An integrated conceptual framework for long-term social–ecological research

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The global reach of human activities affects all natural ecosystems, so that the environment is best viewed as a social–ecological system. Consequently, a more integrative approach to environmental science, one that bridges the biophysical and social domains, is sorely needed. Although models and frameworks for social–ecological systems exist, few are explicitly designed to guide a long-term interdisciplinary research program. Here, we present an iterative framework, "Press–Pulse Dynamics" (PPD), that integrates the biophysical and social sciences through an understanding of how human behaviors affect "press" and "pulse" dynamics and ecosystem processes. Such dynamics and processes, in turn, influence ecosystem services – thereby altering human behaviors and initiating feedbacks that impact the original dynamics and processes. We believe that research guided by the PPD framework will lead to a more thorough understanding of social–ecological systems and generate the knowledge needed to address pervasive environmental problems.

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Over the past 50 years, ecosystems have been altered by humans more than at any other time in recorded history (Vitousek *et al.* 1997; Chapin *et al.* 2010), and those changes have resulted in reciprocal effects on human well-being (MA 2005). Although health and wealth have, on average, improved, in part as a consequence of these ecosystem changes, the social and geographic distribution of benefits to human populations remains uneven. Furthermore, such improvements are often limited by the inability of ecosystem services to keep pace with human demand and unequal opportunity for different people to access these services (MA 2005). Learning how to manage feedbacks between ecosystems and humans is vital if we are to move toward a more sustainable world, in which the health of ecosystems and human well-being are improved and ecosystem services are distributed more equitably for current and future generations. As ecological research expands from site-based science to regional and global scales (Peters *et al.* 2008), the conceptual scope of ecology must also expand to embrace not only other scientific disciplines, but also the pervasive human dimensions of environmental structure and change. Every ecosystem on Earth is influenced by human actions (Vitousek *et al.* 1997; Palmer *et al.* 2005), and the consensus view now holds that, for many of today's most pressing issues, the environment is best understood and studied as a social–ecological system (Liu *et al.* 2007).

In a nutshell:

- There is growing recognition that the environment must be viewed and studied as a social–ecological system
- Various conceptual models have been proposed to characterize social–ecological systems, but new thinking is needed to guide long-term research that links humans with their environment
- We describe a new model for integrated social–ecological research, the key components of which include environmental and social sciences, press and pulse interactions, and ecosystem services
- Application of this approach will bridge the social and natural sciences and build a knowledge base that can be used to help solve current and future environmental challenges

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As recognition of the importance of social–ecological science increases, new interdisciplinary linkages are evolving. Global research programs, such as the International Geosphere–Biosphere Programme and the International Human Dimensions Programme on Global Environmental Change (Steffen *et al.* 2004; Carpenter and Folke 2006), have driven important advances. Collaborations between physical scientists and biologists have occurred with the advent of regional- and global-scale science, whereas in applied sciences, such as agronomy and fisheries, collaborations between ecologists and social scientists are more recent. For example, studies on how ecosystem services benefit society formed the core of the Millennium Ecosystem Assessment (MA 2005), the first interdisciplinary global assessment of Earth's ecosystems conducted at the behest of world leaders. Many early advances in social–ecological research were driven by coalitions of ecologists and economists (Goulder and

Kennedy 1997; Berkes and Folke 1998; Berkes *et al.* 2003) seeking to understand how institutions and economies solve common-property resource problems (Ostrom 1990; Dietz *et al.* 2003), and more recently by studies of resiliency in regional social–ecological systems (Gunderson and Holling 2002; Walker and Salt 2006). Liu *et al.* (2007) illustrated the diversity of approaches that have been applied to site-based social–ecological research, while emphasizing the enormous gaps in interdisciplinary science that remain and the need for new theory that will better integrate conceptual and empirical research across disciplines.

Although research in "pure" social and biophysical sciences must continue, new emphasis and approaches are also needed to understand the dynamic processes that are unique to social–ecological systems. Ecosystems are composed of numerous species – across the trophic spectrum – that interact at varying rates and at multiple scales, from which the patterns and dynamics that we observe emerge (Levin 1999). Social systems also self-organize and exhibit scale dependencies, but humans within such systems possess capabilities that qualitatively change these dynamics in important ways (Gibson *et al.* 2000; Westley *et al.* 2002). For example, people make forward-looking decisions (ie they act on expectations of the future), generate and respond to abstract perceptions that shape their worlds and their expectations, create feedbacks that act on various time scales over multiple spatial extents, and develop technologies with far-reaching consequences (Westley *et al.* 2002). These consequences create complex dynamics and often unexpected outcomes, which may have long-term effects on social–ecological systems (Liu *et al.* 2007).

We are now beginning to see some of the emerging trends, dynamics, feedbacks, and surprises that are important for human well-being, but we are a long way from understanding or being able to manage them. A combination of theory development and multiple research approaches (place-based, cross-scale, long-term, and comparative) that harmonize diverse disciplinary perspectives is needed to develop understanding and build the capacity to sustainably manage social–ecological systems. Here, we propose a new mechanistic framework to guide this research, which integrates the internal and interactive dynamics of social and natural systems.

"Press–Pulse Dynamics" and ecosystem services: an integrated, long-term, social–ecological research framework

As noted above, scientists have called repeatedly for greater integration between the social and biophysical domains (eg Robertson *et al.* 2004; Palmer *et al.* 2005; Pickett *et al.* 2005; Farber *et al.* 2006; Haberl *et al.* 2006; Liu *et al.* 2007). Typically, these calls are accompanied by illustrative case studies and provide general rationales for why such research is needed, yet rarely do they propose useful roadmaps for implementing truly integrated, hypothesis-driven research in social–ecological systems. There is therefore a compelling need for a comprehensive conceptual framework that is based on highly relevant disciplinary research, but at the same time facilitates linkages among disciplines over the time frames and spatial scales at which social–ecological systems operate and interact.

Understanding change is a fundamental challenge for environmental science. Social–ecological systems can transform incrementally and, at times, predictably. Some of the most important routine changes (eg post-fire succession or housing prices) are reasonably well understood and are incorporated into management practices, yet these changes are best understood primarily within the biophysical or social-system contexts. Other changes are large in magnitude, are spatially extensive, and alter social–ecological systems for long time periods; examples include the loss of keystone species, land-use change drivers (such as zoning practices and homestead policy), or the increased demand for biofuels. Although large changes may account for most of the cumulative dynamics observed, they are infrequent – or pulsed – in nature. As a consequence, observations of these pulsed events are few, individual cases may be unique, and our ability to generalize or predict their impacts on social–ecological systems remains severely limited. Understanding the drivers and interactions between sudden events ("pulse" dynamics) and extensive, pervasive, and subtle change ("press" dynamics) is therefore one of the most important challenges for social–ecological science.

We propose that press–pulse dynamics and ecosystem services can form the critical linkage between social and biophysical domains and serve as the foundation for long-term, integrated, social–ecological research across scales. Figure 1 presents the basic components of a framework, known as the "Press–Pulse Dynamics" (PPD) framework, to accomplish this goal. The PPD framework contains four core components: (1) press and pulse events, (2) a biophysical template, (3) ecosystem services, and (4) a social template. The biophysical and social domains (areas of study) represent traditional disciplinary research paradigms that define processes within each domain. The biophysical template (eg geology, hydrology) constrains fundamental and well-documented relationships between biotic structure and ecosystem functioning, whereas the social template (eg legal regulation, social networks) encloses a range of possible human outcomes and behaviors, and the dynamics between them.

In the PPD framework, unlike in other models, the dynamics of biophysical systems are driven by press and pulse events (Smith *et al.* 2009). Pulse events, such as floods (both natural and human regulated), are relatively discrete and rapidly alter species abundances and ecosystem functioning. Most ecosystems have a characteristic natural disturbance regime that includes the size, frequency, and intensity of pulse disturbances. The natural disturbance regime in most ecosystems has been altered by human activities, including those related to species extinctions, as well as land-use change and management decisions (eg flood control). In contrast, press events, such as sea-level rise, eutrophication, or mean temperature increases, are sustained and chronic. Ecosystems are now subjected to a variety of environmental presses (eg increasing atmospheric carbon dioxide concentrations, nitrogen deposition, global warming). Over time, presses, pulses, and pulse–press interactions alter species abundances and the relationships between biotic structure and ecosystem functioning (Smith *et al.* 2009), which ultimately change the quantity and quality of essential services that humans gain from ecosystems.

Most research in the social sciences has historically focused on social, economic, and political systems in isolation from their biophysical surroundings, or has considered the environment as merely a backdrop for the functioning of social systems. The PPD framework overcomes this isolation by explicitly articulating the reciprocal relationship between the biophysical and social templates through press–pulse events and changes in the quantity or quality of selected ecosystem services. Though much attention has been given to the pattern, if not the process, of interaction between the social and the biophysical systems that represent extreme examples in a human-dominated world – ie urban and wildland areas – the PPD framework provides the means for a more nuanced understanding of social–ecological systems across a continuum of developed to undeveloped lands. This has important implications for social–ecological science, given that the environmental changes of greatest consequence that are expected in the coming decades will derive from human migration and population growth on rural and quasi-rural lands (Brown *et al.* 2005). The connectivity between places and people across this continuum demands that scientists and managers, for example, understand water as a natural hydrologic system that supports human life – or fails to do so, depending on how the system is altered and managed. Only with such an integrative understanding will it be possible to address (and even resolve) the tradeoffs and social equities of differing needs, responsibilities, and activities required to sustain humans in their broader environment.

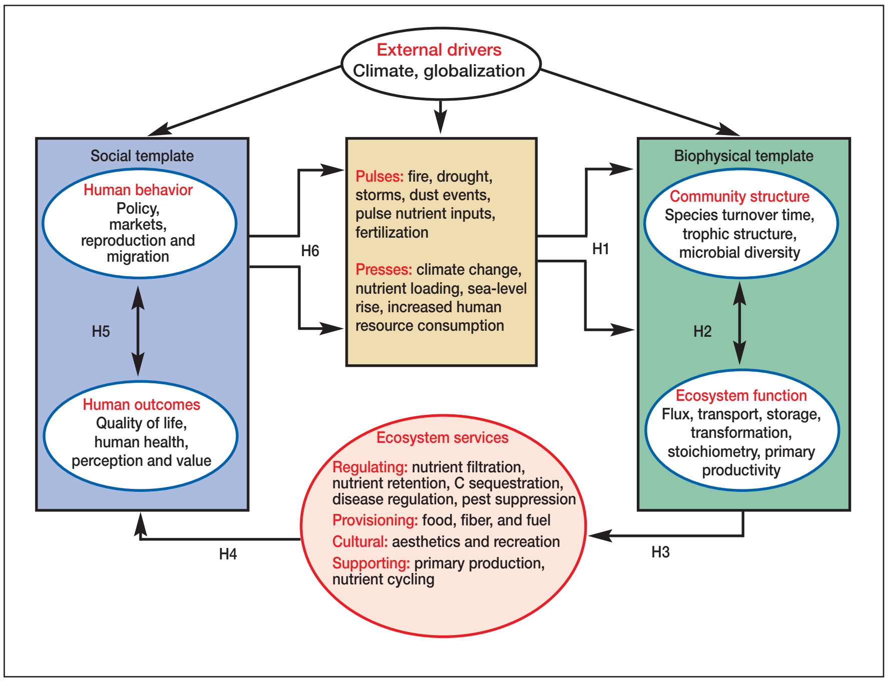

Figure 1. *The PPD framework provides the basis for long-term, integrated, social–ecological research. The right-hand side represents the domain of traditional ecological research; the left-hand side represents human dimensions of environmental change; the two are linked by ecosystem services and by pulse and press events influenced or caused by human behavior (bottom and top, respectively). H1–H6 refer to integrating hypotheses that focus the long-term research agenda. Framework hypotheses: H1 – long-term press disturbances and short-term pulse disturbances interact to alter ecosystem structure and function; H2 – biotic structure is both a cause and a consequence of ecological fluxes of energy and matter; H3 – altered ecosystem dynamics negatively affect most ecosystem services; H4 – changes in vital ecosystem services alter human outcomes; H5 – changes in human outcomes, such as quality of life or perceptions, affect human behavior; H6 – predictable and unpredictable human behavioral responses influence the frequency, magnitude, or form of press and pulse disturbance regimes across ecosystems.*

Together, the biophysical and social templates accommodate core disciplinary research activities that feed information into a larger research framework. In essence, the model assumes a continuous cycle of human decision making, which affects the biophysical template via changes in (1) the intensity of press events and (2) the frequency, intensity, and scale of pulse events. Collectively, altered press and pulse events have quantifiable implications for and impacts on ecosystem services, and changes in these services feed back to alter human behaviors and outcomes (Figure 1).

Because they represent both quantifiable and qualitative benefits that humans derive from ecosystems, ecosystem services form the bridge between the biophysical and social templates. Ecosystem services can be classified as provisioning, regulating, cultural, and supporting (MA 2005). Provisioning ecosystem services that have markets (eg food, fiber, biofuel) have been studied extensively from the standpoint of enhancing supplies. The same is true of certain cultural ecosystem services, notably recreational ones. But the regulating ecosystem services that maintain essential balance in terrestrial ecosystems – as well as the supporting ecosystem services that enable ecosystems to supply other types of services that humans experience directly – are much less obvious to people,

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Figure 2. *Indian Bend Wash, Scottsdale, Arizona, during a flood that covered a large portion of the "greenway"; the flood spread out over parks, golf courses, and streets, but resulted in minimal damage. This design was one of the first non-structural flood management systems in the US, created by local and federal government officials after damaging floods occurred in the 1960s.*

and are therefore often ignored in decision-making processes (Daily *et al.* 2009). Human behavioral decisions – from the individual to the institutional levels – affect ecosystem processes that in turn determine the quality and quantity of ecosystem services that influence human well-being. The concept of ecosystem services therefore constitutes the crucial link between natural capital and social capital in the PPD framework.

The PPD framework is hypothesis driven, iterative, and scalable, as illustrated by an example from metropolitan Phoenix, Arizona. Over the past century, irrigated fields in central Arizona have increasingly been lost to housing development (Redman and Foster 2008). Land conversion – a press – was a direct result of increased post-World War II migration to the region, coincident with the invention of air conditioning and the rise of the automobile. Flash flooding, a pulse disturbance common in the arid southwestern US, was incompatible with maintaining residences that encroached on unregulated, ephemeral streams – such as Indian Bend Wash, which runs through Scottsdale, a suburb to the northeast of Phoenix. In the late 1960s, loss of the floodplain buffer led to substantial property damage associated with a particularly severe flood (Roach *et al.* 2008). Both municipal and federal authorities proposed modifications to handle subsequent flooding, and these transformed the wash into a greenbelt – a chain of small lakes connected by stream channels and surrounded by parks and golf courses. The new ecosystem provides flood modulation (Figure 2), recreational amenities, and aesthetic values, and is supported by an altered biogeochemistry as compared with that of the pre-modification phase (Grimm *et al.* 2005). Low-flow periods must be maintained by means of imported water, a management decision that has further consequences for nutrient concentrations (Roach and Grimm 2009) and can lead to algal blooms in the lakes, which are in turn treated with algicides by park managers.

The PPD framework incorporates and allows for relevant disciplinary research on hypotheses (Figure 1), such as "biotic structure is both a cause and a consequence of ecological fluxes of energy and matter". However, the more important features of the PPD framework are the crucial integrative hypotheses, such as "changes in ecosystem services feed back to alter human outcomes". Such hypotheses are designed to integrate social and ecological drivers and feedbacks. For example, hurricanes, as pulse events, periodically reshape the social and ecological landscape of southern Florida. In 1992, the aftermath of Hurricane Andrew spurred suburbanization considerably, which in turn altered the availability of key ecosystem services associated with agricultural and undeveloped lands (Ogden *et al.* unpublished data). Another example illustrates the role of altered press–pulse drivers; in the Yahara Lakes region of southern Wisconsin, non-point-source pollution historically has been a consistent press, as phosphorus-saturated soils slowly eroded and drove lake eutrophication. However, the economic shift toward confined animal feeding operations has led to large pulse manure runoff events, and such events are likely to increase as climate change leads to more frequent severe storm events. The shift from press- to pulse-driven dynamics will lead to new conflicts and new policy issues for managing water quality, as well as floodwaters, in this region (Carpenter *et al.* 2006). These interdisciplinary linkages arise from understanding the ecological importance of ecosystem services, as well as how humans value and experience those services, which in turn conditions their actions and responses to the environment. In sum, the PPD framework guides the development of falsifiable hypotheses, not only on how subsets of social–ecological systems interact over time, but also on how integrated social–ecological systems respond, change, and adapt.

To be useful, a unifying framework must also be scalable, to address hypotheses across relevant spatial and temporal domains. Indeed, the PPD framework itself could be viewed as a general testable hypothesis about how social–ecological systems behave within and across scales, and all of the hypotheses presented in Figure 1 can also be addressed locally, regionally, and globally. As an example, we illustrate the regional application of this framework for the study of social–ecological systems in the Negev Desert in Israel (Panel 1).

Relationship to other frameworks

Several conceptual frameworks for social–ecological integration have emerged as this interdisciplinary

Panel 1. Land-use change in Israel's Negev Desert

In Israel, scientists associated with the local Long Term Ecological Research (LTER) network are using the PPD model to study the linkages and feedbacks between large-scale land-use changes (residential development, forestry, anti-desertification management) and ecological impacts in the northern Negev Desert (Figure 3). While the Israeli LTER network has a long history of ecology and management research in the Negev (Shachak *et al.* 1998; Hoekstra and Shachak 1999), the social component is relatively new. Thus, the PPD model has been used to (1) organize previous and current research into a comprehensive and interdisciplinary framework, (2) encourage an interdisciplinary approach to hypothesis formulation and driven research, and (3) conceptualize the feedbacks between human behavior–decision making and ecosystem change at multiple scales. The ultimate goal is to identify gaps in understanding and research needs.

The northern Negev Desert is a large and relatively sparsely populated region of an otherwise very densely populated country. As such, in national-scale land-use planning, it has a central role in future development, even though its status as a semiarid demographic periphery has made it a relatively unpopular destination for potential residents (Teschner *et al.* 2010). Land-use managers have responded by increasing the region's attractiveness to current and potential residents through investment in economic opportunities (agriculture, industry, tourism) and development of recreational areas (forests, parks, and reservoirs). Because the region is a transition zone between the arid desert in the south and the Mediterranean climate zone in the north, forestry is also promoted as an anti-desertification strategy (Orlovsky 2008). An additional factor in land-use decision making is the status of the indigenous Bedouin population and its contentious relationship with the state on issues of settlement and grazing/cultivation rights (Yahel 2006; Abu-Saad 2008).

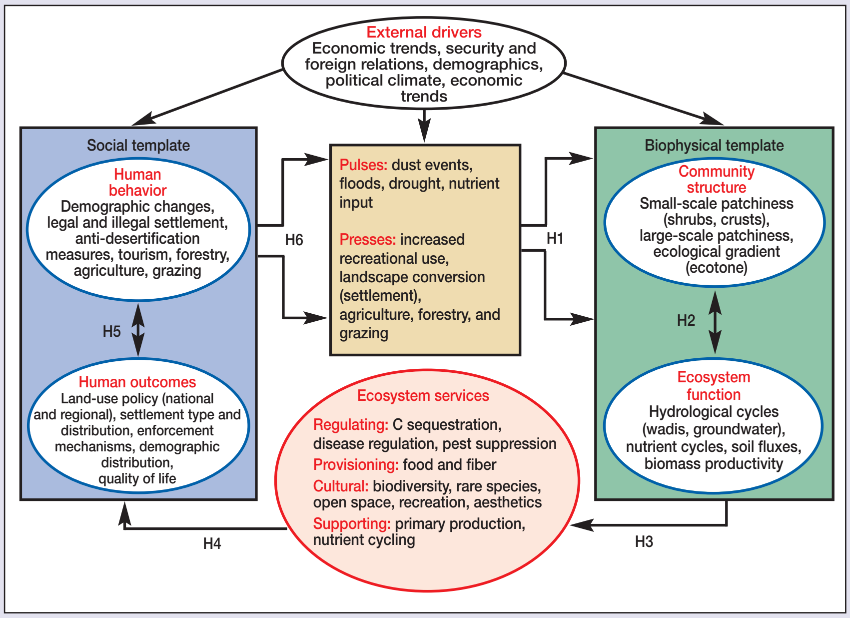

Figure 3. *Example of the PPD framework for social–ecological research in the Negev Desert. Hypotheses are shown in the text box below the figure. H1 – changes in landscape characteristics influence ecosystem processes (eg water, soil) and landscape structure (eg patchiness); H2 – human residential patches (eg farms and neighborhoods) affect aboveground water flows at the landscape scale; H3 – changes in resource flows influence species diversity; H4 – changes in species diversity affect land-use decision-making; H5 – ecosystem services play a role in determining open space preservation policy and biodiversity preservation policy in Israel; H6 – different residential community types (eg city, town, farm) create unique disturbance regimes on the landscape.*

The fundamental relationships we are conceptualizing and analyzing via the PPD model are large-scale (kilometers) and small-scale (meters) land-use changes, their impact on ecosystem structure and function, the resultant changes in ecosystem service provision, and the responses by the public and policy makers (and so on in this cyclic relationship). The predominant changes are afforestation with high- and low-density plantings, increased land cultivation, and expanding residential settlement. Unplanned cultivation and residential development also have important ecological and social implications. The most important pulses in this semiarid ecosystem are floods and droughts, soil erosion (accompanying floods), dust deposition, and human landscape modifications. The presses are primarily increased human activities, such as recreational use, landscape conversion by settlements, agriculture, forestry, and grazing (Figure 4). The landscape is viewed at various scales as a mosaic of patches with distinctive structures that control the flow of materials and energy across the landscape (Shachak *et al.* 1998), and changes in disturbance regimes alter the mosaic – and thus the distribution – of materials, energy, and ecosystem services (Figure 3).

Importantly, most of the shifts of ecosystem services in the northern Negev are considered by decision makers as desirable in terms of human quality of life. Afforestation efforts lead to increased water infiltration and carbon sequestration (Grunzweig *et al.* 2003; Rotenberg and Yakir 2010), decreased erosion and airborne dust concentrations, as well as the creation of a network of recreational areas popular with local residents (Ginsberg 2000). On the other hand, the impact on biodiversity is mixed; plant diversity may increase (Boeken and Shachak 1994), for example, but abundance of local specialist species may decrease (Shochat *et al.* 2001; Hawlena *et al.* 2010). The aesthetic impact is widely debated, as are the political–demographic implications vis-à-vis the Negev Bedouin. Policies to increase residential opportunities are politically popular, though residential development, depending on the type, leads to potentially detrimental impacts on ecosystem function and on biodiversity (Orenstein *et al.* 2009).

The PPD framework is assisting researchers and policy makers to conceptualize these multiple, concurrent, and often conflicting impacts and generate hypotheses regarding how changes in land-use policies will affect different ecosystem service flows. One such study is looking at the ecological implications at the local and regional scale of low-density residential settlement in the Negev. This study considers the political–demographic drivers of such human settlement patterns (Orenstein and Hamburg 2009), the ecological implications, and the popular response to perceived changes in the provision of ecosystem services (Orenstein *et al.* 2009). Such relationships are investigated at the regional scale (eg northern Negev) with regard to impact on desert aesthetics and landscape fragmentation, and at the local scale (eg the wadi, an Arabic term for a dry riverbed or intermittent stream) on water flow, and rodent, insect, and shrub diversity.

DE Orenstein

Figure 4. *An olive grove surrounded by pine plantations north of Be'er Sheva, Israel. Land-use changes in the northern Negev Desert have augmented some ecosystem services, like carbon sequestration, food production, water infiltration, and recreational opportunities, but impacts on other services, such as aesthetics and habitat for biodiversity, are more equivocal.*

research paradigm has evolved, yet the purpose and general utility of these frameworks vary widely, suggesting that they serve multiple goals. Several conceptual frameworks provide evidence for why such research is needed on topics such as environmental degradation, conservation planning, and sustainability (eg Kremen and Ostfeld 2005; Haberl *et al.* 2006), but they offer limited information on how to conduct an integrated research agenda. Indeed, some of these models are highly linear and provide no clear mechanism for understanding key feedbacks between social and biophysical systems (Kremen and Ostfeld 2005; Theobold *et al.* 2005). Other frameworks describe the necessary components of interactive social–ecological systems (Grimm *et al.* 2000), or focus on only a subset of potential interactions, such as economics and biodiversity (Ohl *et al.* 2007; Fisher *et al.* 2009). Often such models lack temporal dynamics or specifics on how other components of social–ecological systems should or could be integrated.

A popular research framework in European social–ecological research is the "Driving force–Pressure–State–Impact–Response" model (eg Ohl *et al.* 2007). This general model has similarities to the PPD framework, including key feedbacks, but it lacks an explicit focus on ecosystem services. The same is true of Redman *et al.*'s (2004) social–ecological model, which highlights the areas where social and ecological systems intersect without ecosystem services and press–pulse constructs (Ohl and Swinton 2010). By contrast, quantifiable ecosystem services explicitly link social and biophysical systems in the Millennium Ecosystem Assessment (MA 2005), as well as in Daily *et al.* (2009). But one key difference is that, like Redman *et al.* (2004), the PPD framework emphasizes that human behavior is partly influenced by factors external to ecological feedbacks. Another major difference is the generalizable set of hypotheses within the PPD framework that provide guidance for an integrated, long-term research agenda, as well as the emphasis on press–pulse drivers. Thus, unlike other conceptualizations, the PPD framework is designed to be generalizable, scalar, mechanistic, and hypothesis driven.

Conclusions

Testing the hypotheses embedded in the PPD framework, along with future refinement of the framework itself, will rely on theoretical, empirical, and methodological contributions from a broad suite of biophysical and social sciences. Application of the framework will contribute substantially to the development and testing of theory within these disciplines and, more importantly, will help to build transdisciplinary knowledge of social–ecological systems. Indeed, many of the empirical and methodological building blocks needed to advance such transdisciplinary knowledge are rapidly emerging. Social scientists are relying on progressively more biological constructs to explain social variation and change (Briggs *et al.* 2006; Gragson and Grove 2006). Likewise, natural scientists are using social constructs to understand biophysical variations over the long term (Walker *et al.* 2009). Social data are increasingly spatially explicit (Irwin and Geoghegan 2001), which permits novel hypothesis testing and analysis that is spatially relevant, as well as multi-scaled. Moreover, ecological research is now commonly conducted at socially relevant scales. Eventually, the use of spatial data may lead to unifying theories that view phenomena as integrated social–ecological systems and, with the inclusion of long-term data and analyses, this will move theory from the realm of correlations and associations to a deeper probing of both mechanism and pattern.

Biophysical and social scientists examine how systems are organized and the roles played by internal versus external influences (Pickett *et al.* 2005). Moving environmental science to a new level of research collaboration, synthesis, and integration requires a shift from viewing humans as external drivers of natural systems to viewing them as affected agents acting within social–ecological systems (Grimm *et al.* 2000) – agents that depend on ecosystem services across a range of scales and feedback cycles. As the human population continues to grow, with attendant land-use, technological, and economic changes, it will place additional demands on vital ecosystem services (MA 2005). These demands will require integrated, long-term research that spans multiple disciplines and that will ultimately provide solutions for the environment and society. The PPD framework provides an explicit roadmap to guide this research.

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