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Social-ecological system management in drylands: experiences from Chinese Ecosystem Research Network

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Social-ecological system (SES) management plays an important role in terrestrial carbon dynamics and human well-being in fragile drylands. Over the past four decades, the Chinese Ecosystem Research Network has accumulated valuable experience on the infrastructure safeguarding, vegetation restoration, and watershed improvements, and has made substantial progress in biodiversity, land use, and climate change research, which could provide data and a theoretical base for an explicit and quantitative SES indicator system. Here, we introduced the key findings that could inspire scientific SES trade-off rethinking and presented a conceptual framework based on the observation platforms. Emphasis is placed on the radiative effects of the in situ-site stations involved in local social and natural surroundings, which could link-up the policy makers to enhance the balance of SES elements. It aiming to contribute to full initiatives of station researchers and to promote more productive collaboration for cross-site and interdisciplinary research in SES sustainability management.

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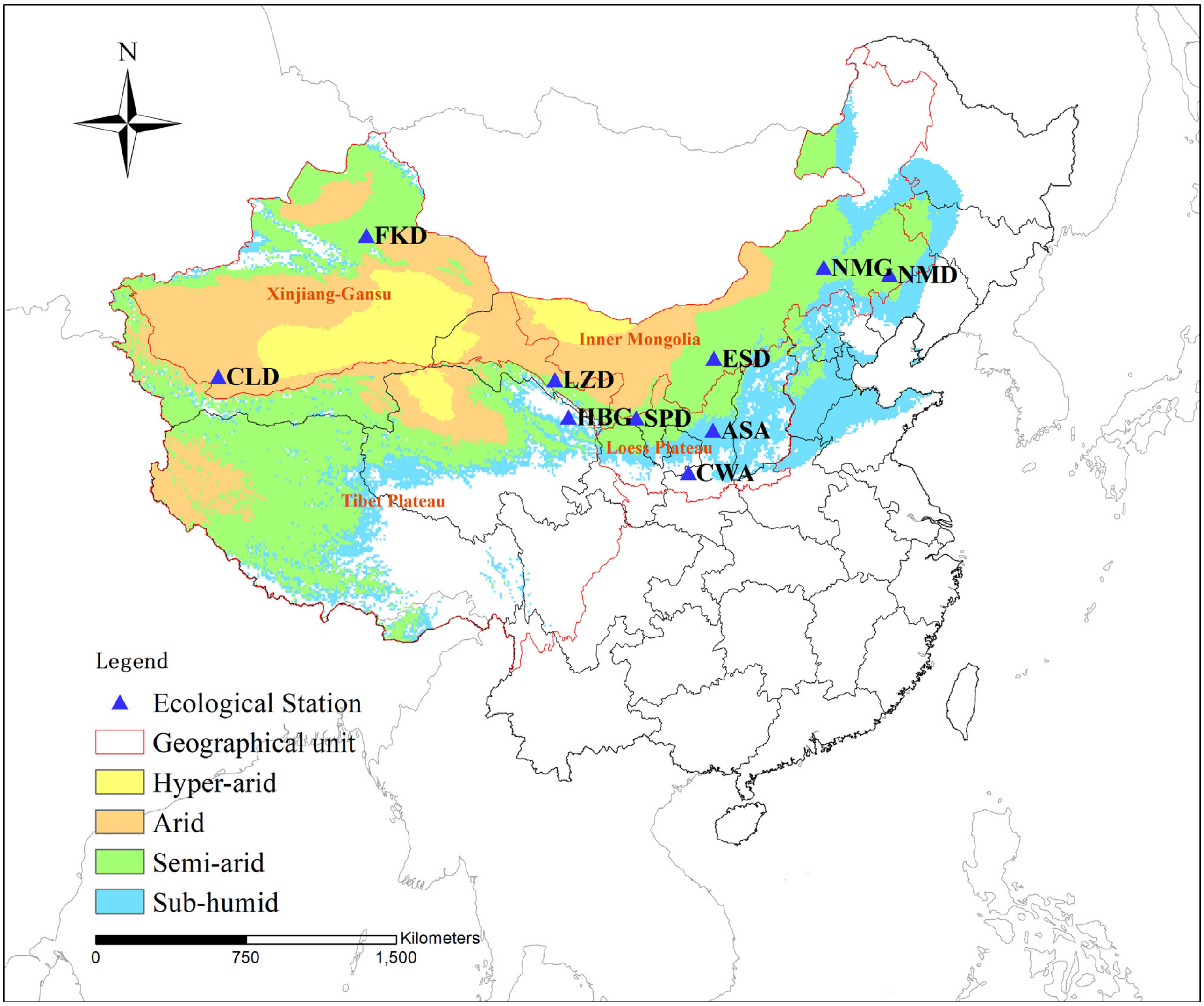
Introduction

The United Nations Sustainable Development Goals (SDG) aim to provide solutions for social, economic, and environmental problems, and to achieve a land degradation-neutral world and the eradication of poverty in present and future ecosystems and societies. Dryland is recognized as regions where precipitation is less than evapotranspiration [1]. Dryland ecosystems cover 51×10^6 km^2, accounting for about 41% of the terrestrial land and supporting about 38% of the world's population [1,2]. Drylands comprise the most sensitive and vulnerable ecosystems [3] and dominate the inter-annual variability of the global carbon sink [3,4,5]. Social-ecological system (SES) management has recently come under scrutiny due to the increasing human-driven degradation of ecosystems, which, in turn, increasingly threatens human well-being [6,7,8]. In drylands, low water availability constrains the ecosystem material support service and human livelihoods. By launching multiple international programs, scientists, governments, and organizations globally have sought to strive for problem and solution-oriented SES management strategies through integrated transdisciplinary research [9]. Longstanding international SES sustainable programs such as the Programme on Ecosystem Change and Society (PECS) [10], Future Earth (www.futureearth.org), and the Global Dryland Ecosystem Programme (Global-DEP) [11•] have been involved in some studies of the global environmental change [12]. A large body of literatures and several approaches [13] are being used to explore the features and mechanisms that underpin the stewardship of SES sustainability.

China is now the world's second largest economic entity and bears large stresses from the trade-off between the needs of society and natural sustainability [14,15•]. It was reported that drylands in China expanded by 12% in 1994–2008 compared with the same regions from 1948–1962 [16]. In order to reduce land degradation and mitigate climate change, the Chinese government has initiated a series of re-vegetation programs such as the Three North Shelter Forest System Project (1979–2050) and the Grain-for-Green Project [17,18•] that have enhanced surface greening and carbon sequestration [19,20,21]. However, large water consumption of forestations and reduced agricultural land have produced overlay threats on ecosystem sustainability and local livelihoods. Therefore, it is urgent to clarify the interactions among SES elements and to conduct comprehensive SES assessments. In addition, how SES structure and function evolve and can be exploited to produce a win-win strategy for social progress and environmental improvements is the critical theme.

The Chinese Ecosystem Research Network (CERN), founded in 1988 and led by the Chinese Academy of Sciences, has conducted continuous monitoring of the hydrological, pedological, atmospheric, and biological elements of typical ecosystems in order to meet the scientific research and societal needs [22,23]. CERN has made significant progresses in social-ecological management and has accumulated a wealth of experience in environmental conservation, safeguarding public infrastructure, and improving livelihoods for dryland sustainable development. CERN is one of the founding members of the International Long-Term Ecosystem Research (ILTER) network, which concerns global site-based long-term monitoring research to improve the scientific knowledge of multiple scales to benefit policy making, ecosystem management, and public environmental improvement [24,25]. In fact, many currently running ecological stations located in drylands were established before CERN and initially aimed to meet socioeconomic needs, e.g., protecting the railway from wind and sand, improving the productivity of low-yield agricultural areas, and restoring vegetation. CERN conducts a series of cross-scale and trans-site studies on the structure and function of SES progress. SES is regarded as complex resilient adaptive systems within the biosphere in diverse contexts, but they face a long-term sustainability crisis [26] under the rapid global change. A comprehensive study of SES has been a part of CERN's mission since its establishment, and transdisciplinary research between the academic community and the local stakeholders has been

Figure 1



Current Opinion in Environmental Sustainability

Ecological stations of CERN in northwest drylands of China. Drylands are divided into four subtypes according to the mean value of aridity index (AI) during 1982–2015: hyper-arid ($AI < 0.05$), arid ($0.05 \leq AI < 0.2$), semi-arid ($0.2 \leq AI < 0.5$), and dry sub-humid ($0.5 \leq AI < 0.65$). AI was calculated using annual precipitation and potential evapotranspiration. Abbreviations of names of the ecological stations are shown in Table 1.

Table 1

Names of ten CERN ecological stations and their locations

Ecological Station	Abbreviation	Location	Type
Ansai Integrated Experiment Station on Water and Soil Conservation	ASA	E109°19′, N36°51′	Agricultural Ecosystem
Cele Desert Research Station	CLD	E80°43′, N37°00′	Desert Ecosystem
Changwu Agro-Ecological Experiment Station in Loess Plateau	CWA	E107°40′, N35°12′	Agricultural Ecosystem
Ordos Sandland Ecological Research Station	ESD	E110°11′, N39°29′	Desert Ecosystem
Fukang Station of Desert Ecology	FKD	E87°55′, N44°17′	Desert Ecosystem
Haibei Alpine Meadow Ecosystem Research Station	HBG	E101°19′, N37°37′	Grassland Ecosystem
Linze Inland River Basin Research Station	LZD	E100°07′, N39°21′	Desert Ecosystem
Naiman Desertification Research Station	NMD	E120°42′, N42°55′	Desert Ecosystem
Inner Mongolia Grassland Ecosystem Research Station	NMG	E116°42′, N43°38′	Grassland Ecosystem
Shapotou Desert Research and Experiment Station	SPD	E104°57′, N37°27′	Desert Ecosystem

conducted for decades. Hence, it is urgent and important to connect the social and ecological systems for the prosperous evolution (present and future) of biophysical and biochemical processes on Earth.

This paper is a contribution to a Special Feature on the Global-DEP related to SES issue [11•]. Our objectives of this study were to introduce the development of ecological research and the social concerns from ten CERN ecological stations situated in drylands (Figure 1). A growing body of experimental technologies has improved environmental conditions, and have integrated scientific mechanisms into ecological processes to complement social applications. First, windbreak and sand-fixation grid technology contributed to safeguarding the national railway infrastructure and ecosystem restoration; Second, comprehensive management of small watersheds has reduced soil erosion and increased farmers' income; Lastly, a coordinated effort of SES sustainability framework was provided to balance the trade-offs between ecological processes and societal needs, based on the interaction between policy influence and in situ-site station participation. Here are two examples presenting the contribution of CERN to SES management in drylands.

Sand fixation and degraded grassland restoration

SES elements interactions are regulated by climate change and human activities. In the northwest drylands of China, intense wind and sand activities not only affect the ecosystem production and life of residents but also pose a threat to the construction of the national railway infrastructure facilities. Field research observation stations were established to solve the technological problems of windbreak and sand fixation and vegetation restoration. Experiments and observations have provided technical solutions and scientific support to keep the railway from being buried and damaged by wind and sand. A desert railway protection system utilizing plants without the need for irrigation which was proposed by Shapotou Desert Research and Experiment Station (SPD) has safeguarded the Baolan Railway passing through the Tengger desert for more than 60 years [27]. This involved the building of mechanical sand barriers of 1.5 metre height obstructing wind and sand, and establishing fix sand grids at a 1 m × 3 m resolution with grass and xerophytic shrubs (e.g., *Caragana korshinskii*, *Artemisia ordosica*, *Hedysarum scoparium*) (Figure 2). Naiman Desertification Research Station (NMD) created an allocation system for planting forest-shrub-grass combinations and implemented an experimental area for biological sand fixation that has allowed the Beijing-Tongliao railway to pass through the Horqin Sandy Land. Decision-making policies and the scientific results of ecological stations together allowed efficient safeguarding of the railway and have made substantial contributions to ecological improvement, local human well-being, and associated economic development.

Vegetation restoration and ecosystem stability are two of the foundations of sustainable development to support ecosystem services and human populations in drylands. CERN have developed some key technologies for re-vegetation in drylands and revealed the mechanisms of the vegetation-soil-water nexus for ecosystem restoration stability. Ecological restoration technology that controlled grassland desertification was implemented by Inner Mongolia Grassland Ecosystem Research Station (NMG) according to the terrain characteristics and available conditions of suitable plant species [28]. (i) In steep slope regions, mechanical sand barrier (reed curtain), re-seeding (e.g., *Leymus chinensis*, *Agropyron cristatum*), withered grass and nylon sand fixing net laying, and grazing prohibition were implemented from 2016 (Figure 3 a) to 2017 (Figure 3b). (ii) In gentle slope regions, biological sand barrier (*Salix gordejevii*), re-seeding (e.g., *L. chinensis*, *A. cristatum*), and grazing prohibition were implemented from 2015 (Figure 3c) to 2017 (Figure 3d). (iii) In blowout areas, mechanical sand barrier (reed curtain), biological sand barrier (*S. gordejevii*), re-seeding (e.g., *L. chinensis*, *A. cristatum*), withered grass laying, and grazing prohibition were implemented from 2016 (Figure 3e) to 2017 (Figure 3f). The re-vegetation governance model that combined effects of ecological management technology and grazing prohibition measures implicated that the importance of both construction and subsequent management in vegetation restoration.

Figure 2

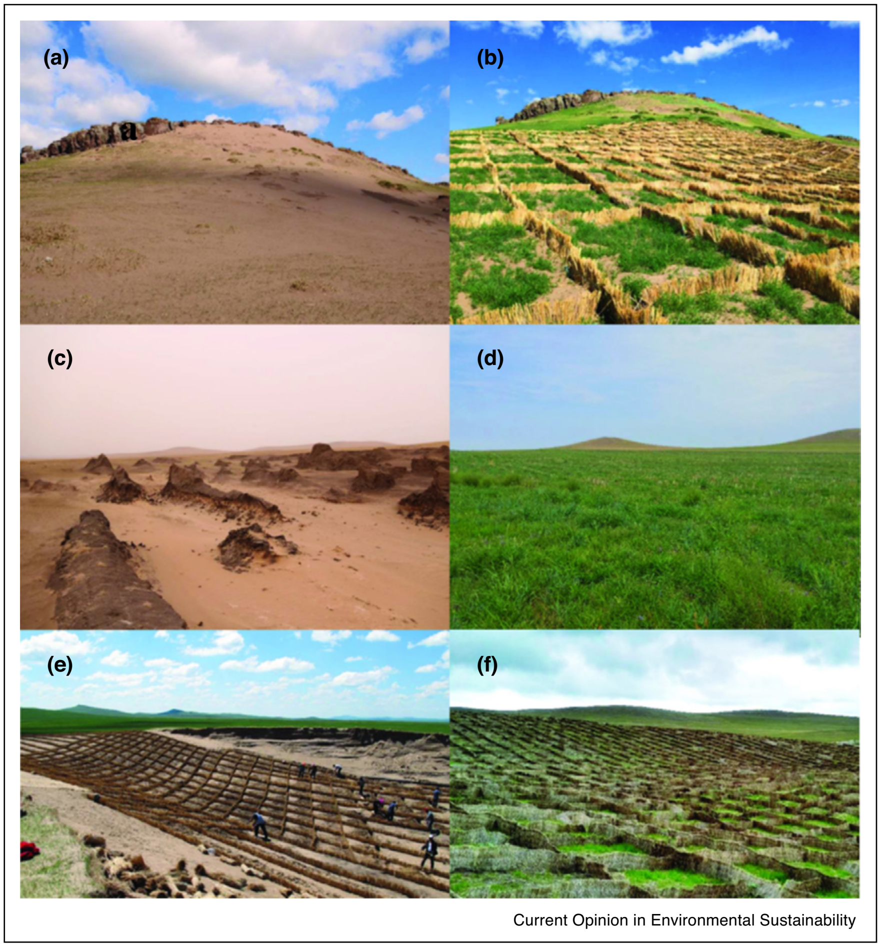
Artificial sand fixation vegetation protection system in Shapotou section of Baolan Railway (picture from SPD).

CERN ecological restoration experiences have provided a paradigm for global drylands and some of the practices have been successfully used in desertification control in other countries around the world (such as the Republic of Mali and Kenya) [29]. Other technologies also appeared together which enhance the ecosystem stability. A vegetation system based on xerophytic shrubs and microbial cultivation techniques increased soil organic carbon and total nitrogen levels of the surface soil and accelerate biological soil crust formation to maintain ecological security and health [30,31,32]. It is important of the maintenance of a high biodiversity and biotic heterogeneity as insurance against the various risks incurred by ecosystems [33]. Human management (e.g. mowing) exacerbated negative effects on ecosystem stability by nitrogen addition, threatening semi-arid regional food security [34,35]. An effective eco-hydrological threshold was determined for the assessment of sand vegetation stability in drylands [36]. These subsequent achievements have continuously consolidated the previous results of desertification control. Top-down guidance and bottom-up feedback would form a self-driven positive feedback loop for environment improvement and local human living.

Carbon-water coupling and watershed management

Vegetation restoration has promoted carbon accumulation in Chinese drylands [37,38,39] to mitigate climate warming through the biogeochemical cycle. Carbon-water coupling cycles are regulated by multiple factors, e.g., precipitation, land use, land-use change and management strategies [40,41,42]. The continuous ecological restoration and soil conservation project has resulted in a decrease in farmlands, but an increase in forests and shrublands [43], which has reduced annual streamflow and sediment load. The highly water consumption of revegetation has subsequently exacerbated the shortage of regional water resources [41]. Comprehensive management of small watersheds has produced a gratifying progress in SES sustainability on the Loess Plateau. An example of watershed named Zhifanggou is as follows. (i) Reverting croplands to grasslands or shrublands reduced soil erosion in the steep slope region (top of the picture, Figure 4). (ii) Planting forests (*Robinia pseudoacacia*) could improve the stability and erosion resistance of shallow slopes (middle of the picture, Figure 4). (iii) Planting apples increased farmers' income in the available farmland (bottom of the picture, Figure 4). All these measures

Figure 3

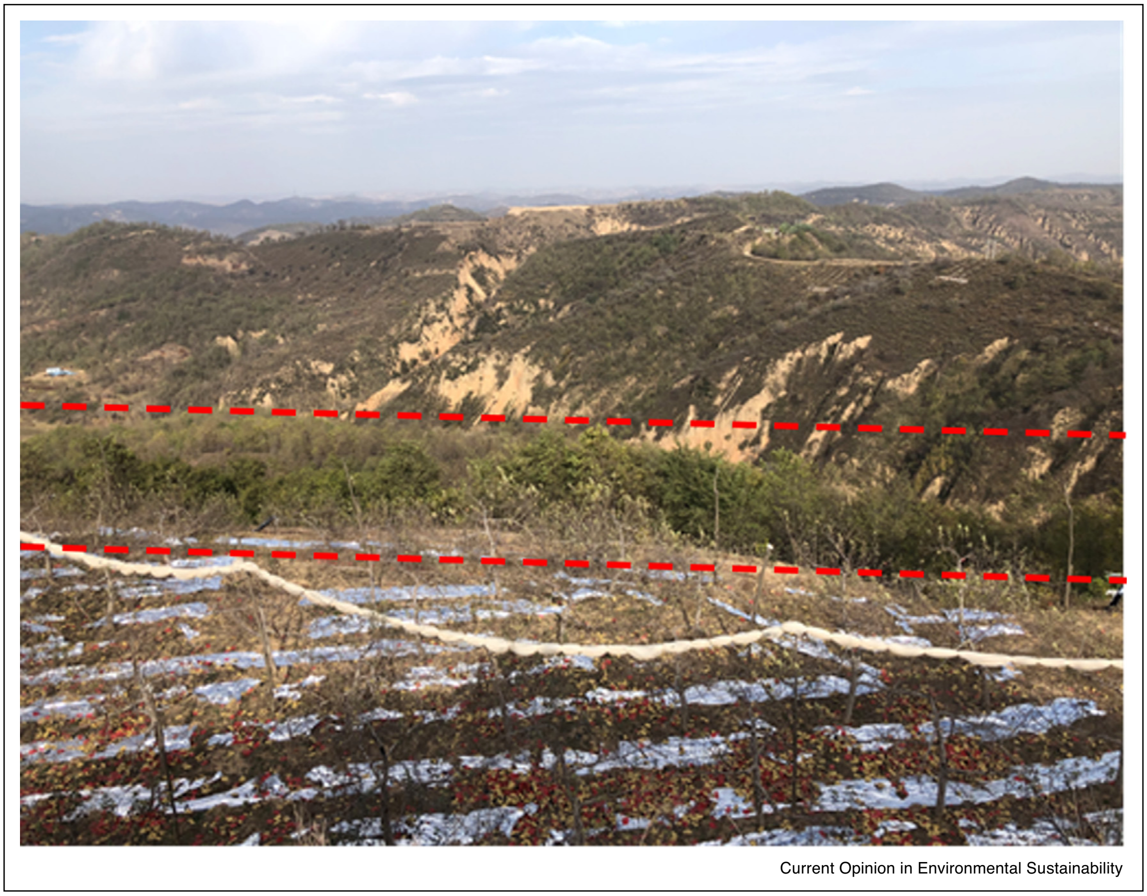


Before and after ecological restoration in Wulagai grassland, Inner Mongolia, China (picture from NMG).

have improved the ecosystem function to increase carbon sequestration and the incomes of local farmers. Furthermore, the implementation of the GGP has substantially enhanced the transformation of livelihoods from subsistence farming into off-farm activities such as migrant labor and market-oriented orchard farming [44•]. Ecological compensation as a component of watershed management has promoted the shift of croplands to grasslands or forests that could improve participants' incomes and diversify the economic structure, at the end, ensured the SES sustainability.

The follow-up management and comprehensive evaluation of watershed management are still in progress. A conceptual framework of a coupled anthropogenic-biological system predicted the lowest threshold of net primary production that would suffer under water shortages in the Loess Plateau [41]. Ecosystem services have been quantified in an SES for landscape changes, e.g., a cascade framework for soil erosion control services [45•]. Moreover, knowledge of the impact of land use and management (e.g., grazing) on the SES structure and function will provide scientific support for policy-makers [46]. Water use efficiency, which indicates the vegetation-mediated tradeoffs between ecosystem water and carbon cycles were enhanced in groundwater-dependent ecosystems after the re-vegetation from 2000–2014 in the Loess Plateau [47,48]. There have also been some uncertainties and challenges. Owing to the contrasting response of leaf physical structures to climate change, there are still some uncertainties to predict the carbon and water coupling cycle [49]. The comprehensive SES assessment methodology for the series actions, such as natural vegetation restoration, large-scale plantations, vegetation capacity, and its spatial distribution, is also unclear [50]. Therefore, it is essential to achieve carbon-water balance and comprehensive watershed management assessment for SES sustainability in drylands.

Figure 4


Current Opinion in Environmental Sustainability

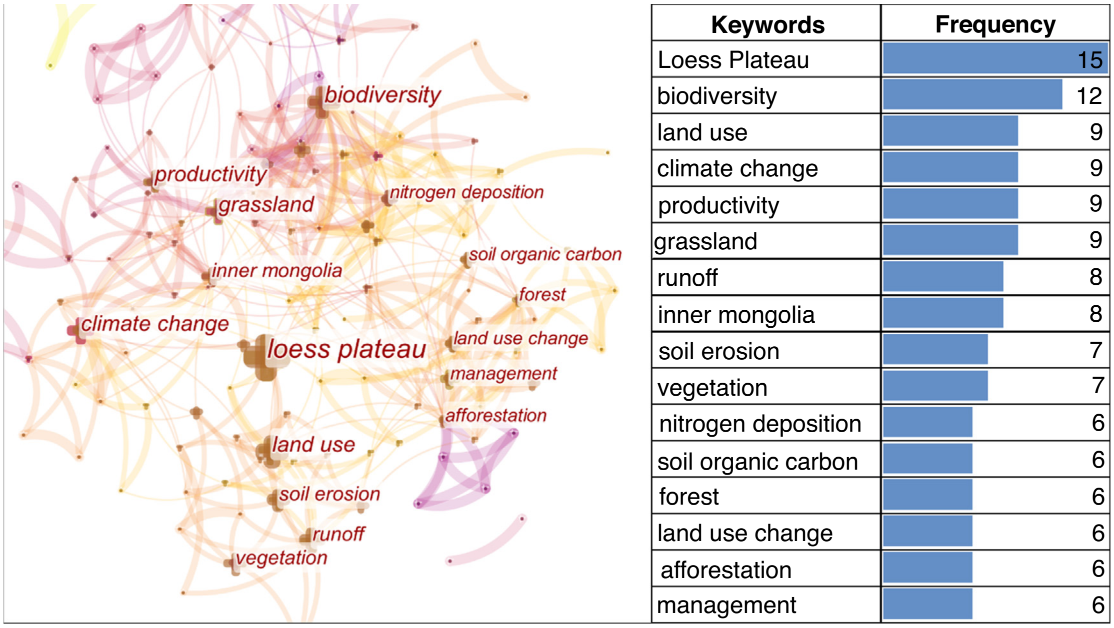
Watershed management in Loess hilly and gully region, Zhifanggou in the Loess Plateau (picture from W. ZH.).

Rethinking SES management from CERN experiences

SES discourse is a steadily growing scientific field [51•], and we need to explore a common analytical framework and consistent standards to compare effective management strategies. The applicability of a beneficial SES management paradigm requires an assessment strategy. To quantify the complexity among social, economic, and ecological factors is still difficult, owing to a lack of long-term social survey data and accurate mathematical models of SES. Using biocultural approaches to conservation [52], Tang & Gavin (2018) found that positive social and ecological outcomes could be improved if the principle would be much more adhered to in typical regions of Inner Mongolia, China [53]. Pacheco-Romero et al. (2020) developed a reference list of 60 variables for the characterization and monitoring of SESs and found that variable relevance was positively correlated with consensus across respondents [54]. Chen et al. proposed a framework of coupled dynamics of social, economic, and ecosystem functions and performed a preliminary analysis of the inter-relationships among key SES indicators in the Asian Drylands Belt, that included four main indicators [55,56]. However, the trajectory of SES structure and function, as well as its mechanisms related to stakeholders and managers, are unclear, and the identification of a probable SES regime shift is also a challenge. The application of an accurate and appropriate methodology could be more efficient in evaluating comparisons and predictions owing to the high heterogeneity of SESs and coexistence of qualitative and quantitative data.

CERN is committed to exploring the development paths of optimizing ecosystem structure and function while ensuring human well-being, and to clarifying the challenges and directions for social and ecological sustainable science. Ecological stations are involved in the research of local natural and societal surroundings and bridge the knowledge gaps of policy makers and the real SES state to achieve better guidance and assessment. Using Citespace software, we analyzed the frequency of key words in 100 high quality articles (Impact Factor > 5) published by ten CERN ecological stations in drylands from 2011 to 2018 (Figure 5). Biodiversity, land use, and climate change are the key

Figure 5



Keywords	Frequency
Loess Plateau	15
biodiversity	12
land use	9
climate change	9
productivity	9
grassland	9
runoff	8
inner mongolia	8
soil erosion	7
vegetation	7
nitrogen deposition	6
soil organic carbon	6
forest	6
land use change	6
afforestation	6
management	6

Current Opinion in Environmental Sustainability

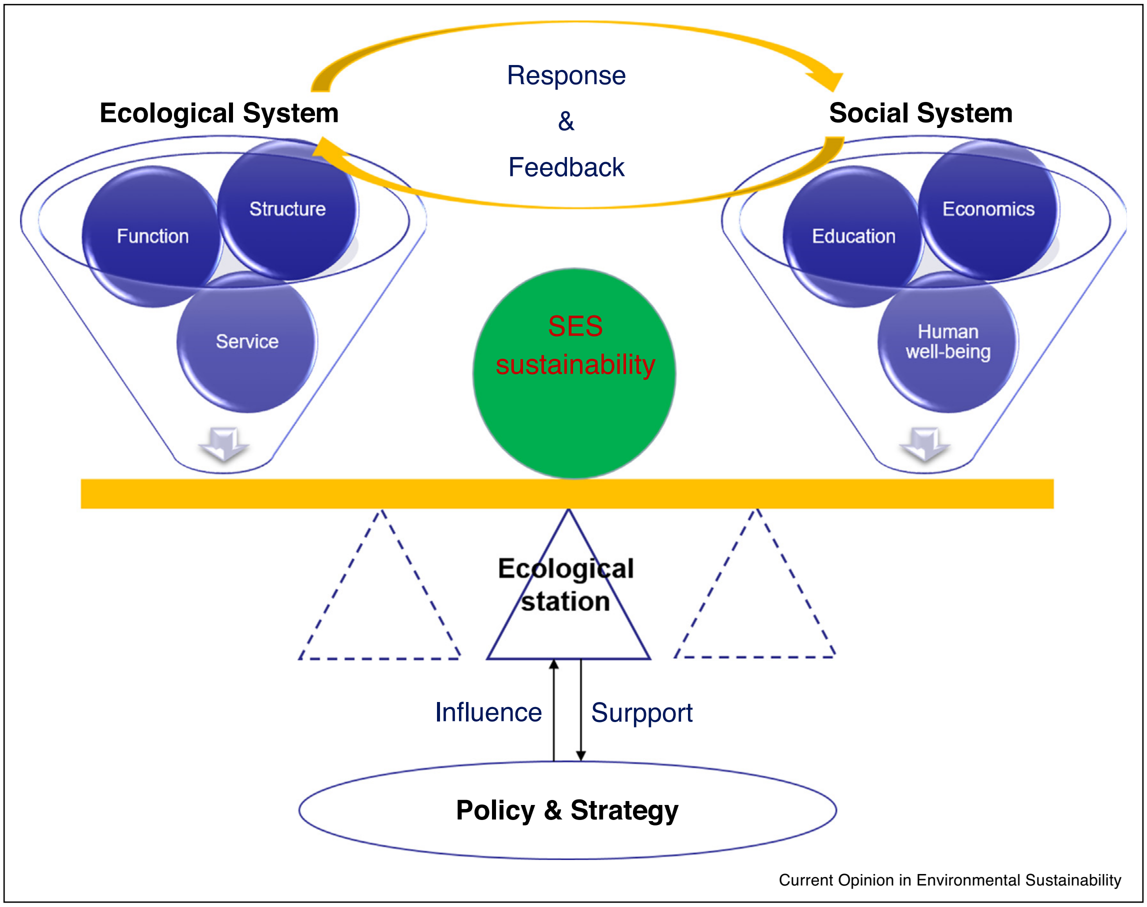
Frequency graph of key words from published journal articles by CERN's stations in drylands, 2011–2018.

research topics, which are the important tenets of SES sustainability. These achievements provide a potential robust foundation for the cross-scale and trans-site research and are significant for the exploration of SES regional patterns. There will be a series of ecological and livelihood improvement policies such as "green mountains and clear water," Yellow River Basin management, and Qinling Mountains (important north-south geographic boundary of China) protection to enhance the importance of SES sustainable management. CERN ecological stations will be included in the Global Dryland Ecosystem Programme, which will be launched in 2021 [11•]. All the above policies and accumulated experiences have offered an important instruction for the comparable research conceptual framework and indicators.

Some efforts have also been made to integrate societal concerns into the SES comprehensive practice. CERN stations have provided field practice guide for college students and an open scientific cooperation platform for researchers from institutes and universities around the world, and established Children & Youth Science Education Bases to convey scientific knowledge to teenagers and local people, thereby increasing the public's scientific understanding of SES sustainability [29,57,58,59]. These activities improved participant enthusiasm and the efficiency of policies and strategies conducted. Noted, the poverty alleviation work conducted by CERN ecological stations has provided a guidance in agriculture, education, and economy to improve people's livelihoods [60]. However, comprehensive evaluations of the impact of these activities on the SES are still insufficient for the absence of an effective approach. The public social services of ecological stations have been successful in guiding practical policies. Response and feedback of SES elements formed a sustainable path loop between ecosystems and social systems, which is closely related to the ecological stations (Figure 6).

Conceptual framework of SES based on ecological stations emphasizes the interaction of policy and wisdom of local stakeholders in the response and feedbacks between ecosystems and social systems. Long-term sustainability depends on a focal SES self-organized stability which was not ruled by policy and in turn heterogeneous costs and benefits model derived from SES variables data could improve policies [8]. Local and national institutes mediate the coordinate effects among policies and strategies for the actual actions that make efficient of one another through the flux of influence and support. The first principle of the conceptual framework is Human-Earth Relationship and the SES sustainability from the response and feedback of coupling nature and society ecosystem elements. Human beings are a part of the social system, while, they could regulate the SES balance through policies due to their subjective initiatives, and the ecological station plays a regulatory role in policy implementation. The essence of the conceptual

Figure 6



Conceptual framework of social and ecological system sustainability based on ecological stations. Balancing social-ecological trade-offs is fully dependent on the response and feedback of coupling nature and society ecosystem elements.

framework is the self-adjustment of SES trade-offs. In drylands, SES structure and function are tightly linked with water availability and high sensitivity to natural and anthropogenic disturbances. Here are three associated themes: (i) the spatial and temporal pattern evolution of SES; (ii) the response and feedbacks of SES under climate change and implementation of management strategies; (iii) assessment of the interaction of natural and societal measurements and their mechanisms. Together, these aim to explore the nexus trajectory of the nature and society coupling mechanism and determine the early-warning indicators for identifying SES regime shift [11•], which will help to provide the basis for SES management strategies and human well-being.

Challenges and outlook

Overall, the mission and vision of CERN are aligned with the ILTER to commit a series of transdisciplinary research projects, to improve understanding of the interaction of nature and society, and to thus provide solutions on current and future SES trade-off issues to achieve sustainable development at the global scale. The efficiency of policy implementation and the participation of stakeholders have evenly balanced the trade-offs of SES sustainability. This key foundation drives the contention of ecology, society, and economics. The results are significant for model exploitation and SES system spatial upscaling from local to regional sites and beneficial for making nature-based solution response strategies for SES to coordinate developments in global drylands. To this end, more attention should be paid to human-initiated behavior related to the evolution of earth and human activities. International cooperation on SES at multiple temporal and spatial scales for adaptive ecosystem management to environmental changes in drylands needs to be carried out through in-depth data mining of long-term monitoring and network comparisons of cross-site typical ecosystems. We call to adopt the SES conceptual framework in global drylands management to achieve a dynamic and stable response-feedback cycle in ecological and social elements based on long-term monitoring stations. The SES sustainability in global drylands requires an open sharing of scientific and social knowledge, interdisciplinary studies, and the widespread application of successful management approaches.

Conflict of interest statement

Nothing declared.

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