of ecosystem goods and services, and a central factor affecting the sustainability of iconic species and landscapes in an international network of national parks. Further, tourism heightens social knowledge regarding the central issues related to the sustainability of iconic parks.

To study the questions, we propose:

- A theoretical perspective, rooted in biocomplexity, involving a coupled human–natural system that is representative of the interactions and feedback loops within and among ecological systems, the physical systems on which they depend, and the human systems with which they interact (Michener et al. 2003; Walsh et al. 2011);
- Identification of the linkages between social–ecological subsystems for a group of national parks that are internationally recognized for their emblematic species and iconic landscapes and arrayed along a multi-dimensional gradient of social and ecological vulnerability;
- A description of how these linkages are influenced by internal and external perturbations;
- An assessment of local to national challenges to their sustainability; and,
- Use of dynamic simulation models to explore scenarios of change that are capable of accommodating human–environment interactions (including management interventions) and endogenous and exogenous dynamics (Walsh et al. 2013; Malanson et al. 2014).

This general approach provides a global model and perspective for assessing the health of national parks and other fragile and vulnerable sites under stress from human activity and natural forces (Coombes and Jones 2010).

The biocomplexity context. This context provides a link to the identification of critical thresholds in system dynamics, feedback mechanisms that mediate systems, and the emergence of new system behaviors that offer insights into social and ecological interactions in non-linear systems. This will necessitate modeling multiple components, interacting in ways that link patterns and processes across scales (Walsh et al. 2011, 2013). Endogenous and exogenous factors combine in complex ways to alter the vulnerability and resilience of system components (White and Engelen 1993), but complex systems evolve through time, and their past is co-responsible for their present behavior (Cilliers 1998). Further, the uses of complex systems focus on irreducible complexity arising from simplicity. This view sees the complex nature of systems as emerging from nonlinearities due to large numbers of interactions involving feedbacks occurring at one or more lower levels within the system. Complex systems are generally far from being in equilibrium (Bak 1998), with a constant set of interactions that maintain system organization through negative feedbacks or alter subsequent alternatives through positive feedbacks. Thus, complexity theory holds that systems cannot be suitably understood without focusing on the feedbacks and nonlinearities that lead to emergent multi-scale phenomena (Matthews et al. 1999). A complexity theory analysis aims at understanding feedback mechanisms and changes in state-space through nonlinearities and thresholds, in relation to a dynamic environment with the goal of understanding how simple, fundamental processes combine to produce complex holistic systems (Luhmann 1985).

While global changes, including the forces associated with tourism and population migration, exert exogenous pressures on ecosystems, the coupled human–natural systems have their own spatially contingent endogenous dynamics (Gonzalez et al. 2008). Positive and negative feedbacks that shape and re-shape the relationships between people and the environment are critically important. For example, the consumptive pressures on the environment by the expanding human dimension has serious consequences for national park sustainability, but these pressures can be ameliorated by increased adoption of a conservation ideology, scientific knowledge, and adaptive policies.

The application of biocomplexity theory is providing insights on the dynamics occurring in such settings by looking for universal properties in spatially extended systems (see the special issue of *GeoForum*, edited by Walsh and McGinnis 2008). Feedbacks between people, places, and the environment constrain or even reverse some of the original changes in land cover and land use through system dynamics (Matthews et al. 1999). In this way, properties emerging from local nonlinear feedbacks constrain the evolving patterns of land use (Blackman 2000). Critical points in the spatial structure of the environment patterns and feedbacks can produce a system with identifiable future alternative states in which instabilities can "flip" a system into another regime of behavior by changing the processes that control social–ecological interactions (Parker et al. 2003).

Adaptive capacity and resilience within a biocomplexity frame. The intent is to examine the adaptive capacity and resilience of iconic national parks and management responses by examining a suite of multi-dimensional forces and factors that threaten their social–ecological sustainability (Figure 1). These factors can be divided into three broad areas: (1) global change impacts on the biophysical and socioeconomic conditions within and around the national park that affect the status of the iconic features of the park; (2) the resource management response to these changes and their outcomes; and (3) the socioeconomic responses

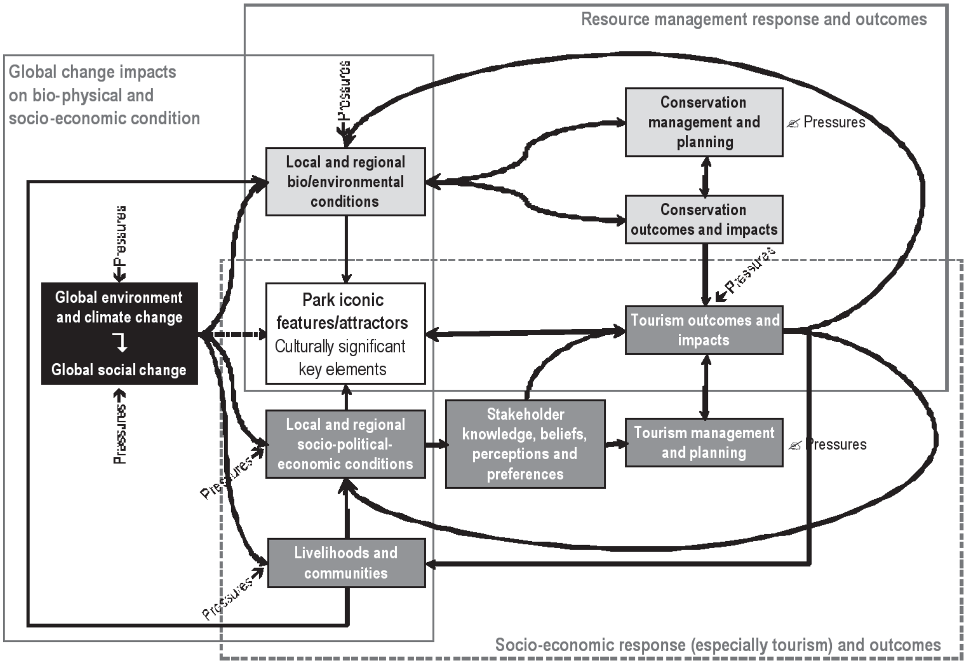


Figure 1. A biocomplexity framework for exploring coupled natural–human components of iconic national park systems towards addressing vulnerability.

and outcomes. We propose to consider tourism specifically, because of its interdependency with the status of iconic features of the parks.

The social–ecological threats to iconic national parks that we address include:

- Demographic changes (including tourist flows, migrants, and endogenous population growth);
- Economic changes (including the development of local, national, and global markets for terrestrial and/or marine resources, tourism, agricultural products, and household livelihood alternatives);
- Biophysical changes (including changes in ecosystem goods and services, such as habitat dynamics, which affect iconic, native, and endemic as well as invasive species, their influence on land productivity, and changes in system elements such a fire frequency and associated disturbance regimes);
- Marine and land use changes (including "foundational" effects on fringing mangroves and their ability to serve as nurseries for juvenile fish, crustaceans, and marine mammals linked to sea-level rise, and the impact of within and among island connectivity of marine species on habitat dynamics and value of local fisheries); and
- Global climate change, including the impacts of ENSO (El Niño–Southern Oscillation) and PDO (Pacific Decadal Oscillation) events, such as the effects of El Niño on ocean upwelling, marine productivity, and species migration.

Choice of case study national parks

We propose selecting 15 to 20 iconic national parks through a preliminary review of over 100 areas, which vary by geographic settings and circumstances, to collectively represent a social–ecological gradient as an analogue of other similarly challenged iconic national parks around the globe.

Capturing the diversity of iconic national parks. Secondary analysis of iconic national parks is needed to objectively capture the diversity of case-specific global change issues. The purpose of this secondary analysis is to select in-depth case study sites representative of the diversity of contexts in which iconic national parks exist. The set would offer differences in their direct and indirect impacts on the environment caused by an expanding human dimension (e.g., increases in tourism and the demand for economic development in bordering areas and nearby communities). They would also capture differences in ecological dynamics and changes caused by exogenous factors (e.g., ablation of alpine glaciers, increases in coral reef change, and threats within their local and regional surroundings).

Parks would need to meet four criteria: they must (1) be high profile, with nature-based tourism; (2) be potentially heavily impacted by climate and global change; (3) have local communities that rely on national park tourism, and (4) exhibit ecosystem diversity and vulnerability to change. One approach would be to plot iconic national parks against multiple axes or dimensions to develop the gradient of vulnerability. Existing databases from the World Commission on Protected Areas and other data sources could be used for this purpose. For example, the first axis might be a measure of the park's susceptibility to global change and the second a measure of the its adaptive capacity to accommodate social and ecological change (Figure 2) (cf. Leverington et al. 2010).

Among the factors to be considered to ordinate is a sample of candidate sites in multi-dimensional space (and within a space–time context). Additionally, the selection of parks for study might include: (1) population migration and tourism; (2) invasive flora and fauna; (3) land use change and food security and provisioning; (4) quality and quantity of available freshwater; (5) old versus new human settlement patterns; (6) social and ecological disturbance regimes; (7) climate change and the attendant threats related to sea-level rise, ocean warming, and ENSO and PDO events; (8) conservation and development infrastructure; (9) geographic position and accessibility; (10) governance, institutions, and policies; (11) natural hazards, geodynamics, and tectonic deformation; (12) national park status; (13) globalization and local to international connectivity; (14) terrestrial and marine participatory management and their effectiveness; and (15) levels of biodiversity and endemism.

Proof-of-concept park selection. Through a preliminary assessment, we have chosen five study areas to anchor our sustainability gradient. For each national park, we examine elements of the social, terrestrial, and/or marine subsystems with the intent of conducting innovative research that supports transformative

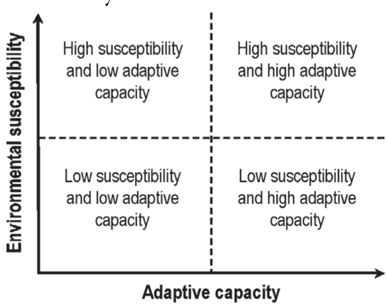


Figure 2. A two-dimensional plot for the selection of detailed case study sites.

interdisciplinary understanding of biocomplexity, dynamic systems modeling, and endogenous and exogenous forces that threaten park sustainability.

Generally, case study parks have been chosen for their biodiversity; namely, their broad representation of the planet's biological communities, species richness, biological distinctiveness, and intactness. Protection is not only about space, but also about functional groups, keystone species, climatic refugia, and multiple habitats within a biome to provide adequate representation and protection. There are a myriad of stressors that affect natural systems, and the limited body of research on the effects of climate and non-climate stressors suggests synergistic responses. Management and policy are essential to reduce local stressors on natural systems and to increase the overall resilience of systems (Tompkins and Adger 2004). If climatic alterations take place as predicted, for example, static national parks may not assure habitat persistence, ecosystem functioning, and the capacity to support all the species they were designed to protect (Burrows et al. 2011).

Our proposed research is a case study of multiple national parks recognized not only for their iconic species and landscapes, but also their international tourism markets (their possible negative consequences for the environment), and their vulnerability to global change and its effect on their associated social and ecological systems. We begin through a phased approach in which a network of "primary" national parks are used for initial study, followed by the inclusion of a "secondary" group that extends representation within the social and ecological gradient. The primary group of national parks is the Changbai Mountains Nature Reserve, China; Galapagos National Park, Ecuador; Great Barrier Reef Marine Park and Fraser Island, Australia; Kruger National Park, South Africa; and Yellowstone National Park, USA (Table 1). These have been chosen because of their diversity of stages of community reliance on tourism, available information to assess their vulnerability, personal links to the national parks and the conservation management teams, and the presence of associated project teams and institutions that have conducted preliminary research to guide more substantial and expansive efforts. In addition, these parks are high-profile and iconic tourism destinations, and management is cognizant of the need to provide leadership in addressing the impacts of climate and global change due to tourism's vulnerability.

The similarities and differences of the ecosystems allow for meaningful comparison of the issues and impacts associated with climate change on tourism as well as on ecosystems goods and services. The collective case studies provide comparative opportunities across continents where reliance on tourism, as a contributor to the local and regional GDP, is substantial. Internationally renowned, iconic national parks attract high levels of media interest. Therefore, they draw the attention of the global community to the need to reconcile social and ecological threats to the sustainability of biodiversity and endemism that enables the conservation of iconic megafauna, such as the grizzly bears and bison of Yellowstone; the giant tortoises, marine iguanas, and hammerhead sharks of the Galapagos; the Big Five wildlife species of Kruger; and the dingoes of Fraser Island.

These selected national parks capture differences in iconic species; landscape morphology; residential, migrant, and tourist populations; levels of economic and infrastructure development in the nearby communities; household livelihood alternatives in agriculture,

Table 1. Summary general vulnerability status, threat level and type, adaptive capacity, and community and tourism dependence of the selected network of international iconic national parks. (Type: HC–habitat change, SLR–sea-level rise.)

National park	Iconicity	Tourism type	Threat level	Type	Adaptive capacity	Commercial dependence	Tourism dependence	Presence of humans and local communities
Changbai Mountains, China	Wilderness	Land (drive and hike)	Medium	HC	Medium	Medium	Medium	Medium
Fraser Island, Australia	Landscape (wilderness)	Land (drive and hike)	High	SLR	High	Medium	High	Medium
Galapagos National Park, Ecuador	Landscape & Animals	Marine (boat) and land	High	HC	Low	High	Very high	Very high
Great Barrier Reef Marine Park, Australia	Animals	Marine (boat)	High	SLR	High	High	High	Very high
Kruger National Park South Africa	Animals	Land (drive and hike)	Medium	HC	Low	High	Very high	High
Yellowstone National Park, USA	Landscape & Animals	Land (drive and hike)	High	HC	High	Medium	High	Medium

fisheries, and tourism; and forecasted climate change impacts on ecosystem goods and services. The diversity of their geographic situations, both social and ecological, as well as their dynamics and change trajectories caused by human and natural forces, generate measurable differences in social and ecological characteristics and vulnerabilities that extend our findings to an array of conditions, circumstances, and geographic settings.

Proof-of-concept research tasks

Beginning with the selected national park settings, the foundational tasks involve synthesizing case study research on natural–human systems.

1. Expand the literature review of iconicity, national park status, threats to sustainability and metrics of vulnerability and resilience, tourism patterns and indicators of tourist satisfaction, social and ecological change in national parks and surrounding areas, and ecosystem responses and indicators to climate and environment change.
2. Inventory, assess, and consolidate multi-scale and multi-thematic social and ecological data for the iconic national parks as a step towards realizing the general intent of the collaborations.

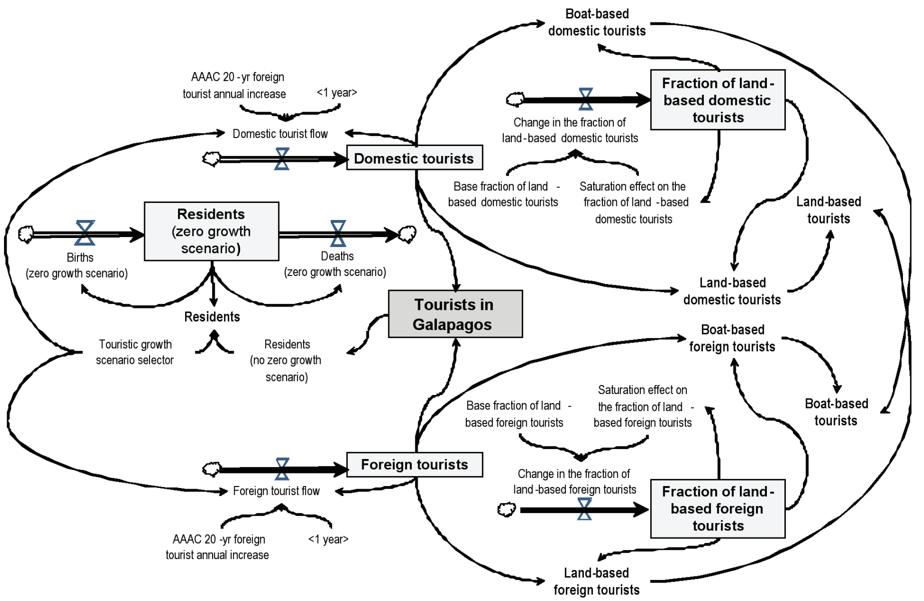
3. Determine data gaps and gaps in scientific understanding of iconic species and landscapes relative to stressors imposed by demographic change, tourism, land use/land cover change, disturbance regimes, invasive species, and climate and environmental change in social, terrestrial, and marine subsystems.
4. Develop measurement and monitoring approaches to assess the vulnerability and resilience of iconic national parks and their social and ecological connectivity using, for example, social and organizational surveys, remote sensing image analysis and data fusion techniques, statistical and ecological process models, and dynamic simulation models for examining exogenous dynamics and non-linear relationships with feedbacks and critical thresholds examined within a scenario-testing context.
5. Interpret collected and/or simulated social and ecological data to examine individual and household connections and linked effects among social and ecological subsystems.
6. Within the context of each site and relying on the disciplinary and interdisciplinary expertise of each member of the project team, define and implement specific approaches for generating and visualizing preliminary relationships and project results that link people and environment, and assess the sustainability of iconic landscapes and species under scenarios of change.
7. Synthesize across approaches, data, and methods to define best practices for assessing iconic species and landscapes within the global network of iconic national parks.
8. Compare and contrast the multiple cases to increase understanding of the implications of local and global contexts and historical–contemporary–future processes and conditions on the social and ecological vulnerability of iconic national parks and their local to regional environs.
9. Examine the key descriptors of the social, terrestrial, and/or marine subsystems by focusing on important relationships unique to each study area, operating through their integrated and linked effects. Then further develop indicators of social, terrestrial, and/or marine subsystems, behaviors, and dynamics around a locally compelling and internationally important set of questions to construct system perspectives that can be used to conceptualize and model national parks as a complex, adaptive, and dynamic systems.
10. Apply integrative geospatial data and methods (e.g., GIS and satellite remote sensing) to assess landscape conditions and states. This will require the development of metrics, indices, and data fusion strategies for landscape characterization for each study area.
11. Develop dynamic simulation models for case study national parks, extended to global settings through generalization approaches, so scenarios of change can be examined that involve multi-scale processes, both in space and time, and explicitly link social and ecological threats to park sustainability. Linking adaptive management to scenarios of change will be vital as we explore the impacts of climate and environmental change on tourism with direct and indirect implications on the environment and for management.

The key to undertaking these foundation tasks and expanded application is to identify local collaborative groups and shared data sets for a broader, multi-dimensional analysis that extends the pilot studies to give greater validity to generalizations. In application, the tasks will emphasize co-learning between science, management, and national park stakeholders. These tasks will also build on the findings of the pilot studies, relevant literature and local informal knowledge, measurement networks, and multi-resolution satellite image time-series and ecological models of changes in ecosystem properties. In doing this, it will be important to be mindful of the need for developing compatible data, methods, and comparable approaches across the study areas, while allowing for local contexts, data, and constraints to be infused into subsequent studies.

Developing dynamic systems models

We propose developing dynamic systems models that examine social–ecological vulnerability of ecosystems using a predator–prey relationship as the general test-bed to examine the drivers of change. For example, ecosystem goods and services are the prey, whereas tourism and the resident population are predators. Our models will enable examination of the evolution of "physical" capital (e.g., water), "social" capital (e.g., social networks), and "natural" capital (e.g., landscape structure) on the adaptive behaviors of tourists and residents (locals and brokers, see Miller et al., this issue) relative to changes in ecosystem goods and services (Hernandez and Leon 2006). Ordinary least squares regression can link key variables in the dynamic systems models, such as the number of tourist arrivals and growth in the local population (Villacis and Carrillo 2013). Biocomplexity serves as the lens through which we can study social–ecological processes and their co-evolution and adaptive resilience to synthesize the feedbacks among system parameters. A dynamic simulation model for the Galapagos National Park exemplifies what is possible for other iconic parks (Figure 3).

Figure 3. A preliminary template example of a dynamic systems model for the Galapagos Islands. (Residents = Local and Brokers; see Miller et al., this issue.)



Several studies have used dynamic systems models to assess the economic, environmental, and/or social impacts of tourism development on social–ecological processes (see, for example, Johnston and Tyrell 2005; Sainaghi 2006; Garin-Munoz and Montero-Martin 207: Lacitignola et al. 2007; Xing and Dangerfield 2011).

Using a dynamic simulation model, Rey-Maquierira et al. (2009) examined the dynamics between tourism policy, environmental externalities, and policy tools (e.g., tourism taxation, land management policies, and accommodation standards). Sinay et al. (2008) used Bayesian logic to model the dynamics between tourism, national park ecosystem services, and cultural change. Finally, dynamic systems models are used to study the dynamic resilience of tourism or the ability of social–ecological systems to recover or move to an alternative and dynamic form of equilibrium once perturbed (Tyrrell and Johnson 2008). In these examples, the models have integrated social–ecological factors to emphasize "whole-system" assessments. Interdisciplinary perspectives were achieved through a framework conceptualizing human–environment impacts and tourism development strategies (Patterson et al. 2004). Such models simulate, predict, or mediate conditions given specified feedbacks between key parameters.

Facilitating collaboration and data-sharing

The foundation network of scholars in the USA, Australia, Ecuador, and South Africa align thematically, theoretically, and geographically to selected national park settings and contexts, represented by key discriminant factors that are integrated in multi-dimensional space and viewed within a space-time context. To advance this work with an expanded network of selected scholars, we will enable the coupled natural–human research initiatives by developing an open and pluggable cyber infrastructure (CI). This will use off-the-shelf technologies wherever possible, and unique systems and linkages to campus and national research resources, programs, and expertise for analysis, discovery, collaboration, and dissemination. Data and information will integrate across a range of disciplines using disparate data models that must be made interoperable with advanced CI tools. A highly functional and adaptable CI layer is critical to the success of our long-term research objectives. The required services will include the full range of CI capabilities including: data and telecommunications; sensor networks and reconfigurable computing; data assimilation, management, analysis, and mining; visualization and collaborative technologies; remote sensing image analysis; and statistical and spatial modeling using high-performance and distributed computing. The CI framework also will need to support a diverse set of virtual organizations and project affiliates on different continents.

Technical sustainability will be achieved through the use of data preservation standards, hardware and software system revision, and the virtualization and evolution of the CI as the project evolves to accommodate new findings, data collections, and analyses. CI contributions in mapping, data management, and geo-analytics will involve a system for sharing and building applications using geographic data consisting of distributed data models, data management schemes, and web services that can be used for data assimilation, analytics, and visualization, and to manage the processes and results involved in high-performance computation.

Conclusion

To understand and conserve sensitive ecosystems, it is imperative to investigate the connections among social, terrestrial, and marine subsystems of iconic national parks at multiple space-time scales. Doing so requires working across traditional disciplinary boundaries as well as developing international collaborations among universities, conservation groups, government organizations, and key entities in the management of iconic national parks. The interdisciplinary nature of coupled natural–human systems has been well documented, so we have identified an initial set of international iconic national parks and an associated international network of scholars and institutions that extend across the social, natural, spatial, and computational sciences. How tourism is shaped by global change, shifts in ecosystem goods and services, changes in land use and land cover, and the corresponding patterns and dynamics of iconic landscapes and behavioral shifts of iconic species is our fundamental concern.

This initiative aims to build understanding, raise awareness, and strengthen capacity to manage the world's iconic national parks in the face of global change. The partnerships envisaged will ensure that the research incorporates local knowledge, a gradient of vulnerability for a global network of iconic national parks, and buy-in from local to global management agencies, conservation organizations, and national and international funding institutions that emphasize research, education, and community outreach and engagement.

The project's focus on iconic national parks is based on: (1) the ability of these areas to attract international attention to the risks of global change on natural and cultural heritage; (2) recognition of inherent values of these areas to local communities and global societies; (3) importance of international tourism to the socioeconomic vitality and ecological integrity of national parks and the places that border them; (4) changes in the integrative effects of population and environment as a consequence of global change and the expanding human dimension; (5) impact of ecosystem dynamics on iconic species and landscapes around the globe; (6) the strengthening of management capacity of iconic national park managers through the engagement of management agencies and the implementation of findings through training and development programs and technology transfer to local constituencies; and (7) the building of community capacity and resilience to social and ecological change.

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