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Achieving a fit between social and ecological systems in drylands for sustainability

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The fit of social-ecological systems (SESs) is regarded as an important criterion for achieving sustainability. However, there is still a shortage of approaches to achieve this matching, especially for dryland areas, where ecosystems are more vulnerable and sensitive than other areas, and mismatches between institutions and ecological processes can cause worse consequences in a shorter time. By drawing on the cases of SES management in dryland areas, we propose three distinct but complementary approaches to promote SES fit based on comprehensive and systematic analyses, which can be summarized as structural, dynamic, and scale approaches. These approaches could contribute to enhance the fit of SES, but more quantitative indicators and tools are needed to analyze complex SES structure–function relationships.

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Introduction

Ensuring ecological and socioeconomic sustainability is always challenging. In the Anthropocene, mankind has become the dominant force affecting the structure, function, and resilience of biophysical systems [1]. Reconciling the increasing demands of the growing human population with ecological sustainability is more difficult than ever [2,3•]. Obviously, there are tight bidirectional coupling processes between humans and nature, and it is usually impossible to draw a clear dividing line in the real world [4]. A commonly mentioned term, the social-ecological system (SES), is used to describe this mutual relationship [5]. However, due to the lack of consideration of these complex interactions among the components within SESs, a series of social and environmental problems such as food deficits, water shortages, and land degradation have emerged, despite many efforts at ecological restoration and environmental protection [4,6,7]. Therefore, maintaining a fit between social and ecological systems is regarded as necessary for sustainable management [8,9].

The challenge in achieving SES fit is related to the interplays between humans and nature across temporal and spatial scales and organizational levels [10,11••,12••]. Because human behavior is mainly constrained by formal and informal institutions, achieving SES fit means we must appropriately match social institutions and biophysical processes [8,9]. Maintaining that fit means relating social and ecological components in such a manner so as to produce desirable outcomes [8]. Conversely, a mismatch between these two subsystems will result in environmental degradation and possibly negative cascading effects [13••]. Hence, we need effective and robust approaches to examine and enhance the level of social-ecological fit, but there is still a lack of a comprehensive and systematic analysis on this topic. Especially for dryland regions, where ecosystems are more vulnerable and sensitive than others [14–16], the mismatch between institutions and ecological processes can cause worse consequences in a shorter period of time [17,18]. Drylands are predicted to expand by up to 23% by the end of the twenty-first century, and increasing aridity and land degradation are expected [19–21]. At the same time, rapid population growth and the corresponding increased need for resources will increase pressures on the functions of drylands ecosystems [21–23]. Although humans are trying to manage and maintain dryland ecosystems, different combinations of interventions may have complementary or conflicting effects. Thus, it is particularly crucial to achieve and maintain SES fit in drylands areas [24].

This paper focuses on approaches to achieve and maintain SES fit, illustrated by examples in dryland areas. We draw on the literature on SES governance in dryland areas to propose three distinct but complementary approaches to formulate the institutions that will be conducive to promoting SES fit: 1) structural fit, which refers to the alignment between social and ecological structures, including capacity boundaries and spatial heterogeneity; 2) dynamic fit, which focuses on adaption or transformation to deal with dynamically variable environments; and 3) scale fit, which aims at resolving mismatches between a system's parts and its whole, both inside and outside of the SES and with short-term and long-term interests at different spatial and temporal scales.

The curved surfaces consist of system state curves, and the state of the social-ecological system and are changing with time as shown by the timeline arrow. By applying the three approaches (dynamic, scale, and structural), the system shifts towards sustainability from an unsustainable trajectory.

Structural fit

The structural approach focuses on the fit between social and ecological structures to produce an emergent structure of SES with desirable functions. Ecological structure refers to the pattern of constituent elements of ecosystems, including their quantity and spatial and temporal distributions, which determine ecological processes, such as material circulation and energy flow [25]. Social structure encompasses not only the distribution of population and administrative divisions, but also contains the composition of culture, norms, economy, and politics [26,27,28••]. Therefore, structural fit includes safety capacity boundaries and the alignment of system elements or institutions. The boundary fit defines a safe operating space for humanity based on intrinsic biophysical processes and keeps the needs of society within the critical natural threshold in which humanity can continue to develop and thrive. Based on analyses of the planetary boundaries of critical ecological processes [29,30•,31], the reasonable regulation of human behavior will promote SES fit and effectively avoid the collapse of SES [3•,30•].

The structural approach gives primacy to the fundamental connections within SESs with the goal of long-term sustainability. Bodin conceptualized alignment between the structure of social networks (the actors and their relationships in a social system) and the structures of the ecological system being governed, and he summarized the structural configuration between society and ecology in two dimensions [11••]: horizontal and vertical connections. Horizontal connections refer to interlinks of actors within a social system or of functional units within an ecosystem, whereas vertical connections are concerned with how these two subsystems are interconnected. SES structures are often measured by networks (nodes and links that represent system elements and their relationships) [32], which can help researchers gain substantive insights into different environmental problems from local to global scales [25,33,34]. However, there is still a lack of a unified set of reference standards when conceptualizing complex SES structure into networks [34], and this process needs to be improved, particularly from three aspects: network abstraction, network dynamic visualization, and function analysis.

In arid areas, balancing the demand for water from nature against that from humans is always difficult [35,36]. It requires not only balancing the needs of humans in different areas, but also balancing the water needs of humans and ecosystems [37]. The alignment of social and ecological structures can internalize externalities and lead to desirable outcomes [13••,38]. Wang *et al.* [13••] used a minimal socio-ecological framework to provide empirical evidence that the political division of hydrologic basins can result in serious ecological degradation. The introduction of a new authority with whole-basin responsibility facilitated better alignment of social and ecological structures, leading to the successful rescue of downstream oases and the restoration of a dried terminal lake. However, the lack of any direct connection between actors of the middle and lower reaches resulted in the paradox of an increase in water demand [13••]. Therefore, measures to stimulate the emergence of horizontal social ties linking different critical groups of actors across the watershed, which could improve the alignment of institutional and biophysical structures, were suggested. Without these changes, sustainable management of river basins and other common pool resources in this area will remain problematic.

Dynamic fit

Because SESs are dynamic and contain many uncertainties, dynamic fit refers to adjusting and adapting to these constant challenges through social learning and training. The SES equilibrium state will be affected by the historical processes, and influencing factors usually include endogenous variables (such as knowledge, values, and policies) and exogenous variables (such as climate change and international institutions) [26,39,40]. Once a tipping point is reached, these disturbances can trigger reorganizations of a system's structure and function, a process known as a regime shift [40,41••,42]. Adaptive SESs can tolerate unknown or unforeseen disturbances by absorbing, accommodating, or embracing change [43]. They can restructure themselves after disturbances and maintain their critical functions [44]. When the challenges are impossible to address within a current SES state or regime, transformation is needed to fundamentally reorganize [45]. Therefore, in the face of disturbances of global changes, dynamic approaches are needed to maintain the fit of an SES.

The dynamic fit approach pays more attention to building or increasing human capacities to cope with disturbance and to adapt or transform in the face of uncertainty [46]. It focuses on cultivating people's various capabilities that are conducive to achieving sustainable development goals, such as risk assessment, risk management, and collective action. This ability can maintain the stability and resilience of a local SES, which is important to reduce dryland degradation and support livelihoods. For example, although water resources usually limit social and economic development of dryland regions [47,48], seasonal rainstorms still cause flood disasters in many dryland areas [36]. Constructing appropriate water conservancy facilities can effectively convert floodwaters into usable water resources [36,39]. However, the lack of flexible response measures to droughts, for example, by using only farmland expansion to counter a decline in agricultural productivity caused by prolonged drought, may exacerbate the damage to SES resilience [10] and result in the emergence of a poverty trap [3•,39,48]. In addition, as indigenous peoples or communities have usually adapted to the local natural environment and formed production methods that can meet their own needs [49,50], the use of indigenous knowledge is an effective measure to deal with drought and to increase adaptive capacity.

Quantifying system resilience and identifying potential regime shifts is the basis for implementing the dynamic approach, whose methods include statistical analysis and system simulation [51,52]. The statistical methods include Mann-Kendall trend analysis, singular spectrum analysis, and the use of sequential t-tests and F-tests for the analysis of time series of long-term sequence variables [51,53]. System simulation methods use system dynamics models, equilibrium models, and agent-based models to simulate SES dynamics and potential regime shifts [54,55]. The regime shift database from the Stockholm Resilience Centre has shown that climate change and agriculture-related activities are the most prominent drivers of regime shifts [56]. Studies conducted to understand the driving forces, analyze their impacts, and predict future trends have provided a basic knowledge of dynamic SESs under the challenges of global changes, but additional studies on adaptive or transformative capacity based on a dynamic approach are needed [57,58].

Scale fit

Scale fit considers the impact of social institutions or human behavior on the resilience and stability of SES at different spatial and temporal scales [7,41••,59]. In terms of spatial scale, humans and nature around the world are closely linked through cross-scale interactions such as international agricultural trade, land-use changes, and species invasion [60–62]. Decisions made in one place can undermine the achievement of sustainability in other places [41••]. For example, studies conducted in China's loess plateau, a typical arid and semi-arid area, found that revegetation and soil-erosion control measures reduced soil erosion, but the accompanying reduced sediment supply to lower reach and estuaries has already shifted the Yellow River delta to an erosional phase. This change potentially affects more than two million people and biodiversity in distant-coupled environments [63]. Thus, a comprehensive evaluation of the social, economic, and ecological benefits of social institutions at different spatial scales is needed for humans to obtain optimal ecosystem services from natural capital [64,65].

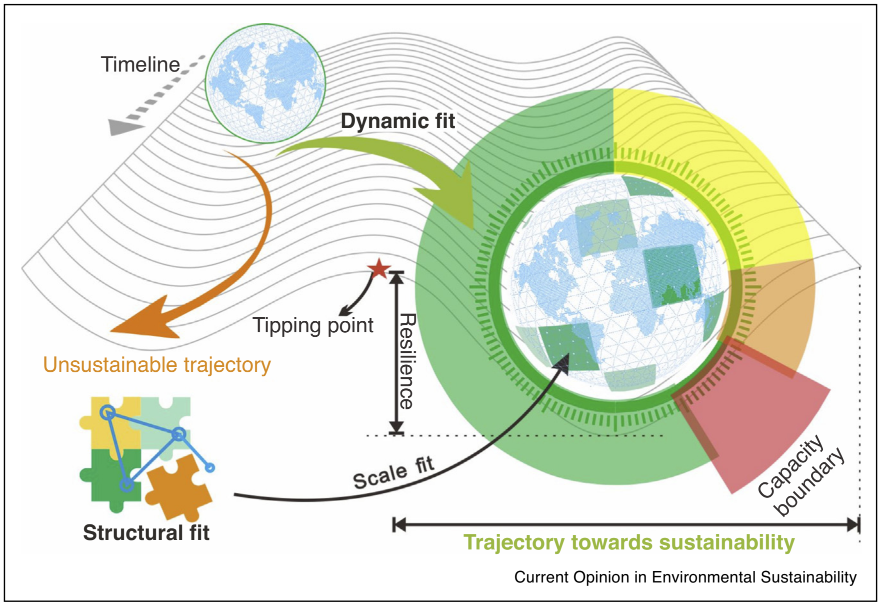
Furthermore, the temporal scale effect of an institution also has a significant impact on SES resilience. Although some human behaviors have slow or imperceptible effects on ecosystem processes in the short term, exceeding certain tipping points may lead to an ecosystem regime shift and endanger human survival [66]. In the 1980s, the Chinese government implemented large-scale afforestation projects to control sandstorms and soil erosion in arid and semi-arid areas. As a result, vegetation coverage increased rapidly in the early stages of vegetation restoration. However, from a long-term perspective, the survival rate of plantations during 1980–2000 was only about 15% because of mismatches between the selected tree species and local soil and climate conditions [17,67]. Even worse, these exotic tree species consumed a great deal of soil moisture and caused a dry layer of soil, which exacerbated land degradation in these areas [17]. These results indicate that an effective institution needs to guarantee SES fit on different temporal scales, which means that humans should not obtain short-term benefits at the expense of doing harm to long-term benefits [66,68].

The scale approach provides a holistic analysis for the formulation of institutions related to socio-economic development and environmental protection. This approach considers changes in the impact of human activities on the resilience of SES at different spatial and temporal scales. It is worth emphasizing that the spatial and temporal scale effects of institutions are often intertwined and need to be considered simultaneously [66]. Especially for dryland areas, the production methods of many countries and regions do not match the resource endowments of local ecosystems, resulting in large-scale land degradation [16]. The rapid transformation of social structures, including institutions and technologies, will help improve the sustainable development capacity of these regions [69], but in-depth investigations and research by policymakers and scientists are needed to learn how to achieve this transformation and formulate feasible implementation plans [70].

Complementary perspectives

The three approaches proposed in this paper could help formulate effective and robust institutions to maintain the fit of SESs. In addition, these three approaches are complementary rather than mutually exclusive. The structural approach focuses on whether human activities will exceed the capacity boundaries of critical ecosystem processes, and emphasizes the adjustment of social organization structures to avoid bad outcomes. The dynamic approach focuses on the capacity of adaptation or transformation response to environment changes. Therefore,

Figure 1



Three approaches to maintaining an appropriate fit among social and ecological systems and their relationships.

the combination of structural and dynamic approaches can encourage social systems to change production methods and enhance innovation capabilities, thereby enhancing the resistance and resilience of SESs to external disturbances. However, although the above two approaches can promote an appropriate fit between social institutions and biophysical processes at a certain spatiotemporal scale, it is important to judge whether this fit will still be appropriate as the spatiotemporal scale changes. Therefore, the scale approach is also needed.

Considering the above approaches is important for understanding the trajectory towards sustainability in drylands. To guarantee sustainable livelihoods in dryland regions and enhance human well-being, a new international initiative was proposed by the Chinese Academy of Sciences in August 2017, that is, the Global Dryland Ecosystem Programme (Global-DEP) [71]. The research framework of Global-DEP is focused on the impacts of climate change and land-use change on global dryland ecosystems and their services. It will integrate the knowledge and information on typical dryland ecosystems around the world to monitor changes in their structure and functions, assess their services, and summarize good practices for dryland ecosystem management at different scales, thereby contributing to scientific research and sustainable management of global dryland ecosystems. Global-DEP will serve as a good platform for global research collaboration on dryland ecosystems and make a scientific contribution to international efforts to achieve and maintain social-ecological fit for global drylands.

Conclusions and future directions

Drylands are Earth's largest biome and home to more than 38% of the world's population [15]. Maintaining SES fit in dryland areas is one of the most important parts of global sustainable development. Compared with the functional redundancy or resource richness of other regions, it is more difficult to maintain an appropriate fit in dryland areas. Additional studies are needed to achieve and maintain it, including on developing theories and methods, analyzing structure and functions, and achieving transformation and adaptation. As research on each of the SES fit approaches advances and knowledge is integrated, society will be better able to pursue a more sustainable future.

This paper reviewed the literature to identify three coherent and complementary approaches to achieve and maintain SES fit from an integrated and systematic perspective, as summarized in Figure 1. Whereas existing research on each theme can advance our understanding of SESs, existing studies are limited in their focus and lack a holistic balance between space configurations, temporal processes, and hierarchical structures. These challenges must be addressed to achieve the ultimate goal of success in sustainability.

Conflict of interest statement

Nothing declared.

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