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Resilience, Adaptability, and Regime Shifts Thinking: A Perspective of Dryland Socio-ecology System

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Abstract: Arid areas are widespread globally and support a third of the world's population's livelihoods. The increasing population, urbanization, land-use changes, and the climate significantly affect coupled natural and human systems and threaten environments and socio-ecological land systems. The degradation of drylands poses a severe and widespread threat to the lives of millions of people, especially in developing countries and in the global environment. This review assesses published literature on dryland socio-ecological systems to reveal current research trends and changes in research themes over time and introduces basic theories and advances in dryland socio-ecological system frameworks, resilience measurement, and regime shifts. Developing a more general but adaptable framework and a more practical strategy for long-term coordination and partnership and attaining specific insights into ecological services should receive more attention and be strengthened in future studies on drylands sustainability.

Key words: dryland; socio-ecological system; coupled human-natural system; adaptability; resilience; sustainability

1 Introduction

The sustainable management of natural resources requires sufficient knowledge of the complex relationships between human and natural systems (Aminpour et al., 2020). Socio-ecological systems (SESs), known as "coupled human and natural systems" are integrated systems in which people interact with natural components (Liu et al., 2007). Owing to environmental changes and human activities worldwide, such integrated systems have become more complex, non-linear, and uncertain (Levin et al., 2013). Determining the interaction mechanism will allow the resilience and sustainability of SESs to be maintained and enhanced, focusing on recent research (Reyers et al., 2018). Drylands in this article followed the definition of UNCCD, which describes it as arid land areas where the aridity index value of between 0.05 and 0.65. It was found in most biomes and climatic zones worldwide (Sapir et al., 2004; Feng and Fu, 2013), constituting 41.3% of the global land surface (nearly 6 billion ha) and feeding 2.5 billion people in the

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world (Reynolds et al., 2007; Yirdaw et al., 2017). Moreover, it is also accounting for approximately 40% of the global net primary productivity (Wang et al., 2012, Fisher et al., 2015). The drylands in the world consist of 10% forest, and 90% grassland and cropland, and the severe degradation would lead to the provision of ecosystem services. Therefore, food insecurity, social and political instability and the reduced resilience of ecosystems to natural climate change are among the most important issues facing drylands (Reynolds et al., 2007; Wang et al., 2012; Guissé et al., 2013; Menz et al., 2013).

Understanding how drylands respond to ongoing environmental and social change is crucial for ensuring global dryland sustainability. Exploring a connected and integrated dryland socio-ecological system through the explicit analysis of the processes and dynamics between the system's environmental and human components will aid in enhancing dryland vulnerability, maintaining dryland ecological services, and meeting the demands of sustainable dryland development (Chen et al., 2013).

The following research questions guide this review and discussions:

- What are the core theories and the latest advances for the dryland socio-ecology system?
- What are the trends in the dryland SES?
- What are the current research gaps and remained challenges for the sustainable realization of dryland SESs?

2 Basic dryland SES theories and advances

The SES concept has evolved into a mainstream field of research that focuses on interdependent linkages between social and environmental changes and how those interdependent linkages influence the achievement of sustainable development goals (SDGs) across different systems, levels, and scales. Revealing the SES feedback mechanism of coupled systems is the scientific basis for maintaining and enhancing resilience and sustainability, which is also a core concept of social-ecological system research (Reyers et al., 2018). Moreover, SES concepts, such as resilience, adaptability, and transformability, are essential for understanding the non-linear process of climate change-affected SESs (Folke et al., 2010).

2.1 Conceptual framework

The social-ecological systems framework is a conceptual framework that provides a list of variables that may interact and affect outcomes in SESs (Poteete et al., 2010), which guide the assessment of the social and ecological dimensions that contribute to sustainable resource use and management (Partelow, 2018). This framework can be structured into tiers of nested and related concepts and variables (Fig. 1). The first tiers include the Economic and Political Settings (S), Resource System (RS), Resource Units (RU), Governance System (GS), Actors (A), Interactions (I), External Ecosystems (EE), and Outcomes (O) (Ostrom, 2009). There are 56 second-tier variables nested within each first-tier variable (McGinnis and Ostrom, 2014). The outcomes of responses, in turn leads to shifts in the resource and governance systems. There are two main conceptual pillars for SESs. One aims to understand their functioning, and the other aims to understand all aspects related to the development, implementation, and transformation of the system towards normative sustainability goals.

New environmental inputs and social actors will disturb the original interactions that occur between abiotic or biotic factors, basic conditions, and human activities in SESs. Although the environmental and social factors are unbalanced, they all still react and interact with one another. This indicates that the ability of SESs to respond to external drivers and internal processes shifts to develop along the existing trajectory. Such abilities are referred to as adaption, a concept of resilience (Folke et al., 2010). The ability of a system to absorb disturbances and reorganize to maintain its structure, function, characteristics, and feedback when changes occur is referred to as resilience (Walker et al., 2004). When disturbances are severe, the structure and function of SESs may change dramatically, suddenly, and continuously. Once a critical threshold is crossed, SESs will transition into another steady regime, referred to as a regime shift (Angeler and Allen, 2016). The input exposure is also affected by the system's adjustment and adaptation in turn. This process demonstrates the vulnerability of SESs to disasters (Turner et al., 2003). The interaction mechanism, vulnerability, resilience, and regime shift are all essential concepts within research on the dynamic evolution of systems and feedback mechanisms in dryland SES frameworks.

2.2 Interaction mechanisms

The interaction mechanisms of dryland SESs currently follow three main trends. The first is the increasing research scale from regional to global. The second is the increasing complexity, and the third is a change in the theoretical framework from neighborhood effects to telecoupling, which is an integrated framework that reveals socio-economic and environmental interactions between distant coupled human and natural systems (Hull and Liu, 2018). This integrated framework can examine flows of information, energy, matter, people, organisms, and other factors, such as financial capital and goods and products, around the globe, and can explain the causes and effects arising from the engagement of diverse agents worldwide.

Several vital factors should be known when considering dryland SESs' interaction mechanism. First, the imminent climate warming in the upcoming decades should be considered when investigating dryland SES interactions. Furthermore, the concept that "dry gets drier, but more than wet

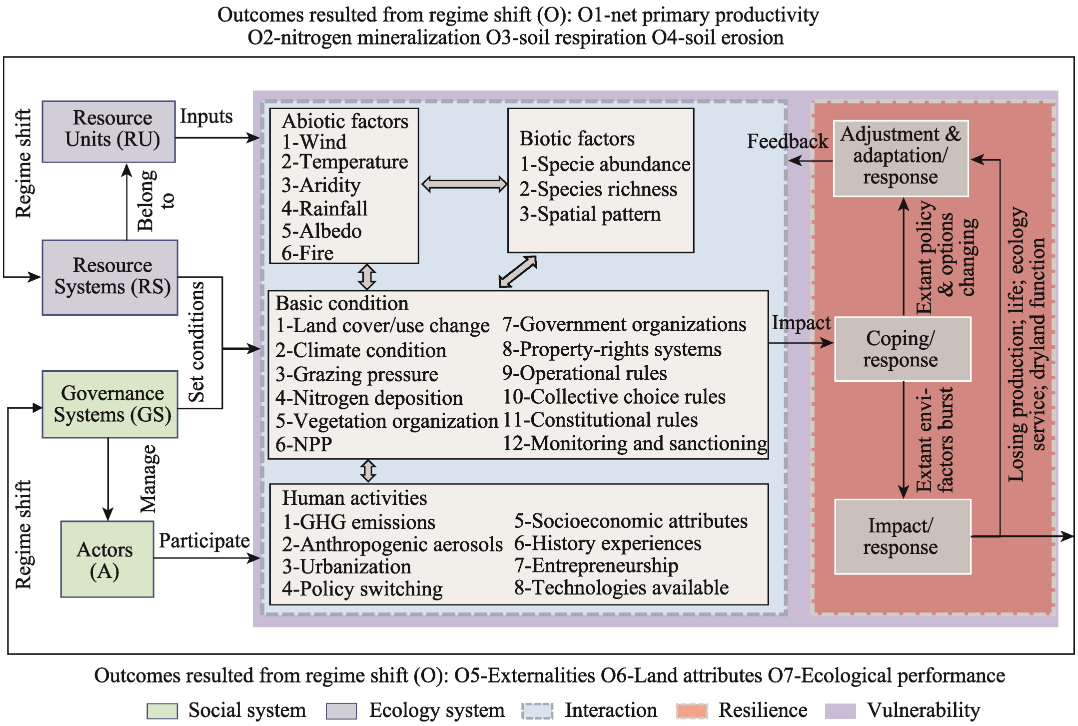

Fig. 1 Basic conceptual framework for dryland SESs

Note: Outcomes of resulted from regime shift represent the essential natural and social elements affected locally or spillover. This framework is modified by summaring different general socio-ecology systems. The general SESs conceptual framework is also applicable to drylands but needs to be adapted and modified according to their characteristics. More specific applications and examples are described in more details in sections 2.1–2.4.

gets wetter" should be regarded as the more current background of dryland SESs, rather than the unanimously acknowledged "dry gets drier, wet gets wetter" paradigm (Prăvălie, 2016).

The climate and its interactions with abiotic features (i.e., geomorphology and soil texture) significantly influence the structure and functioning of the dryland ecosystem. Biotic features, such as species richness, abundance, and spatial patterns, and their interactions with abiotic factors, play critical roles as drivers of ecosystem functioning in drylands. As well as the climate, the links and interactions between abiotic, biotic, and multifunctional factors play essential roles in guiding conservation and restoration efforts, improving our ability to forecast and monitor desertification processes (Guissé et al., 2013; Maestre et al., 2016).

Increases in aridity result in the formation of thresholds regarding the structure and functioning of drylands (Miguel et al., 2020). Other negative impacts include increases in water stress and reductions in the abundance and diversity of vascular plants and soil microbes. Dryland grazing significantly and negatively impacts plant cover, species composition, soil C and N contents, and primary productivity, particularly at local and regional scales. Changing the type of livestock and establishing suitable protection policies could reduce such impacts. Another negative process is woody encroachment. Differences in the encroaching species, functions, and climatic conditions affect ecosystem structure and functioning. In the driest areas, woody encroachment often occurs with worse negative influences (Maestre et al., 2016).

2.3 Measuring resilience

Indicators and system models are typically used to measure resilience. However, it is difficult to determine resilience directly due to the complex and non-linear nature of SESs. Two materials significantly contribute to meeting the shortcomings of the system model and provide strong support for selecting indicators and identifying boundaries, as well as the feedback process. One is the *Resilience, Adaptation, and Transformation Assessment Framework*: From Theory to Application published by CSIRO, and the other is *Assessing Resilience in Social-Ecological Systems*: Workbook for Practitioners by Resilience Alliance (Resilience Alliance, 2010; O'Connell et al., 2015). The performance of this dynamic system model is better for analysis under various conditions than individual indicators or system models. Meyer et al. (2018) developed a mathematical flow-kick framework that uses dynamic system tools to explicitly quantify resilience to disturbances based on their magnitude and frequency. Ingrisch and Bahn (2018) proposed a variable framework that jointly considers the impacts of disturbance and recovery rate normalized to the undisturbed state of the system to avoid disturbance responses across ecosystems and their properties and functions, which allows a broadly comparative assessment of resilience.

Although much progress has been made, the measurement and evaluation of resilience are still weak, and flexible assessment frameworks and methodologies are still lacking. Therefore, they are still not widely recognized. Two obstacles must be overcome to advance our understanding of cross-scale resilience dynamics. The first is the lack of availability and high cost of data with high spatial resolution. The other is the lack of adequate resources for processing such data (Council, 2010). Recent studies made some progress in overcoming these obstacles. Large observation networks, such as the Chinese Ecosystem Research Network (CERN) and National Ecological Observatory Network (NEON), provide large amounts of vegetation, landform, climate, and ecosystem performance observation data, can support the measurement of resilience (Fu et al., 2010; Lindenmayer et al., 2018; Barnett et al., 2019), the quantification of decades of atmospheric nitrogen deposition data (Yu et al., 2019), the evaluation of resource-use efficiency and ecosystem service values (Daryanto et al., 2020), and the monitoring of carbon fluxes at large scales (Chen and Yu, 2019), Related studies will greatly benefit from tools such as those mentioned above. Developing observation methods can provide more powerful tools for measuring resilience. Currently, the Big Earth Data Science Engineering Project (CASEarth) of the Chinese Academy of Sciences Strategic Priority Research Program facilitates the development of new rapid and accurate approaches to monitoring the Earth (Guo, 2017). This would advance methods of measuring the cross-scale resilience dynamics and understanding vulnerability studies with multiple and nested scales.

It is worth noting that resilience measurements in dryland are particularly specific. Many recent research efforts have contributed to the precise dryland measuring. In Mongolia's arid rangeland degradation practices, several ecological indicators, including plant cover, standing biomass, palatability, species richness, forage quality, vegetation gaps, and soil surface characteristics, are measured for resilience assessment (Jamsranjav et al., 2018). Such regional cases have formed lots of globally applicable rangeland degradation frameworks. Except for the indicators, other contributions areobservation networks. The MARAS system launched in 2018 consisted of 379 ground monitors in a 624.5 km^2 semi-arid area of southern Argentina and Chile to record 11 landscape indicators (Oliva et al., 2019). And the related vegetation and soil characteristics of dryland rangelands across Patagonia were released this year (Oliva et al., 2020). Other studies have looked at using the correlation between the easier-collecting surface indicators and soil multi-functionality in further to conduct resilience measuring in global drylands (Eldridge et al., 2020).

2.4 Regime shifts

Shifts in dryland SESs refer to the movement of system factors across a threshold and the formation of a new steady-state, while ecological, economic, or social conditions make it difficult to maintain existing systems (Walker et al., 2004; Folke et al., 2010). These dramatic, sudden, and continuous changes in the structure and function of the SESs are essential for understanding the evolution of SESs and changes in their resilience (Biggs et al., 2009). Current studies on such regime shifts mainly focused on the identification and analysis of driving mechanisms. The influencing factors, cascades within and across scales, and the reciprocity of regime shifts have also attracted attention (Reyers et al., 2018; Rocha et al., 2018). Methods of identifying steady-state transitions include statistical and model analyses, which are the main methods involved in regime shift identification (Filatova et al., 2016). Unlike statistical analysis that depends on long-term sequence data, model analysis can identify regime shifts by selecting indicators, building inner feedback mechanisms, and simulating system processes. Typical models include equilibrium, agent-based, and system dynamics models (Wang et al., 2020). The Stockholm Resilience Centre developed the Regime Shifts Database (RSDB) to introduce systematic synthesis. It can act as a wide-ranging information resource for environmental planning, assessment, research, and teaching initiatives. The database contains 28 generic types of regime shifts and over 300 specific case studies (Biggs et al., 2018). Climate change and agriculture are the most active elements in research on dryland SESs. However, some anthropogenic changes also significantly affect the regime shift, such as reducing soil erosion in the Loess Plateau (Wang et al., 2016). Nexus approaches provide an efficient method of studying synergy and detecting trade-offs between policy-making and governance for implementing integrated SDGs (Liu et al., 2018).

Specific to the research on regime shift in dryland, the general approach can be summarized in Fig. 2. For instance, a comprehensive framework has been proposed in China's semi-arid regions to determine the stages of evolution of the Loess Plateau from a socio-ecological system perspective (Wu et al., 2020). Furthermore, such frameworks are also used in other dryland ecological components, such as the Yellow River's sand transfer capacity (Song et al., 2020). In a nutshell, such a workflow can be summarized as looking for change drivers in a socio-ecological system. And then, assessing how these drivers have changed their internal functions and properties. After this, the local and spillover effects resulting from the above properties changing can be effectively quantified and assessed. Such quantifications of its spillover can be used to set a threshold criteria to measure the regime shift. It should be noted that two indicators need to be taken into account in order to determine whether or not a regime shift has taken place through interactions within the socio-ecological system shown in Fig. 2. One is the relationship, and the other one is the degree of the component of society and ecology.

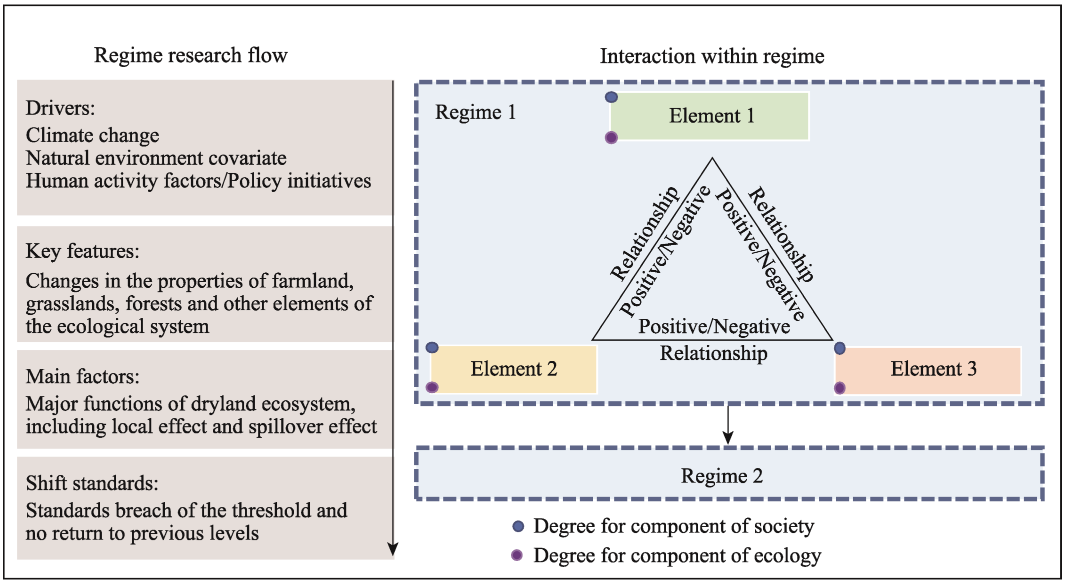

Fig. 2 Dryland Regime Shift detecting workflow

3 Dryland SES trends and topics of interest

Studies on SESs are regarded as recognizing an emerging "third" space that transcends the sum of singular social and ecological research practices and disciplines (Folke et al., 2016). Such studies represent a better understanding of the complex and evolving links between ecosystems and human societies (Fischer et al., 2015). These coupled and compositive characteristics have resulted in methodological pluralism and the formation of a weak coherent methodological identity in SES studies (Bodin and Tengö, 2012). Although numerous ambiguities remain, SES research has designed nomenclatures with integrated social and ecological components commonly used in the title, keywords, and abstracts of such work (de Vos et al., 2019). Changes in these nomenclatures reflect changes in the main thematic topic of dryland SES research over time. Therefore, we analyzed 1446 articles collected in the Web of Science using keywords related to dryland SESs. The number of studies published annually in dryland SES research increased from 1 to 235 between 1986 to 2019, and Science of Total Environment, Global Change Biology, and Journal of Arid Environments were the top three journal sources, occupying 2%–3% of all the publications. Based on the raw number of publications, Consejo Superior de Investigaciones Científicas (62 publications), University of California (54 publications), Chinese Academy of Sciences (50 publications), and the United States Department of Agriculture (46 publications) contributed most to dryland SES research. The lead authors are J. Julio Camarero and Antonio Gazol of CSIC, who contributed to almost 2% of all 1446 papers. We then followed the Co-word method to assess changes in the main topics of interest over time (Chen, 2017). By counting how frequently each combination of term words extracted from the keywords, abstracts, and titles of different articles occurred in published literature, we could identify the research terms that appeared most frequently in recent years, which were as follows: climate change, resilience, drought, and vulnerability (Fig. 2). We subsequently clustered all term words and labelled each cluster using the term words occurring with the highest frequency. The most extensive research cluster is related to ecosystem services, landscape functioning, and semi-arid agriculture soils. The typical research terms indicate that extreme drought, drought resistance, drought severity, and tree species have received more interest since 2017. Pine trees in European drylands are the main object of interest in terms of tree species (Szmidla et al., 2019). However, traditional research topics, such as disturbance and ecosystem functioning, are decreasing in prevalence. The rapid increase in term words used in the cited literature is likely to offer insight into emerging trends.

4 Challenge and perspectives

The increasing aridity worldwide affects the structure and functioning of dryland ecosystems (Miguel et al., 2020). Understanding how drylands respond to ongoing environmental change is crucial for ensuring global sustainability (Maestre et al., 2016). A high number of publications have indicated how climate change or drought events affect social-ecological processes in dryland SESs and have achieved significant progress. However, with the changing environment and neo-dryland SES research trends, some specific points could be considered as a more general set of concluding remarks for future research related to dryland SESs to resolve current research gaps. A more general but adaptable dryland SES framework should be developed. By modifying the definitions of variables, indicators to measure them, data collection, and analysis methods, a more tailored

Topic	Strength	Begin	End	1986–2020
Disturbance	4.364	2007	2016	
Species richness	5.433	2007	2012	
Biodiversity	3.896	2011	2014	
Adaptive capacity	4.272	2012	2014	
Arid rangelands	3.831	2012	2014	
Plant species	3.625	2012	2013	
Ecosystem functioning	3.739	2013	2017	
Drought impacts	3.766	2013	2015	
Water stress	5.633	2014	2016	
Stomatal conductance	3.824	2017	2018	
Extreme droughts	4.515	2017	2020	
Drought resistance	4.382	2017	2020	
Drought severity	4.012	2017	2020	
Tree species	3.684	2017	2020	

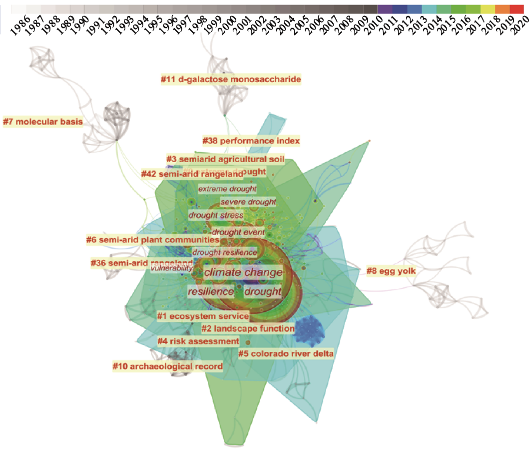

Fig. 3 Changes in the prevalence of top term words

Note: Left part indicated the popular duration of each top term words. The strength showed the popularity of term words in the interior of the field. And the red bar presents the duration when the term words were regarded as a hot study. The right part showed the co-citation relationship of term words in the temporal dimension. Term words in years are distinguished by different colors. And the keywords were ranked and plotted by their popularity. All the raw data was collected in the web of sciences by June 2020.

dryland SESs framework can be produced that could be suitable for different types of dryland systems, such as irrigation land, forests, and grazing land.

Current studies on resilience, sustainability, vulnerability, and feedback mechanisms are mainly theoretical and simulated scenarios. The development of approaches to simulating the coupled dryland SES process under different scenarios, establishing appropriate land-use allocation plans, and the formation of optimized strategies to coordinate regional natural and social needs still face numerous challenges in practice. Moreover, previous dryland SES studies mainly focused on framework and policy management. However, specific insights must be strengthened. Dryland ecology services and functioning should be consistently taken as the basis when exploring dynamic processes, driving mechanisms, and coupled feedback mechanisms in dryland SESs.

For instance, the main challenges of dryland SES can be summarized as Fig. 4. An overarching scientific issue is the dryland's regional dynamics and sustainable development of coupled human and natural systems. The three sub-points underneath this can be summarized as coupling process and structure, dynamic mechanisms and function, and sustainable realization. Correspondingly, under each of the scientific questions, there are challenges for subsequent research to solve. For example, the integration of natural element

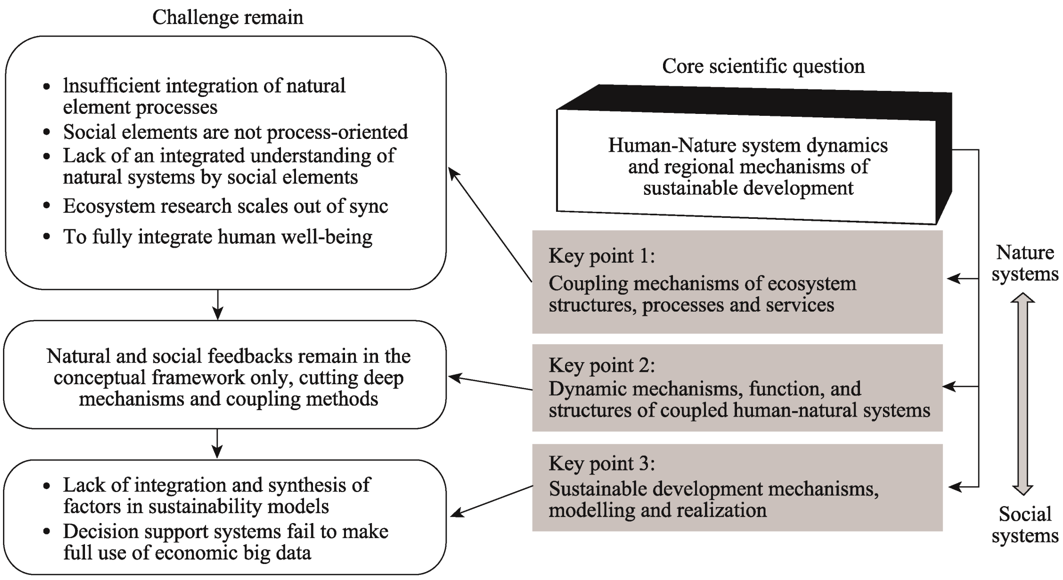

Fig. 4 Core scientific questions and challenges for dryland SESs

processes in dryland needs to be more enhanced sufficiently. Social elements should be well integrated when understanding natural systems such as Forest and grassland degradation. The major challenge for dynamic mechanisms is that natural and social feedback remains in the conceptual framework only, cutting deep mechanisms and coupling methods. Lacking integration and synthesis of sustainability models and un-useful adopting of economic data are the two main challenge for sustainable realization of dryland SESs.

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旱地社会生态系统的恢复力、适应性和制度转移

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摘要：干旱区在全球范围内广泛分布，并养育超过三分之一的世界人口。人口增加、城市化、土地退化和气候变化对人地耦合系统产生了重大影响，并深刻改变了旱地社会生态系统。特别是在发展中国家和全球环境中，旱地的退化已经对数百万人的生活构成了严重的威胁。这篇综述评估了已发表的关于旱地社会生态系统的文献，以揭示当前研究趋势和热点。介绍了旱地社会生态系统框架、复原力测量和制度转变方面的基本理论和进展。在今后旱地可持续性的研究中，我们应更加重视和加强制定一个更普遍且适应性更强的框架和更实用的战略，以便进行长期协调和建立伙伴关系，并实现对生态服务的具体认识。

关键词：旱地；社会生态系统；人地耦合系统；适应性；弹性；可持续发展