Emergent Sustainability in Open Property Regimes

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Current theoretical models of the commons assert that common-pool resources can only be managed sustainably with clearly defined boundaries around both communities and the resources they use. In these theoretical models, open access inevitably leads to a tragedy of the commons. However, in many open-access systems, use of common-pool resources appears to be sustainable over the long term, i.e., current resource use does not threaten use of common-pool resources for future generations. In this paper, we outline the conditions that support sustainable resource use in open property regimes. We use the conceptual framework of complex adaptive systems to explain how processes within and couplings between human and natural systems can lead to the emergence of efficient, equitable and sustainable resource use. We illustrate these dynamics in eight case studies of different social-ecological systems including mobile pastoralism, marine and freshwater fisheries, swidden agriculture, and desert foraging. Our theoretical framework identifies eight conditions that are critical for the emergence of sustainable use of common-pool resources in open property regimes. In addition, we explain how changes in boundary conditions may push open property regimes either to common property regimes or a tragedy of the commons. Our theoretical model of emergent sustainability helps to understand the diversity and dynamics of property regimes across a wide range of social-ecological systems and explains the enigma of open access without a tragedy. We recommend that policy interventions in such self-organizing systems should focus on managing the conditions that are critical for the emergence and persistence of sustainability.

complex adaptive systems | coupled human and natural systems | common-pool resources | property regimes | ideal free distribution

Introduction

Current theoretical models of the commons assert that common-pool resources can only be managed sustainably with clearly defined boundaries around both communities and the resources they use (1). In these models, open access, or the failure to exclude users, inevitably leads to a tragedy of the commons due to unchecked resource use. Yet, in many social-ecological systems, open access does not lead to resource overuse (2-5). For example, in the Logone Floodplain of Cameroon, pastoralists have open access to common-pool grazing resources yet there is no evidence of overgrazing or rangeland degradation. Here, individual movement decisions lead to an ideal free distribution of grazing pressure over available grazing resources (6). Multiple lines of evidence from ethnographic analysis, spatial analyses, and agent-based modeling show that this open property regime works as a self-organizing system, without central or collective management of resource use, and is efficient, equitable, and sustainable (7). Similar properties characterize other open access systems, including among pastoralists in Turkmenistan (2) and foragers in the desert of Western Australia (8), in which current resource use is sustainable because it does not compromise use of common-pool resources for future generations.

Here we outline a theoretical model that describes the conditions under which sustainability emerges in open property regimes. We argue that sustainability can emerge in the absence of central or collective management, as a product of the resource use strategies of individual users—or, more formally, that sustainability is an emergent property of a self-organizing complex adaptive system (7). Here we define complex adaptive systems as systems "in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution" (9).

Our theoretical model integrates multiple frameworks: theories of the commons provide the terminology we use to describe the users, governance system, resource units, and resource system as well as the overarching question of what makes social-ecological systems sustainable (1, 10); evolutionary frameworks of behavioral ecology and niche construction enable us to generate hypotheses of individual decision-making and the dynamic feedbacks between individual resource use and ecological processes respectively (11, 12); a resilience framework explains how different configurations of resource use can result in different outcomes or property regimes (13, 14); and complexity theory helps us explain how dynamic feedback between processes in

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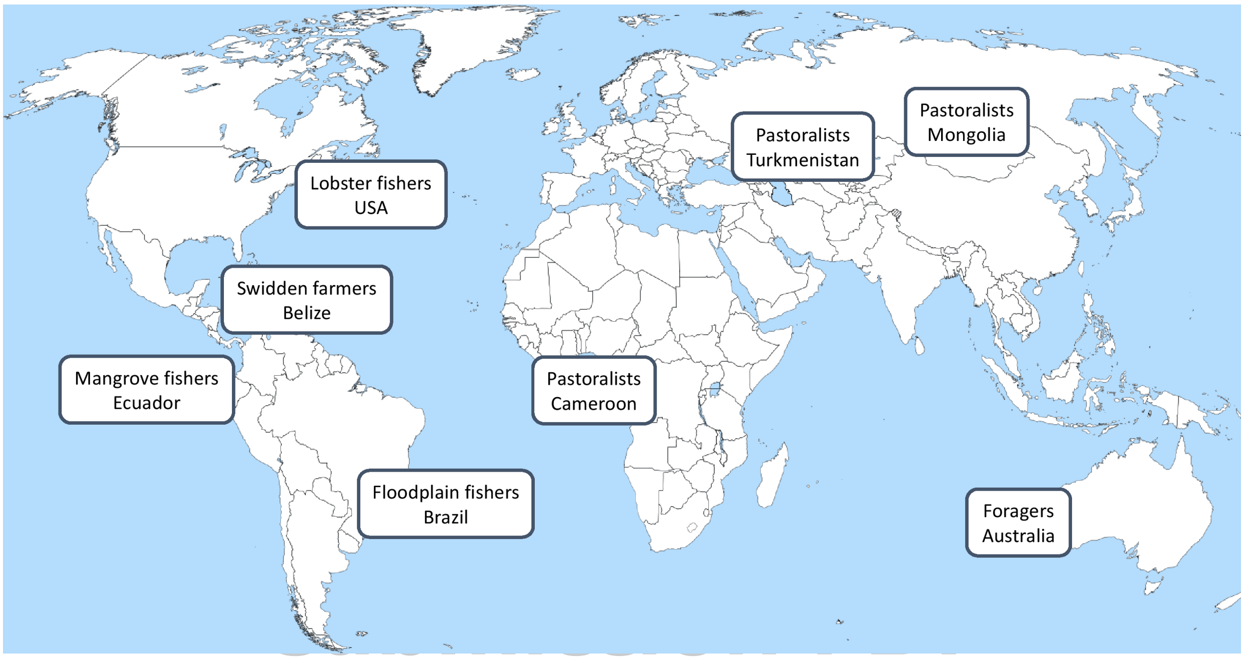

Fig. 1. **Location of cases.**

human and natural systems result in non-linear dynamics that can make open property regimes sustainable (9, 15).

We used a transdisciplinary approach, which not only integrates and synthesizes methods and theories from different disciplines, but also integrates concepts from the cultural communities we have studied, to compare eight empirical cases from a range of social-ecological systems, identify eight critical conditions (CC) for the emergence of sustainability in open property regimes, and explain how changes in boundary conditions (BC) may push open property regimes either to a tragedy of the commons or other types of property regimes. Our empirical cases draw from a wide range of subsistence economies and ecosystems, including pastoralists in the Logone Floodplain of Cameroon (5); pastoralists in the Darkhad Depression in northern Mongolia (16); pastoralists in the Gökdepe District in Turkmenistan (2); freshwater fishers in the Pantanal wetlands of Brazil (17); shellfish gatherers in the mangrove swamps of Ecuador (3); subsistence foragers in the desert of Western Australia (8); swidden agriculturalists in Belize (18); and commercial lobster fishers in Maine (19) (see Figure 1).

This perspective is the synthesis of a research seminar at the School for Advanced Research (SAR) in Santa Fe, where the majority of the authors met to compare the case studies and examine why and how sustainable use of common-pool resources can emerge in open property regimes. The case studies were selected because they represented a wide variety of social-ecological systems that have been studied by the authors and/or other researchers for a decade (e.g., swidden agriculturalists in Belize, shellfish gatherers in Ecuador) or more (e.g., commercial lobster fishers in Maine, mobile pastoralists in Cameroon) and/or for which long-term social and ecological data was available that allowed us to develop and support our argument about the emergence of sustainability in open property regimes.

Theoretical Model

Our integrative theoretical model offers several hypotheses predicting the conditions under which resource use is sustainable with open access to common-pool resources. First, central or collective management is unlikely, and open access tenure regimes more likely, where there are few economic gains from defending exclusive use. Theory in behavioral ecology suggests that the benefits of defending exclusive access to resource patches are greater where there are high levels of exploitation competition and where resources are found in dense, discrete, and predictable patches in both time and space (20). However, when the spatiotemporal distribution of resources is highly variable, sustainable use of resource is more likely where users are free to distribute themselves in proportion to resource availability. Ideal free distribution models predict that under conditions of nearly costless movement, or where the costs of movement are small compared to the gains within resource patches, individuals will distribute themselves in proportion to available resources such that at the landscape scale, the gain rate of all individuals is equalized (21). Individuals are more likely to be able to do this where the renewal rate of resources is high, and knowledge about resource heterogeneity is easily acquired, or shared between individuals. Niche construction theory predicts that sustainability may also be enhanced by intentional or unintentional processes of ecological manipulation (12), while complexity theory predicts that non-linear feedbacks between individual behavior and ecological processes will fine-tune resource use strategies toward more sustainable outcomes over the long term when users adapt to environmental cues (22). Finally, theories of the commons predict that shared norms over the importance of equal access to resources and norms that set limits to status through accumulation are critical to preventing individuals from attempting to claim individual ownership over resources (1).

Our theoretical framework thus identifies the following eight conditions as critical for the emergence of sustainable use of

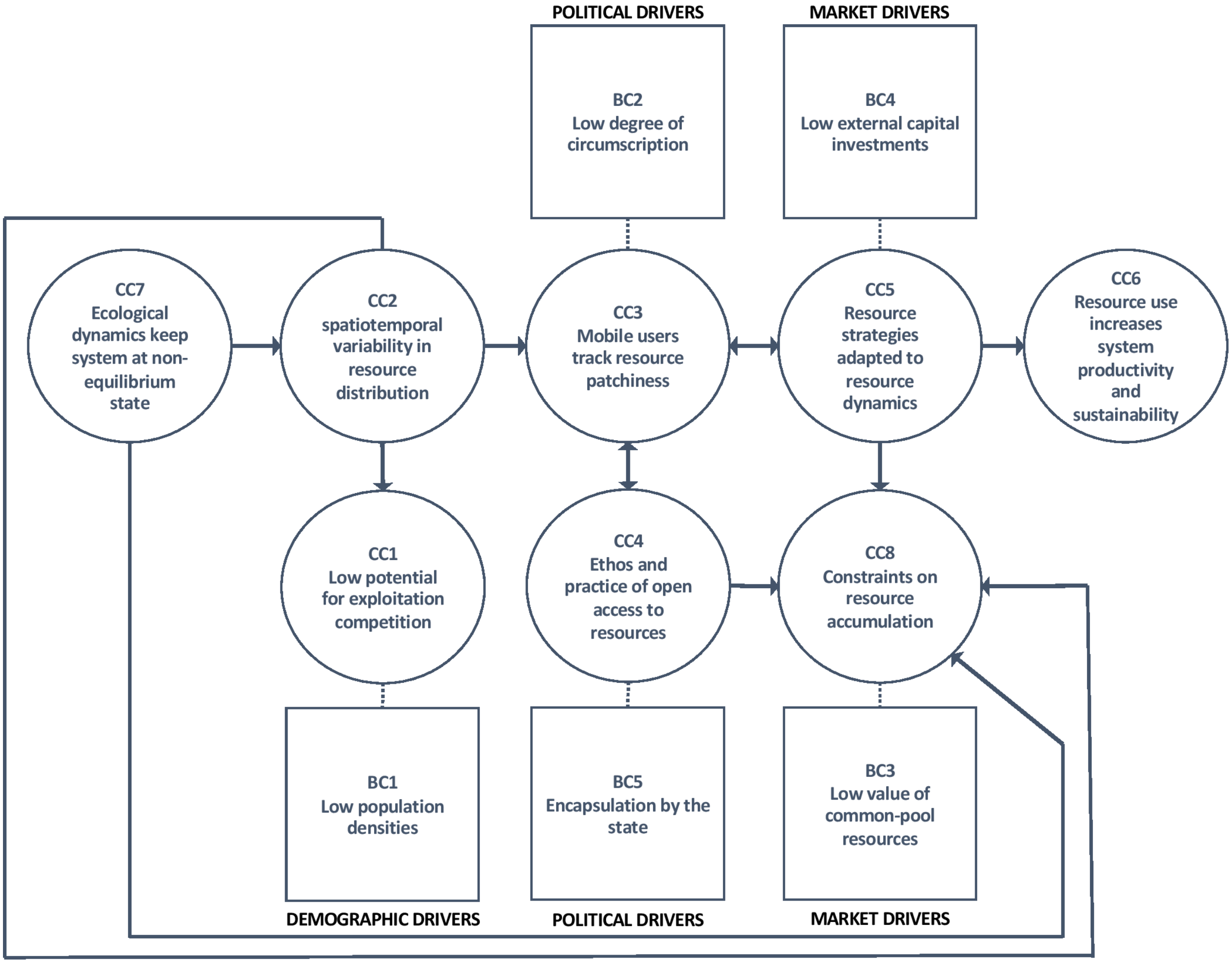

Fig. 2. Theoretical model with interactions between critical and boundary conditions.

common-pool resources in open property regimes: (1) the resource system is highly productive relative to the number of users leading to low levels of exploitation competition; (2) the distribution of resources is patchy in space and time and there is a degree of unpredictability or stochasticity in patch return rates; (3) the costs of individual mobility are low relative to the gains within patches and individuals can track changes in resource density between patches; (4) users share sets of norms which frame common-pool resources as a public good with free access for all; (5) users gain knowledge of the resource system through processes of individual and social learning, which allows them to fine-tune their resource use strategies to particular ecological systems; (6) resource use strategies may shift natural systems towards higher productivity; (7) the non-equilibrium dynamics of the ecological system may buffer or enhance the rate of resource renewal; and (8) there are limits on resource accumulation due to social, economic, and/or technological constraints. Below we will first explain these eight critical conditions (CC) and illustrate them with examples from the eight cases and then discuss five boundary conditions (BC) that are necessary for the emergence of sustainability in these systems (see Figure 2 for the interactions between critical and boundary conditions) (for a more detailed description of all eight critical conditions for each of the cases see Dataset S1).

CC1. Low Potential for Exploitation Competition

A low level of exploitation competition between users for resources is the first critical condition for the emergence of sustainable resource use in open property regime systems. The degree of exploitation competition is a function of multiple factors including the productivity of the resource, the number of resource users and the cost of resource defense. Increases in average density of resources within patches tend to make resources more economically defensible and subject to individual or group ownership. However, when patch productivity is high relative to the number of resource users, either because the number of users is very small or because the patch is extremely productive, there are few benefits for defending exclusive access (20). Similarly, when resources are low value, abundant, and not clumped, like grazing resources, there are few net benefits for defending exclusive access. In all but one of our cases, the resource system is productive enough and population densities are low enough to minimize the potential for exploitation competition. Common-pool grazing resources in Cameroon, for example, are low value, low density and widely distributed and therefore the potential for exploitation competition is low because the benefits do not outweigh the costs of defending the resources.

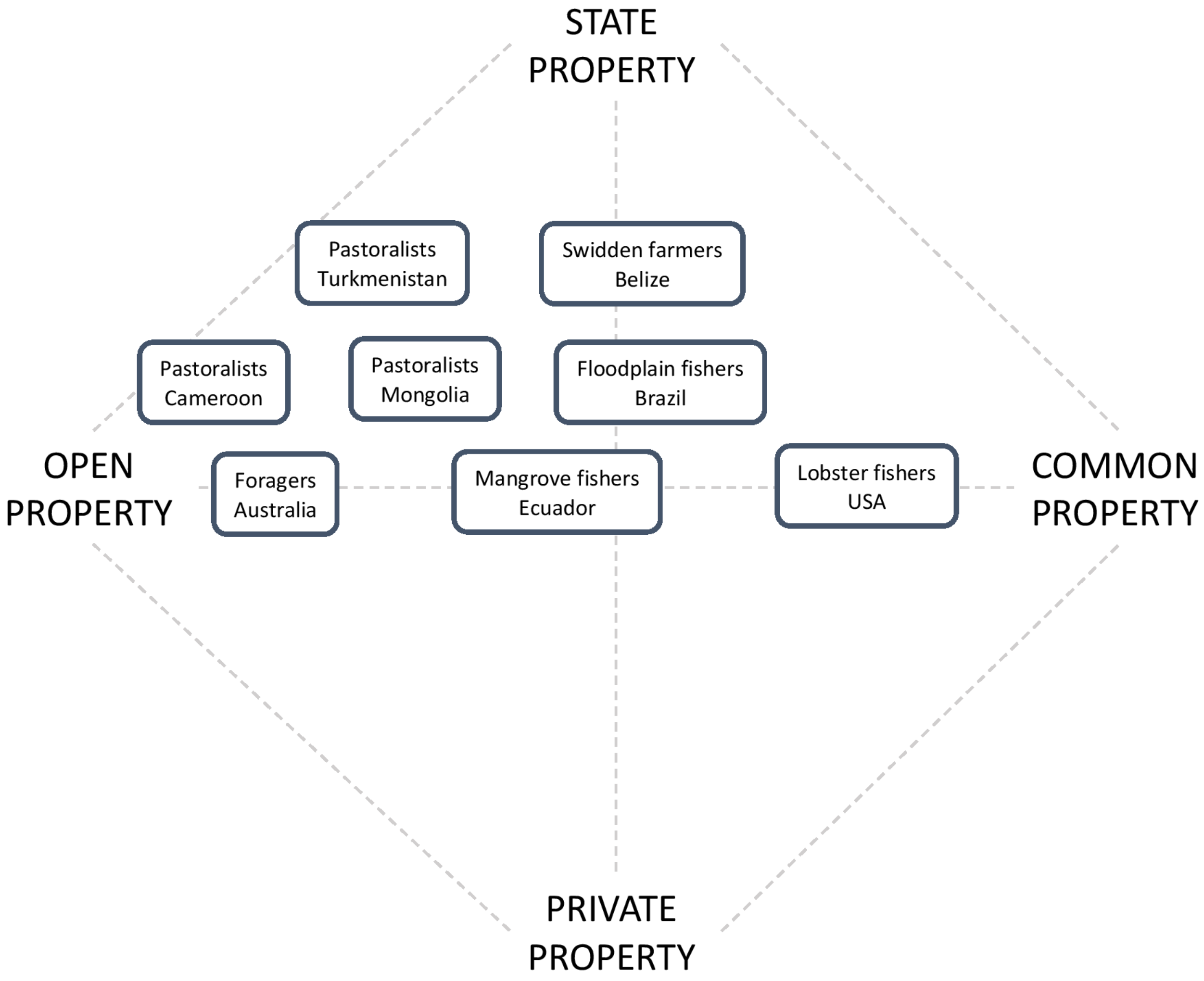

Fig. 3. Cases on continuum of property regimes.

CC2. Spatiotemporal Variability in Resource Distribution

The second critical condition is spatiotemporal variability in resource distribution. Users contending with predictably varying or uniform resource distributions tend to have higher rates of return when resource access is controlled, monitored, and defended by a group of users (20). When the opposite holds and spatiotemporal variability of the resource is high, there are fewer advantages to controlling exclusive access by a smaller group of users, and tenure systems tend toward open property regimes (23). Variability in resource production and distribution can be driven by a wide array of climatic and other natural processes and disturbances, including interannual variation in temperature, precipitation, fire, and flooding, as well as through more complex interactions between human and natural systems. Such is the case in Western Australia, where anthropogenic fire regimes and unpredictable rainfall interact to change the distribution of subsistence resources, leading to substantial spatial and temporal variability in the location of the most productive regions.

CC3. Mobile Users Track Resource Patchiness

The third condition is that users maintain high degrees of mobility to track spatiotemporal variability in resource productivity. When the costs of mobility are low, users optimize their own rates of return by distributing themselves in proportion to resource availability. In moving to maximize their own returns, regions with low productivity are often abandoned, while regions of high productivity support a higher density of resource users. When the costs of mobility are low, resource overuse is less likely because gains are higher from moving than from further exploitation of the current patch. The scale of mobility differs, but, in each case, it is linked to the scale of resource distribution: in low density ecosystems like Australia and Mongolia, residential movements occur at the scale of hundreds of kilometers, while in tropical habitats like Belize, movements in search of more productive habitat occur on the scale of tens of kilometers. Mobility may be driven by search strategies that result from information sharing under conditions of uncertainty as in the case of the Pantanal Floodplain in Brazil (17).

CC4. Ethos and Practice of Open Access to Resources

Mobility as a strategy to maximize returns is only possible when accompanied by an ethos and practice of open access that allows mobile users to track spatiotemporal variability in resource productivity. In all but one of our cases, rules exist to facilitate, rather than hinder, open access to common-pool resources or land, and users share a worldview in which these are considered public goods. In Western Australia, land tenure is a complex set of rights and obligations gained via a flexible set of alternate pathways. Sacred knowledge and sites on the landscape are individually owned, but the rights to hunt, gather, and drink water are generally open to all, or subject to an 'always ask' policy for which the answer is always yes (24). People travelling through country to which they do not belong (or one which is unfamiliar to them) are able to hunt and gather to sustain themselves but must refrain from burning the grass so as not to unintentionally threaten any sacred sites until information about their location has been obtained from local site owners. After consultation, anyone can burn or hunt anywhere they choose. As such, the tenure system regulating use of natural resources functions more like open property than common property: unlike common property systems, there are no boundaries delineating one community's foraging region from another, nor any bounded social group collaborating to exclude others from that region.

CC5. Resource Use Strategies are Adapted to Resource Dynamics

In all of our cases, feedbacks between social and ecological systems create a dynamic, co-evolutionary interaction in which social processes shape the ecological system and ecological processes shape the social system (12). In practice, users gain knowledge of the dynamics of the resource system through processes of individual and social learning, which allows them to fine-tune their resource use strategies to the particulars of the ecological system. While individual experience is certainly a major factor in this learning process, in each of our cases users also gain information about resource dynamics and the state of the resource system from the success or failure of other users, through a process that involve both direct observation and networks of socialization and communication in which people share experiences, knowledge, and information in much the same spirit of generosity as they would share material resources. Importantly, this process of information gathering and sharing leads to future changes in behavior. In the Pantanal Floodplain in Brazil, in order to optimize the search for the best fishing spots, people openly share the location of good fishing spots during iced tea drinking sessions, but also validate this information through direct observation of fishing catches (17). In Belize, swidden farmers carefully study weather patterns and discuss the timing of clearing, burning, planting, and harvesting events in the agricultural cycle. Information about key environmental dynamics are also gained while participating in labor groups to help other farmers with agricultural activities, or by observing, for example, that other farmers are burning by the quantity of smoke in the air on a given day. Farmers use this information to plan where they will clear their next fields (18).

CC6. Resource use Increases System Productivity and Sustainability

In many of our cases, sustainability is a function not just of the intrinsic productivity of the resource system, or the strategies of its users, but also the positive inputs of the resource users themselves, which make the system more productive. In grassland ecosystems, pastoralism often leads to localized shifts in productivity and plant diversity as animals disturb soil, prefer certain vegetation over others, and locally increase soil nutrients through manure deposits (25). In Mongolia, grass productivity around established pastoral camps are higher than areas around more recent camps, indicating that pastoral use, including manuring by flocks, may increase grass productivity. An alternative possibility is that established camps have better grazing because they selected the best sites. Nevertheless, in both explanations, long-term grazing does not threaten the resource system. Similarly, research suggests co-evolution of grazing and floodplain vegetation across African floodplains (26). In Australia, the subsistence practices of Martu foragers center on the burning of grassland habitats to hunt burrowed animals, mainly large monitor lizards. Burning increases immediate hunting returns more than ten-fold but also positively impacts future foraging returns by creating a diverse landscape of vegetation at different stages of recovery following fire. These hunting fires create landscapes that provide people with higher returns over the long term due to increases in both patch productivity and reductions in patch dispersion (4).

CC7. Ecological Dynamics keep the System in a Non-Equilibrium State

The seventh critical condition is non-equilibrium dynamics in which repeated disturbances limit harvesting capability (27). Non-equilibrium systems are driven primarily by stochastic abiotic factors, like fire, rainfall, or snowstorms, which leads to highly variable and unpredictable primary production (28). These dynamics protect system productivity by making it difficult for users to over-exploit resources (29). In Northern Mongolia, pastoralists in the Darkhad Depression experience extensive spatiotemporal variability in pasture productivity. While herd mortality in the winter is an annual constraint on livestock populations, unpredictable bad winter storms, known as *dzuds,* happen on average once every ten years and can kill up to 80% of the herd, further reducing herds below carrying capacity (30). In our Australia case study, the sustainability of the system is maintained in part by a long recovery period before the grass becomes dense enough to carry a fire and thus provide foragers with high hunting returns. In the swidden in Belize, biomass and soil fertility recover slowly and this limits agricultural productivity.

CC8. Limits on Resource Accumulation

The eighth condition, and found in nearly all of our cases, is the presence of mechanisms constraining resource accumulation by individual users. These mechanisms can be social, economic, and/or technological and help to minimize the risk of over-exploitation of common-pool resources, even though they are not necessarily “designed” to constrain resource accumulation. In our pastoral cases, the accumulation of livestock is constrained by natural growth of family herds as there is little external capital investment in the pastoral production system to support faster herd growth. Similarly, tidal cycles dictate accessibility to the mangroves for fishers in Ecuador and cockles and crabs are harvested by hand only during low tide. During neap tides, harvesters stay close to shore, but during spring tides, harvesters are able to travel further out. Few fishers have access to motorized transportation limiting the spatial mobility of harvesters because they are unwilling or unable to pay the transport costs to more distant sites. In Belize’s swidden farms, social norms related to subsistence agriculture and labor reciprocity can limit resource accumulation (18). In Australia, the open access policies in Martu foraging communities are underwritten by an ethos of equitability that ensures any productive surplus or knowledge about the location of that surplus is shared widely among all present. Martu foragers who are more productive are also more generous with their surplus, and in so doing, foster more cooperative relationships with others (31).

Boundary Conditions and Shifts in Property Regimes

External demographic, economic and political drivers influence whether the critical conditions associated with sustainability of open property regimes persist. We have identified five boundary conditions (BC) that describe the states of external drivers that are necessary for the emergence of sustainability in these systems, including: (1) low population densities and thus low levels of resource competition; (2) low circumscription and thus limited restrictions on mobility; (3) low market value of common-pool resources harvested; (4) low capital investments (and appropriate technology); and (5) low encapsulation by the state and thus little interference in everyday use of common-pool resources at the local level (for a more detailed description of these boundary conditions in each of the case studies see Dataset S1). Changes in these boundary conditions may push the system to a common property regime with social and spatial boundaries or toward a tragedy of the commons. Our case studies also illustrate how property regimes may change over time due to different processes (e.g., government interventions, incorporation in the market, population growth) that change the boundary conditions (e.g., increase in market value of resources, increase in population density) and may facilitate a shift from an open property regime to other property regimes (or hybrids thereof) (see Figure 3 for position of the cases on a continuum of property regimes). The lobster fishery in Maine is a good example of a shift from open access to a common property regime, but we have also observed shifts from open to private property regimes. In the Adamawa Region of Cameroon, for example, there is a shift from pastoralism to ranching, which entails the enclosure of privately-owned rangelands that used to be under an open property regime., and in rural Ecuador, individual households have created holding pens for cockle shells that are held until they reach legal size for the market.

BC1. Low Population Densities

Low levels of resource competition are often a product of low population densities (32). When user populations increase there are often negative consequences for resource sustainability. For example, in Turkmenistan, the rural pastoralist population density is low but is increasing because of low urban migration and continued population growth. The grass on which their cattle graze is a scare resource and it is unclear how much more additional livestock the system can sustain. In the Chad Basin, the insecurity caused by Boko Haram has led to forced migration of thousands of pastoralists and hundreds of thousands of cattle from Nigeria to Cameroon doubling the grazing pressure in the region and increasing the resource use (33). There are low levels of exploitation in open property regimes, but under common property regimes with clearly defined boundaries for the user group and resource system, there are *controlled* levels of resource exploitation as resource users regulate access. Thus, open property regimes may change into common property regimes under conditions of increasing population densities and more intense resource exploitation.

BC2. Low Degree of Circumscription

Circumscription refers to the degree to which a user group is constrained politically or physically from moving beyond their resource system (sensu 34). Social-ecological systems are embedded in larger regional and political systems and the extent to which these impact and/or encroach upon the mobility and ability to track resources can prevent the emergence of sustainability. For example, in the Pantanal fisheries in Brazil, the creation of seven strictly protected areas has led to an economic and physical displacement of fishers, which jeopardize their customary rotational fishing system (35). In small coastal fisheries in Ecuador, the development of shrimp aquaculture has degraded the quality of the estuarine habitat and displaced many artisanal fishers from their customary grounds (36). To address the major threats to mangroves by unregulated aquaculture and urbanization, the government began allocating collective stewardship rights to formally organized fishing associations in 2000 for mangrove conservation and fisheries management. Shellfish collectors are concerned they are losing access to their customary gathering grounds to new kinds of enclosure by collective stewardship rights, which are only allocated to fishing associations (37).

BC3. Low Market Value of Common-Pool Resources

Access to markets and commodity production tends to foster more unsustainable exploitation (38). The market value of the common-pool resources in our cases is generally low leading to relatively little competition or interest from other users. For example, the grasses that serve as forage for cattle of pastoralists in Cameroon have practically no market value and thus there are no entrepreneurs cutting grass at the end of the rainy season to dry it and sell it later in the dry season as hay. In Ecuadorian mangrove fisheries, cockles, crabs, and finfish harvested in mangroves are commercially valuable, but market demand is small compared to export-oriented industrial pelagic fisheries and farm-raised shrimp. However, in Maine, lobster is the most economically valuable fishery and the backbone of the state's marine economy, making up three quarters of the total value of all commercial fisheries landings. The high market value of lobsters is one of the reasons why the lobster fisheries in Maine shifted from an open to a common property regime (39). For swidden farmers in southern Belize, accessing markets during most of the 20th century was physically difficult and certain forest-based products were in demand for only a few years or cyclically as development efforts ebbed (40). Growing maize is only commercially viable at low levels because of the intensive labor requirements; but other products such as rice, cacao, and cattle now compete with swidden for land. This increasing demand is reducing the sustainability of the entire social-ecological system and moving it towards a future state as either a common property regime or a tragedy of the commons.

BC4. Low External Capital Investments

In addition to limits on internal capital resource accumulation (CC8), emergent sustainability in open property regimes requires there to be little capital investment from external sources. External capital investment can change resource extraction strategies through investment in technology and lead to overexploitation. For example, technological improvements or mechanization can quickly overcome the ecological dynamics that limit overexploitation of natural resources. In the Adamawa Region of Cameroon, there is a shift from pastoralism with open access to common-pool grazing resources to ranching with private and exclusive ownership of grazing lands. This shift has major implications for the sustainability of the social-ecological system as mobility is reduced and stocking rates increased due to the use of commercially-produced supplementary feed that allows cattle to survive and overcome the dry season bottleneck. Similarly, increased investment in artisanal and small-scale fisheries can shift fishery techniques away from high labor cost and low returns (e.g., hand set gill nets, cast nets, line and hook) to mechanization of marine fisheries, which is a major driver in the decline of global oceanic fish stocks.

BC5. Encapsulation by the State

Encapsulation by the state refers to the degree to which users have the political autonomy to govern common-pool resources (41) or to what extent the state interferes with the everyday use and/or governance of common-pool resources at the local level. As Ostrom and others have shown for common property regimes, state interventions often have negative consequences for sustainable management of common-pool resources. This is also true for open property regimes where state interventions can threaten resource use strategies that are critical for the emergence of sustainability. In the case of Ecuador's cockle fishery, formalizing informal open property regimes into collective stewardship rights, or "custodias" offers substantial tradeoffs (36). The implementation of collective stewardship rights has resulted in larger catch and cockle shell sizes, empowerment of artisanal fishers after decades of struggle against encroaching shrimp farmers, and a new sense of cultural pride among artisanal fishers. However, the allocation of stewardship rights to certain fishing associations has reorganized the spatial distribution of customary norms, and in extreme cases, has resulted in displacement of fishers from their ancestral gathering grounds if they are not formally organized into fishing associations. In contrast to increasing encapsulation in the Ecuadorian case, in the Mongolian and Turkmenistan cases there was decreasing encapsulation, which resulted in greater freedom of movement and ability to track spatiotemporal variability in resource productivity. In the 1990s, the Mongolian state withdrew precipitously from rural areas, dismantling the collective institutions that had regulated and supported pastoralism. The result was unregulated open access in what Mongolians call "the age of the market". Turkmenistan, on the other hand, maintained the collective farms, but changed their names and limited their involvement in day-to-day pastoral decision making. The resulting arrangements have been characterized as regulated open access (2).

Implications

In each case study, sustainable use of common-pool resources emerges from the bottom-up without centralized or collective decision-making. Our theoretical framework proposes that this emergent sustainability is maintained by complex positive and negative feedbacks between people and their environments, including, in many cases, ecological feedbacks, in which use of a resource contributes positively to its own persistence or distribution. As such, our perspective broadens the nature of human-environment interactions to encompass a wide range of ecological functions that go well beyond simply being a force of destructive disturbance (42). When socio-ecological systems are place-based, i.e., entangled locally in a network of positive and negative interaction, there is the opportunity for coevolutionary forces to shape adaptive responses on the part of both the social system and the ecological system.

Our theoretical model has several theoretical and methodological implications. First is the understanding that we gain in approaching the study of the dynamics of highly integrated social-ecological systems. Studying such integrated systems is facilitated by making analytical distinctions between processes within, and coupling between, human and natural systems (43). This coupled-systems approach necessarily requires an equally integrated research approach requiring that research methods integrate both social science and natural science. This goes beyond just different researchers working separately on separately formulated research questions and hypotheses, but must include a research design capable of resolving the interaction between the social and the ecological. This exceeds the call for collaborative projects between social and natural scientists, the standard in coupled human-natural systems work, requiring research that is able to span multiple spatial and temporal scales, especially from individuals to groups, and from patches to landscapes, as well as the interactions between those scales (14).

Because these systems are likely to exhibit nonlinear historical trajectories or out-of-equilibrium states, traditional datasets may be too small and standard statistical approaches may not be adequate to identify or predict transitions between property regimes, thus requiring alternative methods such as long-term high-intensity data collection (44), advanced computational agent-based modeling (45, 46), and long-term ethnographic analysis (22).

Finally, and most importantly, it requires that we study users as part of the ecosystem because it is their use of the resources that is key to sustainability and productivity of the system – it is an integrated system. This has implications for how we conceptualize these interactions. If interactions between humans and other species are framed as 'management', it suggests that humans do something very different than other organisms. Management implies conscious intent to shape ecological interactions to support a unique human value and sets humans apart as stewards of nature, rather than agents whose actions belong there. By calling everything management, we risk misunderstanding the nature of the complex interactions that shape sustainability in societies that do not have such top-down structures and restrictive tenure regimes.

We recommend that policy interventions in such systems should not focus on managing the resource itself, but on managing the critical conditions and boundary conditions that lead to the emergence of sustainability in self-organizing systems (47). For example, in pastoral systems, mobility is a key adaptation to track the spatiotemporal variability in resource distributions and sustainability of pastoral ecosystems can be supported by protecting not only pastoralist access to the resource but also their freedom to move (48). A similar approach would benefit fisheries and swidden farming systems. Our model helps move towards this by identifying the conditions that are critical for the emergence of sustainability in open property regimes.

Another policy recommendation is to view users as an integral part of the social-ecological system. This is not a new idea but it is worth repeating because the default intervention is top-down management that separates people from their country, conceptually and practically (32). An example of such an approach that considers both social and ecological dynamics has been informing policy interventions in both Canada and Australia as part of *Healthy Country, Healthy People* initiatives (49). Such initiatives recognize the critical interaction between the health of ecosystems and the social and cultural well-being of both individuals and the societies of which they are a part—not just recognizing that healthy ecosystems make for healthier people, but that healthy social structures and healthy people create more sustainable ecological systems.

While it may seem that our cases are relatively small and increasingly rare subsistence-oriented social-ecological systems in the age of increasingly telecoupled systems (50), these are modern systems that not only provide livelihoods for the people living within them, but also contribute to the global market economy (51). However, telecouplings, like the incorporation in the global market economy, may lead to changes in the critical and boundaries conditions and threaten the sustainability of these social-ecological systems. In particular, population growth may lead to increasing circumscription and/or competition for common-pool resources, while incorporation in the global market economy may lead to greater capital investments and over-exploitation of these resources.

Conclusion

The framework of complex adaptive system explains how sustainability emerges and persists in social-ecological systems with open access to common-pool resources. It solves the enigma of open access without a tragedy. The key to sustainable use of common-pool resources in these social-ecological systems is self-organization, i.e., the idea that sustainability emerges from individual resource use within dynamic social-ecological systems that are in non-equilibrium. We think that the principles of self-organization not only explain the dynamics of our cases but can also serve as a guide for how to understand and support the emergence of sustainability in other situations of open access to common-pool resources.

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