Chapter 4
Dryland Ecosystem Services and Human Wellbeing in a Changing Environment and Society

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Abstract The framework of the Global Dryland Ecosystem Programme (Global-DEP) combines the ecosystem service (ES) research paradigm and system dynamics thinking. The core of the framework is the resilience of social-ecological systems (SESs) in drylands. This resilience depends on the interaction between ecological and social subsystems. Water shortages, desertification, and poverty are currently the biggest challenges to maintaining resilience and realizing sustainable development in dryland SESs. However, the internal links between ecosystem degradation/restoration and poverty/eradication remain unclear. ESs bridge ecological and social subsystems by forming a "bonding concept" that connects environmental goals and socioeconomic goals, as ESs can directly or indirectly promote almost all land-related sustainable development goals (SDGs). Clarifying the change of ESs and their contributions to human well-being (HWB) is the key to the entangled dryland challenges, promoting the resilience of SESs and finding solutions to coordinate ecological protection and socioeconomic development. This chapter summarizes the research progress in dryland ES and its relationship with HWB in a changing environment and society. It outlines research priorities, focusing on the concept of ES and how its methodologies contribute to dryland research and management for realizing SDGs. The priorities are as follows: ES quantification; the interactions among ESs; mechanisms of ES contributing to HWB; landscape optimization for ESs; and ecological compensation.

Keywords Dryland · Ecosystem services · Human well-being · Global-DEP · SDGs

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4.1 Background and Significance of the Theme

Drylands provide important yet under-appreciated ecosystem services (ESs) that are essential to sustain the well-being of local residents and beyond. These include key provisioning services, such as the production of food, fiber, medicinal and pharmaceutical plants, timber, and biofuels. They also include a variety of regulatory services, such as water purification, pollination and seed dispersal, and climate regulation by sequestering and storing vast amounts of carbon in the soils (Yirdaw et al. 2017). The cultural services deeply rooted in people's lifestyles and beliefs in drylands are an important part of human civilization. Due to the vulnerability of drylands to climate change and land disturbances, it is critical to protect and sustainably manage the ecosystems. So far, many countries still regard biodiversity and ecosystem protection as an obstacle to economic development, ignoring nature's contributions to people (NCP). Their actions related to protection and development usually conflict (Pires et al. 2018).

ESs are not only an object of research but also an object of management. They form a common language for communication and dialogue among researchers, managers, and stakeholders, and they are a source of human well-being (HWB). Thus, it is important to develop a clear understanding of ESs in studying and governing the dryland SESs, which are close combinations of society and nature (e.g., pastures, agropastoral ecotones, agroforestry systems, desert-oasis composite systems, etc.). ESs bridge ecological and social subsystems as a "bonding concept" that connects environmental goals (e.g., ecosystem integrity and biodiversity maintenance) and socioeconomic goals (e.g., sustainable livelihood, poverty reduction and cultural heritage) (Pires et al. 2018), as ESs are directly or indirectly related to almost all land-related sustainable development goals (SDGs) (Preez et al. 2020). Since the Millennium Assessment (MA) in 2005, studies on ESs have gradually increased. Early ES studies mainly focused on the description and quantitative analysis of ESs, including biophysical quantification, valuation, and modeling. Since the efforts of TEEB in 2010 and IPBES in 2012, more studies began to shed light on the contribution of ESs to HWB. Many new keywords emerged in publications from 2010 to 2015, including payment for ESs, willingness to pay, economic valuation, and poverty. After 2015, hotspots shifted to perception, trade-offs, cultural ESs, ES flow, and protected areas (Wang et al. 2021).

Biodiversity in drylands, represented by plant, animal, and microbial diversity and diversified cropping practices (e.g., polycultures, crop rotations, cover crops, agroforestry, etc.), is considered fundamental for the resilience/stability of dryland ESs (Naeem et al. 2012). Countries with high biodiversity have great potential to promote the resilience/stability of ecosystems and socioeconomic systems through the sustainable use of biodiversity and ESs (IPBES 2019). Up to now, dryland biodiversity and ESs have been inadequately evaluated due to limited data availability, the lack of a systematic ES valuing approach, and discord between decision-makers and researchers. Dryland ESs have high temporal and spatial variations, associated with the fast-changing variables (technological change, crop production, rainfall variability, etc.) and slow-changing variables (demographics, land use, annual mean precipitation, soil fertility, etc.) that simultaneously regulate the dynamics of social-ecological processes. As the distribution of the population also presents the characteristics of decentralized aggregation, the supply and demand of ESs usually do not match across different temporal or spatial scales. Poverty, remoteness, inadequate management, and imperfect market systems of drylands all contribute to the high dependence of human livelihood on such land. Land degradation and poverty form a vicious circle, hindering the socioeconomic development.

The widely used ES cascade conceptual framework (emphasizing how ecosystems benefit human society) and the supplementary NCP framework (developed on the basis of the concept of ESs and emphasizing social and cultural attributes of ES demand) provide us with different theoretical angles for understanding the links between nature and society. Specifically, ES indicators can link biophysical and socioeconomic analysis (Boyd et al. 2015). The methodologies of ES, including trade-off analysis and supply–demand (mis)matching analysis, are favorable tools for identifying the problems in dryland SESs, and landscape optimization and payment for ES are providing solutions to managers (Dean et al. 2021). Therefore, it is of great significance to incorporate the ES concept into resilience and sustainability studies in dryland SESs.

4.2 Quantifying Dryland ESs in the Changing Environment

Quantifying ESs is an important and a basic step in understanding the spatiotemporal changes in ESs, their driving forces, and ecosystem management (Lu et al. 2018). ES valuation can reflect human needs, perspectives, and market dynamics, further linking ESs to the social domain. Spatial mapping and scenario simulations can help identify ES degradation and deficit spots under changing climate and socioeconomic conditions, and guide risk management via spatially explicit monitoring of the ecosystems (Everard and Waters 2013; Hauck et al. 2013).

4.2.1 Biophysical Modeling of ESs at Multiple Scales

Modeling is a powerful tool to quantify changes in ESs at different scales. The low availability and high variation of water are the foremost factors in ecosystem processes and functions in drylands. The variation of annual rainfall in drylands can exceed 50% of the annual average, whereas this is only 5–10% in mesic areas (Barnes et al. 2021). Some existing ecosystem models or integrated ES models (such as InVEST) have been applied to quantify and predict ES changes in dryland ecosystems. However, methods of quantifying dryland ESs are still lacking, as drylands are usually regarded as marginal areas. As few models have been developed for dryland ecosystems, simulations of dryland processes are usually poor, particularly in addressing water cycling processes (Turner et al. 2016). They can provide useful information on large-scale patterns, but the fine changes and temporal dynamics on smaller scales require single-ES models or the validation of modules in integrated evaluation models using observations of drylands.

For water-based services, accurate simulations of water balance components are fundamental. Water supply and flooding regulations are important provisioning and regulatory services, respectively, corresponding to evapotranspiration (ET), runoff, soil water storage, groundwater, and reservoirs. Improved hydrological models require the identification and inclusion of key hydrological processes of drylands at different scales, which are usually ignored in existing hydrological models (D'Odorico and Bhattachan 2012; Quichimbo et al. 2021). Accurate characterizations of the hydrological variability are particularly important. Soil water deficit could be a more important driver than atmospheric drought in terms of influencing dryland vegetation and ET, given that vegetation change in the past decades showed no significant correlations with the atmospheric aridity index (i.e., the ratio of annual precipitation to potential ET) (Berg and McColl 2021).

Soil erosion is a significant concern to land managers in global drylands, as it can lead to a reduction of soil organic matter, declining of crop yields, loss of biodiversity, and the intensification of water pollution and dust storms, further affecting food security and exacerbating poverty (Li et al. 2017). Soil retention is a key ES to the residents in drylands and beyond. The USLE Model is the most widely used model for assessing soil erosion at different scales and in different regions, based on which many other erosion models have been modified. However, these models do not perform well for some areas because of the different development purposes and applicable conditions. For example, USLE cannot accurately simulate the erosion process of gully landforms, as it is not well described for the erosion process on steep slopes (Li et al. 2017). Describing the topographic and geomorphic features of drylands and the key hydrological processes at a specific scale is crucial to better describe the erosion process in model development (Sidle et al. 2019). In recent years, new technologies such as hyperspectral remote sensing provide support for optimizing the accuracy of key parameters (such as DEM in meters).

Dryland ecosystems play a very important role in the global carbon cycle (Poulter et al. 2014). Dryland carbon flux is the main driver of variation in the global carbon flux. The greening or browning of dryland vegetation has contributed to significant changes in global ecosystem carbon sequestration over the past 30 years, especially in the southern hemisphere (such as Australia), in which the carbon sink flux increases sharply during La Niña years. By comparison, the decrease of gross primary productivity (GPP) is even greater during El Niño years. This indicates that the responses of dryland vegetation to drought and rainfall pulses are different from those of other ecosystems (Barnes et al. 2021). Understanding carbon–water (both initial water conditions and water constraints) coupling is still the key to improving modeling and spatiotemporal predictions of carbon-related ESs in drylands.

Cultivated lands are a substantial part of the dryland landscape, especially in semi-arid areas. Crop yields largely depend on rainfall and its time allocation. In current crop growth models, water-driven models show better performance than radiation- or carbon-driven models (Lu et al. 2021a, b). However, sensitivity analysis of the key parameters is lacking for dryland crop models. In addition to rainfall variability, phenology and irrigation are important factors affecting the sensitivity and uncertainty of crop models (Plaza-Bonilla et al. 2014), which include ET, soil water, and vegetation parameters (e.g., root development under high water stress and maximum canopy coverage under low water stress) (Hui et al. 2022). Only with an in-depth understanding of sensitivity is it possible to explore the best management practices for dryland agriculture.

In a word, an in-depth understanding and quantification of the hydrological dynamics of dryland ecosystems and the coupling relationships with vegetation and soil processes are crucial for accurately quantifying the critical provisioning and regulatory ESs (including water provision, soil conservation, carbon sequestration, food production, etc.) in this highly variable environment. New simulation methods need to be further innovated to improve ES quantification across spatial and temporal scales. Particularly, the model structure needs to be supplemented by finely describing the characteristics of landforms, soil hydrology, and vegetation in drylands, as well as the ecohydrological and ecophysiological responses to long-term trends and the short-term variability of rainfall (extreme rainfall and drought) to reduce uncertainties when modeling dryland ecosystems. As for non-material services, there is no model to directly simulate cultural services, and indirect simulations merely simulate future scenes.

4.2.2 ES Valuation: More Than Monetary Value

ESs have values beyond biophysical value. They have market value, non-market value, option value, and non-use value. Quantifying the social values of a specific ES can be difficult, particularly for regulatory and cultural services (Martín-López et al. 2014). Currently, ES valuation research most widely focuses on the economic or monetary value of ESs, wherein ESs are regarded as an asset that can be consumed by people and that can be considered in economic accounting. In the view of TEEB, ESs contribute to the economy by creating income and welfare, and by avoiding social impairment (TEEB 2013). In the SEEA framework, ESs that directly contribute to human society are defined as “final services”, and the services flowing within the ecosystems are “intermediate services” (Hein et al. 2016). The differentiation between “final” and “intermediate” ESs is to determine the direct/indirect link between ESs and HWB and avoid double counting. Economic valuations of ESs can arouse peoples’ concern regarding nature and they can provide insights on the outcomes of a specific policy or management intervention according to the marginal change of the ES value and cost effectiveness (TEEB 2013). In a quantitative review of the ES value in drylands, Schild et al. (2018) found that the monetary value of dryland ESs depends on the type of ecosystem assessed and the assessment method adopted. Farmland and forest are regarded as high-value ecosystems because they can provide food or wood. In comparison, for grasslands and semi-desert ecosystems, the monetary value of ESs is very low. Although the total amount of provisioning services that these marginal ecosystems can provide is small, they are of great significance to the livelihoods of local residents. Particularly, under some circumstances, possessing some ESs (such as crops or woods) may indicate social recognition or cultural identity, beyond merely goods for consumption or monetary value. Therefore, economic evaluations alone are not completely reliable for making predictions, tending to cause biased management actions that neglect the sustainable use of ESs with low market value. This is especially true for regulating and cultural services. Future research needs to integrate monetary and non-monetary value methods to uncover the full spectrum of values of these undervalued ecosystems and ESs, so as to avoid further neglecting and destroying these ecosystems.

A framework that considers the multidimensional value of dryland ESs is needed because the multiple values of ESs usually provide different and complementary information for ES assessments (Martín-López et al. 2014). Studies are also needed for developing more appropriate valuation tools that link the biophysical value and social value of ESs in order to obtain dynamic predictions. Some progress is being made towards integrated ES valuations by constructing integrated evaluation frameworks (Boerema et al. 2017). Such approaches introduce ecosystem dynamics into the natural capital account and evaluate the value change of the expected final service flow or the change in ecosystem capacity. Such research connects the value of ESs with the concept of ecosystem dynamics, taking into account multiple stable states, thresholds, and lag effects, with positive and negative feedback in ecosystem dynamics.

4.2.3 Drivers and Scenarios

Climate change, land cover change, urbanization, livestock grazing, biological invasion, and the economy are the main drivers of dryland ecosystems. The increases in temperature, rainfall variation, CO_2 concentrations, duration of drought periods, climate extremes, and their interactions not only have significant direct effects on the ecosystems, but also indirectly affect the processes and services of the ecosystems by changing their phenology and stoichiometry (Burrell et al. 2020; Li et al. 2021). Human activities, including urbanization, sedentarization, land-tenure change, and cropland expansion, fracture drylands into spatially isolated pieces, discouraging mobile livestock herding and accelerating land degradation (Li and Huntsinger 2011). Ecological restoration plans have brought certain ecologically positive effects to project areas, but the pressure of vegetation restoration on regional water resources cannot be ignored (Li et al. 2021). Multiple natural and anthropogenic drivers impact ecosystems at different scales. For example, at broad spatial scales, climate variables determine the distribution and dynamics of vegetation; at finer spatial scales, the successional pathway of the rangeland diverges from the regional trajectory under the pressure of livestock herbivory. That is, the mosaics of foraging suggest decoupling between climate and vegetation (Liao and Clark 2018). In the temporal dimension, the dynamics of ESs are the outcomes of the interwoven influences of the faster and slower drivers. It is fundamental to identify and monitor these driving variables to understand and predict ES changes.

Land degradation or desertification is a comprehensive representation of dryland ecosystem deterioration in responding to the interactions of multiple pressures (Box 4.1). Desertification exists widely in global drylands, although vegetation has become greener in some regions in the past decades. Prăvălie (2021) summarized 17 paths of global land degradation. The first five are drought, water erosion, salinization, soil carbon loss, and vegetation degradation. Among them, drought is the foremost factor for desertification, as it relates to 70% of the agricultural degradation of drylands. Desertification usually leads to losses of biodiversity and wildlife habitat, degradation of ESs, the decay of traditional culture and social identity, and the loss of management practices and knowledge that could help halt and reverse land degradation. It also has strongly adverse impacts on non-drylands, which may be located thousands of kilometers away from the degraded areas (i.e., spillover effects). The cascading or cumulative impact of the multiple stressors may not be additive, but rather magnified by their interactions, leading to abrupt transitions in the ESs, possibly followed by catastrophic changes in the SESs. Therefore, it is significant to understand the impacting mechanisms of the multiple stressors on dryland ESs at local, regional, and global scales (Lucatello et al. 2020), as well as the different drivers of ES modeling and the relative contributions and ecological thresholds (Wu et al. 2015; Hauck and Rubenstein 2017).

Box 4.1 Causes and Consequences of Land Degradation in Drylands

Land degradation, namely desertification in dryland, is a pervasive, systemic phenomenon, which occurs in all parts of the terrestrial world and can take many forms. Combating desertification and restoring degraded land is an urgent priority to protect the biodiversity and ecosystem services in drylands.

- **The causes of land degradation**
  - Climate change; Rapid expansion and unsustainable management of croplands and grazing lands; High consumption lifestyles; Widespread lack of awareness of land degradation; Reactive and fragmented institutional, policy and governance responses to address land degradation.
- **The consequences of land degradation**
  - The biophysical impacts include biodiversity loss, crop yeild reduction, losses of soil fertility and stability, aggravating dust storms, downstream flooding, impairment of global carbon sequestration capacity, and regional and global climate change.
  - The societal impacts relate notably to human migration and economic refugees, leading to aggravated poverty and political instability, threatening the long-established resource-use patterns.

- **Aspirations for addressing land degradation and possible actions and pathways**
  - ***Safeguarded biodiversity***. Strengthen protection of biodiversity through enlarged and more effective protected systems, halting conversion of natural land, and large-scale restoration of degraded land;
  - ***Low-consumption lifestyles***. Lower per-capita consumption patterns, including the adoption of more vegetable-based diets and low- and renewable-energy-based housing, transportation and industrial systems;
  - **Circular economy.** Reduced food loss and waste, sustainable waste and sanitation management systems, reuse and recycling of materials;
  - ***Sustainable land management***. Sustainable land management practices in croplands, rangelands, forestry, water systems, human settlements, and their surrounding landscapes, specifically directed at avoiding, reducing, and reversing land degradation (IPBES, 2018).

Scenarios that examine a range of potential futures for one or more components of a system, instead of attempting to predict just one future, have become an important tool to study the sustainability of SESs (IPBES 2019). They provide a useful tool for treating distinct possible scenarios and exploring plausible future trajectories of the direct and indirect drivers of environmental and social changes. Climate scenarios are currently mostly used to predict the extent and ES consequences of drylands. Using different drought indices, conclusions regarding whether the range of global drylands will expand in future climates are inconsistent. Huang et al. (2016) predicted that drylands would expand by 11% and 23% by the end of this century under different climate scenarios (RCP 4.5 and RCP 8.5, respectively) according to the atmospheric aridity index. In contrast, Berg and McColl (2021) found that the scope of global drylands would not expand, based on an ecohydrological aridity index. The results are also different when using other aridity variables (e.g., vapor pressure deficit, runoff, and soil water) (Lian et al. 2021). Nevertheless, with a large amount of evidence, one consistent view is that under the condition of climate warming, the frequency and severity of extreme events (including drought and fire) will be increasingly likely in drylands in the future.

Demographic, social, economic, and technical factors are also bound to change significantly in the future, and they must be taken into account in scenario assessments of dryland ESs. Population growth and agricultural expansion will be accompanied by an increase in water demand. Intensified livestock grazing and large-scale afforestation may further aggravate water shortages and trade-offs with other ESs; although the application of water-saving technology may somewhat alleviate these shortages (Lian et al. 2021). So far, studies on dryland ES predictions under socioeconomic scenarios are inadequate. Current research on causal mechanisms with modeling and controlled experiments rarely considers socioeconomic feedback (Briske et al.

2015). This knowledge gap makes it difficult to judge whether the economic development path and ecological protection measures to resolve social conflicts and environmental degradation in drylands are reasonable. Groups of scenarios, such as the representative concentration pathways, shared socioeconomic pathways, and the Global Environmental Outlook of the United Nations Environment Programme (UNEP), have many common aspects in the underlying assumptions and can be regarded as "archetype scenarios", which represent synthetic overviews of a range of assumptions about the configuration and consequences of the direct and indirect drivers adopted in the scenarios. It is necessary to simulate dryland ES changes under archetype scenarios that reflect the values and guiding principles of society, i.e., the scenarios representing the regional socioeconomic and sociocultural context (IPBES 2019). The resilience and adaptability of dryland SESs in coping with future climate and socioeconomic conditions can be informed by these scenario simulations.

Future ES assessments of drylands should be directed toward an integrated operating model to examine the mechanisms that lead to the joint outcomes of multiple drivers, how their interactions affect system transitions, and how alternative strategies may depend on socioeconomic contexts and traditional knowledge (Liao et al. 2020). To do this, site observations, modeling, remote sensing, and socioeconomic investigation must be integrated to quantify the temporal dynamics and spatial heterogeneity of ESs and to connect cross-scale findings. Spatial modeling in ES evaluations is particularly important because it can provide key information for spatially explicit decision-making and for monitoring the outcomes of decisions (Everard and Waters 2013; Hauck et al. 2013).

4.3 Interactions Among ESs

A key challenge for balancing the protection and development of drylands is to coordinate economic, social, and environmental benefits. This is important for any region, but particularly pressing in drylands (de Araujo et al. 2021). The 2.1 billion dryland residents face water shortages, and half of them are poor and dependent on cropland, rangeland, and natural systems. This requires positive interactions among the ESs provided by the ecosystems. The interactions among ESs include (1) a broad range of trade-offs or synergies between different types of ESs, or between different locations or time periods for a certain ES, and (2) the relationships between ES supply and ES demand, noting that the supply–demand balance is a (mis)match but not a trade-off. In a world of resource constraints and uneven distributions, trade-offs and supply–demand mismatches occur everywhere. ES trade-off is the core of all trade-off issues in the SESs (the others are the conflicting relationships between ecosystem multifunctions, multidimensional HWB, and management goals) (Lu et al. 2021a, b). Along the cascade from ecosystem to HWB, trade-offs are transferred from the biophysical domain to the social domain. With spatially heterogeneous and temporally dynamic human needs, the trade-offs and mismatches between ESs can be enlarged, causing complex interactions among multiple beneficiaries, locations, time periods and even human generations (Seppelt et al. 2011). In order to serve human needs and improve decision-making for a better nature as well as HWB in drylands, it is necessary to explore ways to improve positive interactions among the ESs, i.e., higher synergies among ESs and better supply–demand matches.

4.3.1 ES Trade-Offs

In dryland ecosystems, water, soil, and nutrients are limited. The trade-offs between multiple ESs can be fierce, especially for food provisions, water yield, sediment control, biodiversity, carbon sequestration, and biofuels, which are the most important conflicts for land-use choices. Social factors such as population growth, economic development, and the transition from a nomadic to sedentary lifestyle further affect ES trade-offs, and sometimes lead to ES degradation. Ecosystems are vulnerable to disturbances when their carrying capacities are exceeded. As a single result can seldom be optimized without affecting the other components of the system, trade-off analysis is required in system modeling and management practice. Understanding the main trade-offs can provide effective solutions for the decision-makers and managers.

By using correlation analysis, scenario analysis, spatial association, or overlap analysis, trade-offs have been sporadically evaluated in some studies. Most of these studies focus on the biophysical value of ESs (Dade et al. 2019). The foremost challenge for future studies is to navigate the trade-offs, i.e., tracking the change of ES trade-offs from the biophysical domain to the transformation into human needs and well-being, and trying to tackle them at different knots of the ES cascade. ES trade-offs are derived from ecosystem functions and their spatial distributions and temporal dynamics. It is difficult to define a win–win situation even for the functional traits of plants. In complex SESs, the trade-offs among stakeholders and the different dimensions of HWB can be more complex. Market systems, sociocultural preferences, and management goals all affect ES trade-offs in varied ways. To some extent, the ES valuation method shapes the trade-off outcomes. That is, the output information of the trade-off can be greatly different when using an inconsistent method to quantify the biophysical, sociocultural, and monetary value of ESs (Martín-López et al. 2014). So far, no theoretical or empirical studies have explored the mechanism of trade-off changes from the biophysical to social value of ESs in drylands (Howe et al. 2013).

Driver analysis is another challenge in ES trade-off research. Different action paths may lead to different trade-offs or synergistic consequences under the same driving factor. The failure to include mechanism analysis in trade-off assessments may lead to the mis-identifications of the effect of policy options (Dade et al. 2019; Turkelboom et al. 2018). Driving analysis has not been used in most ES trade-off studies. Existing studies usually consider changes in land use, biophysical conditions, and policy as the most commonly examined drivers, but cultural factors are rarely investigated (Dade et al. 2019). In the Loess Plateau of China, for example, afforestation in abandoned cropland led to increased soil organic matter and soil nitrogen content but decreased soil water content, and the trade-offs varied along the precipitation gradient (Lu et al. 2014). In drylands, social (e.g., water resource management and restoration policy) and environmental (e.g., climate) factors affect ES trade-offs, but this needs to be further explored at different scales. Alternative scenarios and causal inference methods can be used. A multi-process coupled ES model is advantageous in that it provides the driving mechanisms behind the trade-offs among multiple ESs by conducting scenario and causal analyses.

The SES framework originates from system thinking. However, in reality, it is usually impossible to consider all elements at the same time, and compromises are needed when considering overall benefits. The food, energy, and water nexus (i.e., the FEW nexus) has been used as a concept for addressing the key resource and environmental issues in drylands (Olawuyi 2020; Yadav et al. 2021). It is a useful tool to coordinate several ESs and a great improvement in system studies. Recent research has expanded this concept to include ecological integrity (i.e., FEWI nexus) (Müller et al. 2015), which can be used as a more developed framework for dryland trade-off solutions and sustainability. The FEWI highlights not only provisioning food, water, and energy, but also the overall ecosystem integrity and health, fundamental for regulatory and cultural services. In this sense, ecosystem management should consider not only human needs for food, water, and energy, but also the maintenance of biodiversity and natural habitats (Müller et al. 2015). FEW or FEWI does not represent three or four ESs, but bundles of ESs. However, a common caveat of these nexus frameworks is that they miss the varied value dimensions of ESs and their driving forces. It is necessary to develop more advanced frameworks that consider the trade-offs in the biophysical value as well as the socioeconomic value in order to clarify the spectrum of trade-offs from ecosystems to HWB and the driving mechanisms that regulate the interactions of the ES bundles.

4.3.2 ES Demand and ES Flow

Due to the spatial heterogeneity of dryland ecosystems and the population distribution, the supply and demand of ESs have high spatial variability and mismatch (Castro et al. 2014). Several large-scale famines in human history indicated the lack of food supply was not due to insufficient production, but rather inequitable food distribution. In recent times, the social demands have changed from dependence on provisioning services to the need for more regulatory and cultural services (Geijzendorffer et al. 2015). These changes in human needs intensify the contradiction between humans and land.

Research has also shifted from solely focusing on the aspects of ES supply (including ES quantification and trade-off analysis) to understanding the dynamic relationship between ES supply and demand. Early supply–demand analysis emphasized ES surplus and deficit analysis. The ratio or difference between ES supply and demand as well as their changing trends are used as an index for risk evaluations (Maron et al. 2018). Through risk classification, the risk grades (e.g., security, existing risk, and insufficient supply) can be identified spatially to provide a decision-making basis for risk management. For example, by establishing the dynamic and spatially explicit monitoring system of the water supply–demand balance, managers can obtain information about water deficits and abundance and then use engineering such as artificial or semi-artificial canal systems, inter-city water pipelines, and dam regulations to regulate the spatiotemporal allocation of water in a watershed or region.

Supply areas and demand areas of ESs are usually separated. With urbanization, people are migrating from rural areas to cities. Urbanization has become an important driving force that has affected dryland SESs in recent decades. Of the 1692 cities with a population of more than 300,000 across the globe, 35% (586) are located in drylands, and this number is still rising (Cherlet et al. 2018). Urban areas occupy only about 2% of the area of drylands, but they contain nearly 45% of the dryland population. The spatial connection between ES supply and demand areas has changed significantly. Cities and towns become the demand centers of ESs, while suburbs are the main supply areas of ESs (e.g., grain and livestock). Suburban residents rely on ESs provided by local ecosystems and ES flows from other supply areas. However, cities and towns rely on a variety of substantial service flows from the suburbs. ES flow, which refers to the spatial delivery of services from the supply area to the benefit area, has become a popular research interest in recent years. Besides changing the distributions of ES flows, urbanization also alters the balance of resources between rural and urban populations, as it usually encroaches on natural or agricultural lands (Seitzinger et al. 2012).

ES flow is becoming a critical concept and subject of management for alleviating mismatches in quality or quantity between the supply and demand of ESs in space and time. ES flows can be classified into four categories in terms of transportation paths: biophysical flow through species migration and dispersal, biophysical flow through processes in air, water and soil, biophysical flow of traded goods and embedded ESs through an artificial carrier, and information flow through information networks (Schröter et al. 2018). ES flows can be classified into another four categories in terms of the spatial and directional characteristics of the flows: non-proximal ES flow such as climate change mitigation, directional ES flow such as water yield, omni-directional ES flow such as pollination, and ES flow related to user movement such as cultural services (Xu et al. 2019a, b). These classifications are potentially useful for managers to make correspondingly appropriate strategies of ES delivery, but more empirical studies are needed to explore the mode and mechanism of ES flow transportation and allocation. The ES flow concept is also useful in ecological protection and the restoration of drylands to expand the areas from only those with high biodiversity and ES provisions to those with ES flow paths (e.g., vegetation corridors, waterways, and air channels).

“Telecoupling” refers to socioeconomic and environmental interactions over distances (Liu et al. 2013). It is also used to describe the occurrence of ES flow at large spatial scales (e.g., regional or global). Ecosystems are ever more affected by distant interactions among countries or regions in globalization. The telecoupling analysis framework provides a new method for analyzing the spatial correlation between ES supply and demand. In this framework, multiple supply and demand areas can be regarded as interrelated nodes in a network. The effects of local actions on systems in distant places can be noticed in ecosystem management. Spillovers are a result of these telecouplings whereby effects of seemingly unrelated events in one region can be experienced in other regions. Some studies have demonstrated the substantial impact of telecouplings on environmental benefits in distant countries, such as international trade. Another example is carbon sequestration, which has regional spillovers (i.e., improving agricultural productivity) and global spillovers (i.e., mitigating climate change) (Plaza-Bonilla et al. 2015). Network analysis is expected to become a new technical tool to better reveal the size, direction, and changes of ES flows in time and space (Liu et al. 2013). Establishing and evaluating the ES flow network is an important research direction to deal with supply–demand mismatches. Future studies should combine ES flow or the telecoupling framework with trade-off analysis (noting that it deals with multiple rather than single ESs) and investigate the spillovers.

4.4 Contributions of ESs to HWB

The internal relationship between ESs and HWB is a challenging topic. By clarifying the mechanisms between ESs and HWB, we can explain the interaction and feedback in the “circle” of poverty and land degradation in drylands (Barbier and Hochard 2018). Recent theoretical studies and sporadic empirical studies show that the key is to determine which dimensions of HWB are most relevant to ecosystems (Leviston et al. 2018).

4.4.1 Mediating Factors from ESs to HWB

HWB is multidimensional and includes basic materials, health, safety, good social relations, and freedom of choice and action. Poverty is essentially the lack of wellbeing, and it is also multidimensional. A high percentage of people living in drylands are still reliant on basic needs for survival, and poverty is the largest obstruction to social and economic development.

Although it is commonly understood that HWB depends on natural capital and services, little empirical research has been conducted to explore the mechanism of how ESs contribute to HWB. According to the review of Suich et al. (2015), there are about 250 research papers detailing the relationship between ESs and HWB. Of these, 39 articles offer a quantitative analysis, of which 21 focus on farming systems and only four on dryland ecosystems. The ESs most widely associated with poverty usually include water supply, the diversity of wildlife and crops, species and quantity of livestock, green vegetation, and peatland. For dryland SESs, soil conservation and available habitats are also highlighted (Suich et al. 2015). Some of the internal mechanisms of the transformation from ESs to HWB are more intuitive, but some may be hidden in multiple paths and processes and not easily identified.

Cruz-Garcia et al. (2017) reviewed the relationship between ESs and HWB in Africa, Asia, and Latin America. Of the 462 publications, 71% assumed that there was a link between ESs and HWB, but only 29% reported an empirical test of this hypothesis. The analyses were mainly for European and North American countries, with very few for Asia, Africa, and Latin America. Ten ES-HWB relational frameworks were used in these case studies, but 82% of the studies used the simplified framework of MA. The rest were applied only once, indicating that the current ES-HWB framework is still theoretically oriented and difficult to apply in empirical studies, especially of fisheries, wetland, and grassland systems. Also, studies on the ES–HWB relationship mainly focused on provisioning and regulatory services, with relatively little attention to cultural services (Leviston et al. 2018).

ESs and HWB relations are regulated by a range of overlapping factors in the SESs at different scales (IPBES 2019). Mediating factors are the variables that affect how ecological processes bring benefits (and their values) to people (Mandle et al. 2020; Duraiappah 2011). They are similar to the indirect drivers of ESs, including the market access mechanism, macroeconomic conditions, power and governance, tenure security, institutions and rights, and financial assets (Horcea-Milcu 2015). Mediating factors are important to consider for an accurate representation of ESs in decision-making. In dryland SESs, the core goals of coordinating all the relevant mediating factors should be combating desertification and restoring degraded land and soil. This is related to a range of SDGs. These mediating factors may affect the change and benefit distribution of ESs, ultimately affecting the realization of well-being (Suich et al. 2015). More empirical research is needed to test the connections and reveal their internal mechanisms.

4.4.2 *Quantifying the ES-HWB Relations*

The relationship between ESs and HWB is not one-to-one correspondent. Some methods are used to quantify the ES–HWB relationship in some sporadic studies, including ecosystem accounting, unified indicator (i.e., using a specific ES flow, carbon flow or water flow, as a unified indicator to measure ES and HWB) (Xu et al. 2019a, b), the structural equation model (SEM) (which identifies the direct and potential ES variables that affect well-being) (Santos et al. 2015), the relative rate of change (i.e., the ratio of change in HWB to the change in ecosystem services) (Daw et al. 2016), and Nexus Webs approach (Levistona et al. 2018).

One difficulty in quantifying ES contributions to HWB is that many ES and HWB indicators have different units. Ecosystem accounting aims to quantify the value of ESs to understand how much the value of ESs is involved in social capital (Lavorel et al. 2020). It is intuitive to estimate the economic value of ESs and analyze its contribution to social economy. Challenges to using the economic value of ESs include determining the economic end, avoiding double counting, and reducing uncertainties in valuation methods. Xu et al. (2019a, b) drew on a similar idea, but they directly used biophysical quantities instead of economic value, i.e., carbon flow, as a link for a variety of services and well-being indicators in a "mountain-oasis-desert" system. Santos et al. (2015) used the SEM method to quantitatively analyze the relationship between biodiversity, ESs, and HWB in a national-scale study of Spain. SEMs can incorporate many indicators (including driving forces, biodiversity, ESs, and HWB) into a Driver-Pressure-State-Impact-Response (DPSIR) conceptual framework and analyze the direct and indirect quantitative relationships among indicators, but their disadvantage is the lack of an explanation of the internal mechanism of the relationships. Within the resilience framework, Daw et al. (2016) developed the concept of ES resilience to describe the sensitivity of HWB to ecosystem changes. A high ratio of ΔHWB/Δ ecosystem stocks indicates a close relationship between ESs and HWB, and a low ratio indicates low resilience and decoupled correlations. This resilience method can be applied to compare the elasticity of different benefiting groups at different scales, which is helpful to understand the vulnerability of different social actors to ecosystem change. Some studies also found that the sensitivity of HWB change over ES change depends on the scarcity of the ESs. When the supply (relative to demand) of ESs is sufficient, a marginal increase in ESs can only lead to small changes in HWB; however, when an ES is lower than a threshold, small changes in the ecosystem may lead to a significant reduction in HWB (Liu et al. 2007). However, the application of this elasticity method in a highly dynamic environment is challenging because it is hard to determine under what circumstances the threshold of ESs will be transmitted to HWB and cause abrupt changes. Levistona et al. (2018) employed a Nexus Webs framework to investigate the inter-dependencies of ES and HWB. The Nexus Webs framework provides a method for integrating biophysical and socio-economic modeling and the assessment of HWB. Each Web contains a number of components (e.g., water, energy, and biodiversity), organized sequentially via system dynamics. The challenge of this model is to construct the linkages between the components.

Some theoretical studies suggest that ES value chain analysis and system dynamics should be combined to identify the chain reactions with biophysics and the social economy in each value chain of ESs. For example, it is unclear whether the grassland landscape improves the well-being of residents through the production of animal husbandry or tourism income. The pathways are multidimensional and nonlinear. How ESs affect people's identity cognition, values, spiritual feelings, traditional beliefs, and overall well-being remains unknown (Suich et al. 2015). Due to the complexity of SESs, the behavior of the system is often difficult to predict. System dynamics is relatively simple when analyzing supply services and regulatory services, but for some ESs (cultural services and some other regulatory services) that lack an understanding of the intermediate processes, system analysis is more difficult. More developed methods that include legacy effects, slow effects, and the complementary behavior of ecosystems are needed to better describe and predict the contribution of ESs to the welfare of humans (TEEB 2013), considering that the scale and boundaries of ESs that impact HWB. The resilience framework brings our attention to system dynamics. This framework has the potential to advance ES science and solve complex nonlinear issues in the SESs.

Efforts need to be made to refine variables that represent different dimensions of HWB corresponding to the SDGs of drylands, the demand preferences of residents in drylands for ESs (food security, water security, health, income, assets, and employment), and the influencing factors. Traditional methods to quantify HWB variables include statistics, questionnaires, and social surveys. These methods all have uncertainties associated with a small sample size, poor timeliness, low data availability, and low accuracy. A challenge and opportunity for HWB quantification is to establish a big data platform of indicators and a database of drylands. It is necessary to integrate the existing data and build a data interface for dynamic evaluations of HWB with the help of modern internet technology and artificial intelligence. At present, research of the ES–HWB relationship is mostly theoretical. Many open questions must be answered by empirical studies (Box 4.2). It is also necessary to conduct an in-depth mechanism analysis of the relationship between ESs and well-being by conducting empirical studies so as to test the validity of currently proposed methods and provide clear guidance for ES management practices. ESs and HBW (especially poverty reduction) also need to be effectively integrated into national and global sustainable development agendas and mainstream policies (Pires et al. 2021). Biodiversity is the basis of ESs and HWB, but correlation analyses with biodiversity are still insufficient. For countries with high biodiversity yet drought and poverty, it is particularly important to combine biodiversity, ESs, and HWB (Pries et al. 2018).

Box 4.2 Human Wellbeing Indicators and Key Questions

- ***HWB indicators:***
  - Food security and domestic water security (basic human needs); energy security, economic security, and sense of security (community resilience to change, connection, migration, gender, social cohesion); environmental security (sustainability); health (mental and physical health, spiritual/aesthetic value, peace, free will).
- ***Key questions:***
  - Are primary dimensions of HWB the same across different SESs?
  - Are some dimensions of HWB more critical than others? Are there trade-offs between these dimensions?
  - Which indicator of ES or NCP contributes to well-being in what way? Is this mode diversified among different SESs?
  - Are the relationships between ES and HWB direct and linear, or are there optimal ranges?
  - What roles do aspects of personal sense of control and place attachment play in moderating relationships between HWB and ES?

- What are the ‘threshold points’ beyond which ES decline has a significant, meaningful, lasting impact on dimensions of HWB, and vice-versa?

4.5 Landscape Optimization for ESs

Improving the resilience of the whole SES depends on improving the resilience of both ecological and social subsystems (Cumming 2011). In complexity theory, it is assumed that there are common potential mechanisms in different systems. We expect that the interactions between patterns and processes of social systems and ecosystems may have similarities in terms of the spatial principles and mechanisms (Cumming 2011). Spatial resilience is an important component of resilience theory. A new area of research involves applying resilience theory at the landscape scale (Allen et al. 2016). The landscape scale is a more operable scale in resilience management than local and global scales, as the local scale is too small to be included in the structure and process of the SDGs, and the global scale is too large to describe the fine mechanisms that can guide management strategy. As a geographical unit with the closest combination and the strongest interaction between humans and nature, landscapes are the proper working unit for ES optimization and sustainable path selection in drylands (Wu 2013). Understanding landscape processes, including both natural and social processes and their correlation with the landscape structure, is crucial for forecasting landscape changes and their consequences for ESs and HWB (Yirdaw et al. 2017).

4.5.1 Spatial Resilience

Spatial resilience refers to the interactions between the spatial variations of internal variables (corresponding to spatial heterogeneity), external variables (corresponding to driving feedback factors), and the resilience of the whole SES on multiple spatiotemporal scales (Cumming 2011). It is currently one of the most advanced concepts in ecology, aiming to explain the elasticity and convertibility of heterogeneous and dynamic systems. Identifying disturbances, defining boundaries, quantifying diversity, and identifying connectivity are some important procedures in spatial resilience assessments (Allen et al. 2016).

In dryland SESs, the typical concepts of “patch” and “connectivity” in landscape ecology have the potential to deepen our understanding of pattern–process relations and improve system resilience. The spatial distribution of vegetation patches and connectivity dynamics has a significant impact on ES supply, demand, and flow (the flow of ESs from a “source patch” to a “sink patch”), and also trade-offs (/synergies) and the supply–demand (mis/) matches of ESs. In the biophysical domain, ESs such as carbon sequestration, soil erosion, and crop yields are all affected by vegetation connectivity and hydrology connectivity in drylands. For example, increasing vegetation connectivity in cropland can promote pest movement and reproduction and then potentially reduce crop production, but decreasing the connectivity of natural vegetation can impede pollination; and increasing hydrological connectivity in the vegetation-bareland mosaics can increase soil erosion and water loss, leading to positive feedback between the loss of vegetation patches and an increase of bare soil patches. A review paper suggested that ESs can be negatively affected by decreasing connectivity, especially for regulatory services such as pollination (Mitchell et al. 2013). This indicates that connectivity may have multiple impacts on ES depending on ecosystem type, the expected ES, and connectivity metrics. In fact, dryland residents have been managing the connectivity of their lands throughout history, with runoff control in agricultural practices, no-tillage, farmland shelterbelts, and straw checkerboard fences for vegetation restoration. However, these practices have not been comprehensively evaluated or raised to theory (Okin et al. 2018). Similarly, in the social domain, social exclusion—that is, the unavailability of resources, ESs, and markets—is the manifestation of the fracture of connectivity in the social system. Therefore, social governance is required to strengthen the connections between the key elements that affect ES flows, such as between the locations of ES supply and demand, ES production and the market, residents and green infrastructure, and power and rights. All of the elements and relationships in both domains of SESs (i.e., ecological and social domains) have relevant spatial locations and spatial properties. The concept of connectivity provides new insight to understand dryland ecology and socioecology.

Scaling is a typical challenge in ecological and SES studies. With the spatially hierarchical structure in the SES, spatial resilience at a finer scale can provide spatial countermeasures for optimal regional layouts (Li et al. 2021). Field and Parrot (2022) conducted pioneering research to quantify the functional connectivity of three types of ES (water flow, food, and landscape aesthetics). They explored how the change of one ES provision can affect another by altering functional connectivity. Landscape ecology has the potential to apply its principles, such as corridor theory, to enrich ES flow and spatial trade-off studies and to advance resilience science (Beller et al. 2019). Spatial resilience should be one of the major considerations in landscape optimization. Landscape management and dryland restoration should be designed from the perspective of spatial resilience by establishing a multi-center and multi-scale governance system that considers inter-patch relations and connectivity (Cumming et al. 2017).

4.5.2 Landscape Optimization

Land-use management is one of the basic factors for improving the structure and multifunctionality of landscapes (Plaza-Bonilla et al. 2015). Limited to small scales, earlier ecosystem management and governance inadequately considered the concept of space (Cumming 2011). Agricultural production and many other ESs need to make the best use of the structure of land systems. This requires coordinating integrated designs of landscapes with livelihood acquisitions. Such designs are called “land system architectures” (Verburg et al. 2013). They represent the application of ecological theory to management practice for optimizing land use at the governance level. Although traditional land-use planning objectively reflects the economic function of land use, it ignores the value of multiple ESs.

Landscape optimization originates from the concept of land-use structure optimization, which aims to achieve an optimal ecological and economic solution. As a new research and management tool in ES management, the purpose of landscape optimization is to increase the resilience of the SES by optimizing the landscape, improving the provisions for ESs, decreasing trade-offs, and facilitating ES flow delivery to users. It is impossible to maximize all ESs, and this it is not the nature of optimization. In theory, it is more resilient and more effective if nothing reaches the maximum so that a certain degree of redundancy can be maintained. Such a system is more resilient to environment variability and more economically cost effective. Focusing on optimizing one specific ES is dangerous and insufficient. Rather, the focus should be on the trade-offs of multiple ESs and their connectivity (Nguyen et al.2018; Wu et al. 2018; Field and Parrot 2022).

Landscape-level ecological restoration is considered an effective way to enhance both biodiversity and the provisions of ESs (Schiappacasse et al. 2012), and it pertinent to the rehabilitation of degraded drylands. Identifying appropriate restoration methods to induce short- to long-term recovery is often hindered by inconsistent value systems, knowledge systems, and ruling institutional systems (Gorddard et al. 2016). The empirical work led by the International Network for Sustainable Drylands suggested that it is crucial to promote a transformative framework for sustainable land management considering multiple SDGs, their synergies and trade-offs (Huber-Sannwald et al. 2020), and multiple sectors or actors who determine an optimal combination and compromise of multiple ESs (Lucatello et al. 2020). Combining participatory and spatial optimization modeling can help determine the priority of investment locations to mitigate degradation, and map the supply of ESs by prioritizing the ES of a region. Then, according to the vulnerability of ESs to land degradation, the priority of important investment areas can be determined (Willemen et al. 2017). Combining biophysical and socioeconomic perspectives will help local or regional decision-making by organizing ideas and determining key system attributes (Verón et al. 2017).

Landscape assessments are the basis for landscape optimization. They are used to determine whether the spatial arrangement of the key elements of a landscape is appropriate for ES synergy and delivery before further modifications are made. Landscape optimization and assessment form a feedback process: the landscape can be further optimized based on the results of an assessment. Network analysis is a useful tool to assess the composition of local species, biogeographic modes, and social relations. Bayesian networks have been used to assess ES trade-offs and hydrological connectivity, and to support decision-making and planning in water use in drylands

(Crossman and Pollino 2018). The advantage of this method is that it integrates different forms of data, particularly in relating the potential outcomes of management interventions to a defined set of endpoints by integrating non-commensurate data values and types (McVittie et al. 2015). Spatial scenario modeling is another option in which a large number of landscape scenarios can be tested to select the most favorable ones according to varied optimization goals. For example, restoring cropland to grassland is effective to produce more water, but restoring cropland to a mosaic of grassland, forest, and shrubland is a compromise that offers relatively abundant water and higher carbon sequestration in a semi-arid watershed (Wu et al. 2018). So far, research to identify and evaluate disturbances and boundaries, diversity and redundancy, and the connectivity of multiple ESs—the main aspects for resilience assessments—is still rare (Allen et al. 2016). By only focusing on the flows of individual ESs, previous studies did not consider the interactions and feedback among ESs and how these relationships might influence landscape resilience (Field and Parrott 2017). The procedure of optimization becomes more complex when the goal becomes more oriented to improve system resilience and SDGs. Landscape optimization modeling that includes the elements of ES interaction and spatial connection will be an important research direction for future dryland ES studies.

4.6 Ecological Compensation and Payment for ESs

Ecological compensation is a positive conservation action to counter-balance the loss of ES value in resource use and management (Brown et al. 2013). The relevant projects include compensatory mitigation, biodiversity offsets, mitigation banking, habitat banking, species banking, wetland mitigation, etc. (OECD 2016). Payment for ESs (PES) occurs when a beneficiary or user makes a direct or indirect payment to the provider of ESs (for maintaining or avoiding decreases in ESs) (Nelson et al. 2008), or where the government acts on behalf of the ES buyer and makes payments as a third party (Schomers and Matzdorf 2013). While the terms “ecological compensation” and “PES” are often used interchangeably, ecological compensation is a broader term that includes PES-like policies/programs and a variety of other policy/program types (Zhang et al. 2010). Ecological compensation or PES is theoretically an effective way to achieve the “win–win” goal of coordinating ecosystem protection and socioeconomic development based on the market mechanism or financial transfer mechanism. Increasing investments in drylands is financially promising and socially rewarding. In certain circumstances, PES can create new revenue streams for conservation and has been interpreted as “making trees worth more standing than cut down” (Salzman 2011).

Ecological compensation internalizes ES externalities, and it has been applied in many countries and regions. Most cases involve national compensation plans based on government financial transfer (i.e., the Pigovian concept). Although different terms are used to describe the practices, relatively few cases are PES-like programs based on market economics through private negotiations between stakeholders (i.e., the Coasean concept) (Sommerville et al. 2009). For example, China has implemented large-scale ecological compensation in the Natural Forest Protection Project (NFPP), and the government has provided compensation to areas that experienced economic losses caused by logging restrictions and offered compensation for reforestation and sustainable forest management. In the Green for Grain Project (GfGP) with a more extensive scope, the Chinese government provided grain and living subsidies to farmers for the sake of returning farmland to forests or grasslands. This kind of conceptualized ecological compensation for PES reflects a compensation mechanism limited by national legislation (Schomers and Matzdorf 2013). On a trans-regional or transnational scale, the global environment facility (GEF) and international PES (IPES) may contribute to ecological protection and restoration on the global scale. For example, the IPES can help mitigate deforestation in the regions that contribute significantly to global climate mitigation (e.g., three-quarters of Brazil's carbon emissions come from deforestation).

By developing institutions, expertise, and market infrastructure, government-financed payments, the private sector, and NGOs have driven a rapid increase in market-based PES (Bremmer et al. 2016; Vogl et al. 2017). PES-like programs in watersheds are regarded as the most mature PES in the light of transaction value and geographical distribution (Salzman et al. 2018). However, some studies indicate that most of them are unable to demonstrate the effectiveness of PES on water-related ESs in watersheds (Brouwer et al. 2011; Yan and Joachim 2018). This is because water-related PES studies are usually based on empirically untested assumptions about the relations between land use and water flow. They lack baseline data and a control design, which are required to analyze the externalities and to determine which beneficiaries need to be paid and how much. The root cause is that most PES studies are not originally designed for a rigorous evaluation of PES effectiveness (e.g., comparison between PES and non-payment) (Salzman et al. 2018).

Ecological compensation or PES was proposed as an important measure to combat desertification and land degradation by 2030 (Li et al. 2018). However, the theoretical regime has not been well established. Assessments of ecological compensation for restoring degraded lands are complicated. It is difficult to obtain accurate estimates of the potential costs of avoiding desertification or restoring degraded drylands. Therefore, a common argument in favor of action is to add up the "damage costs" or foreclosed revenue, including the loss of ESs due to degradation, and the approximate cost of restoring a particular area. This usually generates a large amount of monetary value (Nkonya et al. 2016). Existing ES valuation methods still cannot reasonably estimate the value of all ESs, and in fact PES captures only a small part of the value of ESs. Existential value, option value, and many public goods interests are considered to be outside the scope of the PES mechanism. PES actions are often questioned for having the adequacy of the levels of compensation involved (Franco et al. 2013; Dell'Angelo et al. 2018) because inadequate PES level could reverse the initial expected potential benefits due to natural disasters (such as severe drought), reduced policy support, or greater profits through other management alternatives (Plaza-Bonilla et al. 2015). In the cases where the income flow of PES itself is not enough to motivate land owners to adopt beneficial land practices (Salzman et al. 2018), the combination of PES with other strategies such as subsidies is needed. Therefore, fairness and efficiency must be balanced under specific conditions (Bellver-Domingo et al. 2016). PES represents a relatively new policy instrument for drylands but offers great potential as an income generator. Motivated buyers, motivated sellers, metrics, and low-transaction-cost institutions are the important features for PES up-scaling (Salzman et al. 2018). Other options for a better PES design include creating new markets for ESs, such as carbon and water, and establishing subsidy programs that help land users overcome the initial costs of changing land use and management. With improved PES plans, investment in drylands can be promoted (Thomas et al. 2014).

Some researchers argue that ecological compensation or PES is unlikely to be successful for drylands if the action does not consider the goal of poverty reduction, particularly for developing countries (Plaza-Bonilla et al. 2015). Drylands are a global economic community, providing important services for life-support systems worldwide. Like biodiversity and tropical forests, drylands should be treated as global environmental commons (Stafford-Smith and Metternicht 2021). It has been argued that local or regional sustainable development policies for drylands must be included into global development agendas, by mainstreaming and coordinating funds from multiple policies and initiatives to support ecological compensation in dryland restoration (Plaza-Bonilla et al. 2015).

Importantly, targeted governance and management countermeasures should be put forward according to the characteristics of drylands. For example, the total carbon sequestration of drylands is large but distributed in a very large area that is not as concentrated as the carbon storage of forest ecosystems and thus relatively uneasy to measure. Integrating measurements, evaluations, and telecoupling analysis of ES flow and ES value is critical for drylands. A recent study reported an impressive example of payments for wind erosion control services considering regional differences. The physical quantity of wind erosion maintenance services was calculated according to weight factors such as regional GDP, population density, and dust concentration in the atmosphere, combined with the willingness to pay of the people in the beneficiary area. Then, the biophysical quantity of trans-regional and transnational ES flows are transformed into the flow of economic value, and the reference line of PES is given (Xu et al. 2019a, b). The novelty of this study is that it establishes a quantitative relationship between ES flow and PES, and provides a spatially clear visualization tool for PES policymaking from the perspective of ES flow, in which both contributors and beneficiaries are clear.

Theoretically, more rigorous metrics that align with conservation goals and accurately capture ES values and transaction costs need to be further developed (Salzman and Ruhl 2000; Maron et al. 2018). Practically, PES is feasible when the metrics are easily accessed and the exchanges and assessment mechanism are efficient for identifying ES holders (Salzman et al. 2018). Furthermore, approaches and models are needed to guide practices of PES programs to support sustainable development by integrating linkages between influencing factors, livelihood activities, and socioeconomic outcomes (Wu et al. 2021). PES still has some defects, but it can be solved by improving the design. From a research perspective, the challenge is to design PES plans from a multidisciplinary and interdisciplinary perspective, with long-term outcomes as the priority. This design cannot be limited to too small a scale when applied to drylands. It should instead deal with ES externalities with a large span of ES flows and trans-regional impacts. In addition, a deep relationship between cultural services and relationship values and land should be established, which is the internal driving force for landowners to manage ecosystems (Chan et al. 2017). A reasonable PES payment standard can promote the restoration and protection of ecosystems and maintain the sustainable supply of ES biophysical flow and value flow. And, it can close the gap between ecology and regional economic development and provide a poverty reduction path for poor groups who provide ESs, even if it cannot completely solve the problem of poverty. It also opens up a scheme that can be further designed for the realization of the goal of poverty eradication. Therefore, PES is a promising tool of environmental policy to tackle and understand the feedback between social systems and ecosystems.

4.7 Summary

An ES paradigm provides a perspective and method for analyzing the relationship between nature and people in drylands, but many theories and assumptions need to be confirmed by empirical research. Existing research on dryland ES mainly focuses on the evaluation of single services. The trade-off between various ESs, the relationship between the supply and demand, the transfer path of ESs, and the mechanism of the ES–HWB relation are still weak. Cross-scale ES trade-offs and the driving factors of the dynamics and distribution of ES flows remain poorly understood. From the perspective of system feedback, there is also a lack of sufficient practical experience on how to better formulate land use strategies and ecological compensation strategies. As global drylands contain a variety of SES types, each type has specific land use and livelihood characteristics. It is necessary to carry out systematic comparative research across different SES types on different scales, summarizing the general laws and regional dependence characteristics of the relationship between ESs and HWB. Regional comparisons and multi-site syntheses are needed to improve global modeling and the knowledge base of drylands. This is favorable for developing the connotation, methods, and paradigm of ES science, and to provide systematic experience and scientific support for formulating a sustainable development path of drylands from local to global. Future research needs to (1) establish a long-term socioecological monitoring network, (2) further develop the quantitative method of dryland ESs, optimizing the parameters of ES models and strengthening verification and scenario analyses, (3) explore the mechanism of ES change under multiple pressures, (4) clarify the path and direction of ES flow, and (5) make overall land use and PES planning at the policy and management levels. These are all important for understanding the ES–HWB relationship and for combating dryland degradation and reducing poverty.

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